Piia Konstari

CHARACTERISTICS OF SUSTAINABILITY-ORIENTED INNOVATION ACTIVITIES IN A SHARED SEMICONDUCTOR INFRASTRUCTURE – INSIGHTS ON THE EUROPEAN, REGIONAL AND ORGANISATIONAL LEVEL

ACTA UNIVERSITATIS LAPPEENRANTAENSIS 1263

Piia Konstari

CHARACTERISTICS OF SUSTAINABILITY-ORIENTED INNOVATION ACTIVITIES IN A SHARED SEMICONDUCTOR INFRASTRUCTURE – INSIGHTS ON THE EUROPEAN, REGIONAL AND ORGANISATIONAL LEVEL

Dissertation for the degree of Doctor of Science (Technology) to be presented with due permission for public examination and criticism in the Auditorium 1316 at Lappeenranta-Lahti University of Technology LUT, Lappeenranta, Finland on the 10th of December 2025, at noon.

Acta Universitatis
Lappeenrantaensis 1263

Supervisors Professor Ville Ojanen
LUT School of Engineering Sciences
Lappeenranta-Lahti University of Technology LUT
Finland

Professor Leonid Chechurin
LUT School of Engineering Sciences
Lappeenranta-Lahti University of Technology LUT
Finland

Docent, D.Sc. (Tech) Katri Valkokari
Data economy and foresight
VTT Technical Research Centre of Finland Ltd
Finland

Reviewers Professor Magnus Hellström
The Faculty of Science and Engineering
Åbo Akademi
Finland

Associate Professor Laura Piscicelli
Copernicus Institute of Sustainable Development
Utrecht University
The Netherlands

Opponents Professor Magnus Hellström
The Faculty of Science and Engineering
Åbo Akademi
Finland

Associate Professor Laura Piscicelli
Copernicus Institute of Sustainable Development
Utrecht University
The Netherlands

ISBN 978-952-412-380-8
ISBN 978-952-412-381-5 (PDF)
ISSN 1456-4491 (Print)
ISSN 2814-5518 (Online)

Lappeenranta-Lahti University of Technology LUT
LUT University Press 2025

Abstract

Piia Konstari
Characteristics of sustainability-oriented innovation activities in a shared semiconductor infrastructure – Insights on the European, regional and organisational level
Lappeenranta 2025
88 pages
Acta Universitatis Lappeenrantaensis 1263
Diss. Lappeenranta-Lahti University of Technology LUT
ISBN 978-952-412-380-8, ISBN 978-952-412-381-5 (PDF), ISSN 1456-4491 (Print), ISSN 2814-5518 (Online)

Semiconductor device fabs are cost intensive and consume large quantities of energy, water and raw materials, as well as generate waste and greenhouse gas emissions. Shared-use semiconductor infrastructure is a sustainable and cost-efficient option for small- and medium-sized companies in particular. Such shared infrastructures are often provided by research and technology organisations (RTOs) or universities.

The focus of this thesis is on sustainability-oriented innovation (SOI) activities in an RTO-driven shared-use semiconductor infrastructure that can also be studied as a provider-driven living lab. The SOI topic is analysed on three levels: the European level, regional level – i.e. the company ecosystem round and in the shared infrastructure – and the organizational level of the shared infrastructure provider and users. In this setting, this thesis studies characteristics of SOI to determine the focus of SOI activities, the value creation and capture of SOI activities, and the impact on various horizons of the SOI activities within the shared semiconductor infrastructure.

The characteristics of SOI activities have not been previously explored within this type of semiconductor environment in a multi-disciplinary context. The academic discussion about SOI focuses on the integration of economic, environmental and social aspects into the innovation process and management practices. Only a limited number of publications address case studies or incorporate sustainability aspects into industry specific scenarios.

The research methods are qualitative multiple case studies and design science research between 2023 and 2025. This research identifies the SOI activities within the shared semiconductor infrastructure and its users, defines the value creation and capture pathways, and maps the impact pathways of the SOI activities on various horizons.

This research provides avenues for further research of SOI activities in varying industry-specific contexts, of dynamics in shared infrastructures, and for studying SOIs as well as their impact in a variety of industries and geographies.

Keywords: Semiconductors, sustainability-oriented innovation, shared-use infrastructure, green innovation ecosystem.

Acknowledgements

This work was carried out at the Microelectronics and quantum technology research area of VTT Technical Research Centre of Finland Ltd, Finland, between 2023 and 2025.

I would like to express my sincere thank you to Tauno Vähä-Heikkilä, for giving me the possibility to tackle a doctoral thesis at side of my work and for suggesting a topic for it.

A sincere thank you to Professor Ville Ojanen for being my supervisor at Lappeenranta-Lahti University of Technology LUT and for stretching timetables to make this dissertation come true.

Likewise, thank you to Professor Leonid Chechurin for being my secondary supervisor at LUT.

A huge warm thank you to Katri Valkokari, who agreed to be my supervisor at VTT and stretched her schedules to an outermost while guiding me on the journey, as well as was my co-author in all the publications.

I would like to express my sincere gratitude to the preliminary examiners Professor Magnus Hellström and Associate Professor Laura Piscicelli. Likewise, a huge thank you to Professor Magnus Hellström and Associate Professor Laura Piscicelli for agreeing to be my opponents.

Thank you as well to my colleagues at VTT who have engaged into discussions about the subject over time - you know who you are.

Last, but not least, I would like to express a huge thank you to my husband, my mother, and my parents in law for all the support during the process. Thank you as well to my children.

Piia Konstari
November 2025
Espoo, Finland

To Oliver, Frida and Klara.

Contents

List of publications

This dissertation is based on the following papers. The rights have been granted by publishers to include these papers in the dissertation.

I. Konstari, P., & Valkokari, K. (2025a). Green innovation ecosystems in the semiconductor industry - the role of European research and technology organisations. *Sustainable Futures*, *10*, 101127. https://doi.org/10.1016/j.sftr.2025.101127 (Konstari and Valkokari, 2025a)

Authors contribution: Piia Konstari is the principal author and principal investigator. Katri Valkokari has contributed to methodology and supervision.

II. Konstari, P., & Valkokari, K. (2024). Drivers and barriers for open innovation for sustainability in a shared semiconductor infrastructure. *Journal of Open Innovation: Technology, Market, and Complexity*, *10*(4), 100395. https://doi.org/10.1016/j.joitmc.2024.100395 (Konstari and Valkokari, 2024)

Authors contribution: Piia Konstari is the principal author and principal investigator. Katri Valkokari has contributed to methodology, conceptualisation and supervision.

III. Konstari, P., & Valkokari, K. (2025b). Value creation and capture from sustainability-oriented innovations in a shared semiconductor infrastructure. *Sustainable Technology and Entrepreneurship*, *4*(2), 100104. https://doi.org/10.1016/j.stae.2025.100104 (Konstari and Valkokari, 2025b)

Authors contribution: Piia Konstari is the principal author and principal investigator. Katri Valkokari has contributed to methodology, conceptualisation and supervision.

IV. Konstari, Piia, Valkokari, Katri (2025c). *Roles for and impact creation of sustainability-oriented innovations in a shared semiconductor infrastructure*. *International Journal of Innovation Management 29. https://doi.org/10.1142/S1363919625400201* (Konstari and Valkokari, 2025c)

An early version of this article has been published as part of the proceedings of XXXVI ISPIM Innovation Conference, held in Bergen, Norway on 15 June to 18 June 2025. ISBN 978-952-65069-9-9 (Konstari and Valkokari, 2025d)

Authors contribution: Piia Konstari is the principal author and principal investigator. Katri Valkokari has contributed with methodology and supervision.

V. Konstari, Piia, Valkokari, Katri (2025e). *Integration of multi-disciplinary environmental sustainability aspects into early-phase microelectronics research and development. Discover Sustainability 6, 1089*. https://doi.org/10.1007/s43621-025-01980-6 (Konstari and Valkokari, 2025e)

Authors contribution: Piia Konstari is the principal author and principal investigator. Katri Valkokari has contributed with methodology and supervision.

Nomenclature

Abbreviations

ARA	actors, resources & roles, activities
CAGR	compound annual growth rate
GI	green innovation
IP	immaterial properties
LCA	life cycle assessment
LL	living lab
MNC	multi-national coproration
OI	open innovation
R&D	research and development
RIE	regional innovation ecosystem
RQ	research question
RTO	research- and technology organisation
SDG	sustainable development goal
SME	small- and medium-sized company
SOI	sustainability-oriented innovation
Sub-RQ	sub- research question
UN	United Nations

Declarations

Turnitin

The originality of this dissertation has been reviewed with the Turnitin similarity checking service.

Commercial software

This dissertation was prepared with the help of the following commercial software:

NVivo 14 - a qualitative data analysis software that I used for data coding, classification and analysis. NVivo licensed software is provided by VTT Technical Research Centre Ltd for Piia Konstari. I utilised NVivo 14 for the qualitative data coding in Publications II, III, and IV.

AI use

During the preparation of this doctoral dissertation, Piia Konstari, the author of the dissertation, used Microsoft CoPilot to develop the presentation and grammar of textual information in the summary of the dissertation. After using CoPilot, the author reviewed and edited the content and takes full responsibility for the content of the doctoral dissertation.

1 Introduction

This chapter introduces the research by providing background and motivation for the study, introducing the research gap and purpose of research, as well as scope and limitations of research. In addition, this chapter highlights the main contributions of this research and introduces the structure of the thesis.

1.1 Research background and motivation

The evidence and results of climate change and global warming forces policy makers, corporations, and the broader audience to act for sustainability (Pei and Chang, 2025). Industries like the semiconductor industry, which have traditionally not given substantial attention to sustainability topics but rather have focused on superior technology and profitable business modes, are reacting (Ruberti, 2024, 2023). New methods for sustainable semiconductor manufacturing (Bodtker et al., 2024), sustainable supply chains (Holdeman and Howarter, 2025), and novel, more sustainable digital technologies are being introduced and developed (Ueda et al., 2025).

Semiconductors contribute to several of the United Nations' (UN) sustainable development goals (SDGs), especially SDG 7 affordable and clean energy, SDG 9 industry, innovation and infrastructure, SDG 3 good health and well-being, SDG 6 clean water and sanitation, and SDG 13 climate action (Hsieh et al., 2023; Marwala, 2023). Semiconductor chips can, for example, contribute to the improvement of the energy efficiency of devices, enable new technologies like solar panels and wind turbines, and improve the performance of electric vehicles and autonomous driving, thereby reducing dependency on fossil fuels, as well as power medical devices such as pacemakers that improve our health and well-being (Marwala, 2023).

BCC Research reports that the global market for semiconductor chips is projected to increase from $737.2 billion in 2025 to $1.6 trillion by 2030, reflecting a compound annual growth rate (CAGR) of 16.1% during the 2025–2030 forecast period. This growth is driven by the need for rising demands for computing power to process more data, artificial intelligence (AI), and connectivity, as well as the expanding digitisation of consumer electronics, industrial machinery, and vehicles. Semiconductor innovation is accelerating to improve power, efficiency, and miniaturisation (BCC Research, 2025).

Semiconductor fabs consume large quantities of energy, water and raw materials, as well as generate waste and greenhouse gas emissions (Holdeman and Howarter, 2025). Hence, the current focus of sustainability actions in the semiconductor industry is largely on operational topics and reduction of energy- and water consumption of semiconductor fabs to meet the net zero promises, as well as on improving recycling and reducing waste. The decarbonisation through material- and product innovation is considered to be of higher complexity (McKinsey & Company, 2023, 2022; Semi, 2023).

Semiconductor manufacturing is done in semiconductor cleanrooms. These are highly sophisticated and cost-intensive infrastructures that continuously require upgrading. Hence, only large companies can afford their proper infrastructure. Also, some of the large companies choose to be fabless and use foundries to fabricate their device designs (Huggins et al., 2023; Hung et al., 2017). Small- and medium-sized companies (SMEs) are most often dependent on foundries or alternatively shared-use semiconductor infrastructure for the manufacturing of their designs. Such shared-use infrastructure is typically provided by research and technology organisations (RTOs) or universities (Congressional Research Service Report R47508, 2023).

The users of a shared semiconductor infrastructure come from different kinds of organisations, and they use the shared infrastructure for various purposes. Hence, the value the infrastructure provides to the different user groups differs. The capabilities of different kinds of organisations to address sustainability vary. Small- and medium-sized companies (SMEs) typically lack resources and knowledge of sustainability (Jakobs et al., 2024). Various organisations also have varying aims: businesses need to create and capture economic value (Teece, 2010), whereas non-profit organisations, for example, aim at creating societal value (Cotterlaz-Rannard and Ferrary, 2025). Consequently, the interest and capabilities of various organisations to engage into sustainability activities differ.

When several companies and users work side-by-side, sharing the infrastructure and the fabrication equipment, an interesting innovation ecosystem (Pushpananthan and Elmquist, 2022) is formed for open innovation (OI) activities (Chesbrough, 2003; Helman et al., 2021). An RTO-driven, shared semiconductor infrastructure can be studied as a provider-driven living lab (LL) (Leminen et al., 2012) where several users – the infrastructure provider's and companies' employees – work side by side. The various user groups undertake a variety of activities in the shared infrastructure, affecting each other both intentionally and unintentionally. Sustainability is not necessarily on everyone's agenda, and hence the possibilities of collectively engaging various kinds of user groups into sustainability focused activities vary.

RTOs play a central role in driving innovation and advancing sustainability within the electronics industry through participation in private and collaborative projects as well as, in this case, by providing shared-use semiconductor infrastructure. To ensure the industry moves towards greater sustainability, it is essential to increase sustainability awareness among RTO researchers and fab personnel. In additional to operational topics, even when research and development (R&D) projects are not directly focused on sustainability, integrating environmental considerations cost-effectively into every microelectronics R&D initiative is important and exerts a wide impact. This requires researchers to understand and assess the environmental impacts of their decisions throughout the R&D process.

1.2 Research gap, purpose and scope

The academic sustainability-oriented innovations (SOI) discussion is about integrating environmental, social, and economic aspects into innovation processes to address sustainability challenges. The discussion is focused on innovation and management. There are, however, only some qualitative case studies that address SOI in specific industry contexts or integrate deeper industry-specific knowledge with the sustainability dimensions to understand the practical challenges in various technology fields.

Research exists in different kinds of fields linked to the topic of this thesis including SOI in various contexts (Harsanto et al., 2023; Rodríguez-Espíndola et al., 2022), drivers and barriers for sustainability (Neri et al., 2021; Schöggl et al., 2024; Tura et al., 2019), value creation and capture of sustainability (Abadzhiev et al., 2022; Ademi et al., 2024; Badurdeen et al., 2013; Cabral and Gohr, 2023; Hermundsdottir and Aspelund, 2021), LLs (Iliopoulos et al., 2025; Martín-García et al., 2021; Voytenko et al., 2016), shared infrastructure (Helman et al., 2021), regional innovation ecosystems (Fauth et al., 2024), and impact evaluation (Ballon et al., 2018; Ståhlbröst, 2012; Valkokari et al., 2024), though none of the identified previous research combine SOI with a shared infrastructure and the semiconductor technology field. Previously, Baxter and Chipulu (2023), for example, have presented a scale for measuring SOI. Their scale is innovation process-centric, and this research aims to go beyond that by combining technical know-how from the semiconductor field in the evaluation of value creation and impacts of SOIs.

The identified research gap includes various aspects in the context of the shared semiconductor infrastructure, its users and their activities. First, there is a lack of qualitative case studies for SOI in the technology and cost-intensive industry. For example, Harsanto et al. (2024) recommended more research in SOI in other sectors than manufacturing. Furthermore, there is a lack of case studies of what sustainable value a shared infrastructure provides to its various user groups. In addition, the value creation and capture pathways of SOI activities by organisations taking advantage of shared infrastructure have not been studied earlier. Abadzhiev et al. (2022) recognised the need for further research into the dynamics of green innovation in varying contexts and different kinds of companies, due to the fact that green innovations are always context-specific. Neither has the impact of SOI activities in a shared infrastructure been researched nor quantified at various horizons. The need of further research for evaluating success factors and impact pathways of LLs were identified by Valkokari et al. (2024). Compagnucci et al. (2021) urged for more case studies from varying geographical areas and themes to better understand the impact of LLs on innovation and sustainability.

The focus of this research is on SOI activities in an RTO driven shared-use semiconductor infrastructure with multiple users, both organisations and individuals. In this context, the research identifies the SOI activities, the factors motivating users to engage into those, constructs the value creation and capture pathways of the SOI activities, and identifies the impact pathways of SOI activities. Such a shared semiconductor environment has not been previously studied with focus on SOI activities, neither has the previous research of

integrating sustainability consideration into the semiconductor innovation process been identified.

The purpose of this research is to create new knowledge about SOI activities within the context of a shared semiconductor infrastructure, also studied as LL, the drivers and barriers for engaging into SOI activities, the value creation and capture pathways of the SOI activities, and the wider impact of the SOI activities within the shared infrastructure. This research aims at combining SOI with industry-specific technological know-how and in this way create new understanding of SOIs within the semiconductor industry. The SOI topic is studied from the point of view of the main shared infrastructure user groups: user companies and infrastructure provider.

To build up thorough understanding of the topic and validate findings through data triangulation, this research studies various aspects of SOI activities in the shared semiconductor infrastructure on three separate levels, as shown in Figure 1:

(1) State-of-practice at European RTOs through a study of SOI activities at selected European RTOs and the actors round these RTOs for advancing SOI.

(2) The regional ecosystem in and round the shared infrastructure provided by the Finnish RTO, constituting the infrastructure provider, i.e. RTO and the user companies, SOI activities, and why and how these users participate in SOI activities.

(3) The internal factors at the infrastructure user companies and infrastructure provider RTO affecting SOI activities, i.e. the organisational level.

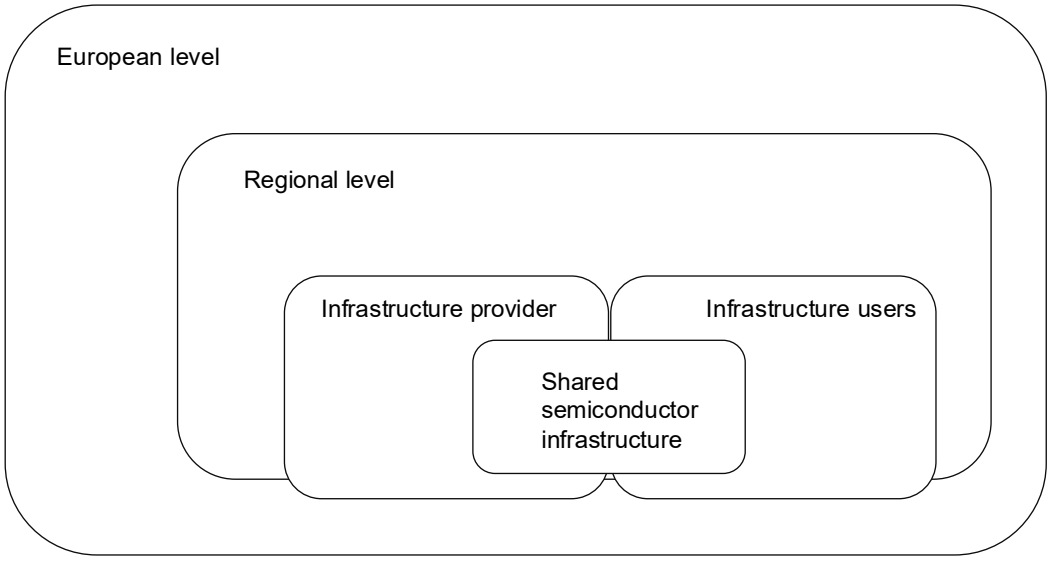


Figure 1 Research framework and various study levels in this thesis: European, regional and organisational.

As previous research was not identified in this specific field, a qualitative approach was chosen as research strategy. The first level, i.e. the European level, involves a multiple case study examining the state of practice for SOI among selected RTOs in Europe. The second level, i.e. the regional level, consists of a multiple case study of selected user companies of the shared semiconductor infrastructure in Finland. The third level, i.e. the organisational level, applies participatory design science research within an RTO to develop an approach for integrating multi-disciplinary environmental sustainability knowledge into microelectronics R&D.

The main research question (RQ) for this thesis is: *What characterises sustainability-oriented innovations in an RTO-driven shared semiconductor infrastructure?* The sub-research questions (sub-RQs) to build up understanding of this topic are listed in Table 1, as well as which publications address these specific topics on which level.

Table 1 Research questions for the thesis and which publication addresses those.

RQ		European	Regional	Organisational
Main RQ	What characterises SOI in an RTO driven shared semiconductor infrastructure?	I, IV	II, III, IV	I, II, IV, V
Sub-RQ1	Who are the actors for SOI in the shared semiconductor infrastructure?	I	II, IV	I, IV, V
Sub-RQ2	What are the concrete SOI activities in the shared semiconductor infrastructure?	I	III, IV	I, V
Sub-RQ3	Which roles do the actors take for advancing SOI in the shared semiconductor infrastructure?	I	IV	IV
Sub-RQ4	How and why do the actors engage in the SOI activities in the shared semiconductor infrastructure?	I	III, IV	I, II, IV, V
Sub-RQ5	What is the impact at various levels of the SOI activities in the shared semiconductor infrastructure?	IV	IV	IV

The main contribution of this research includes a holistic understanding of SOI activities in a shared semiconductor infrastructure and their focus areas, the value creation and capture mechanisms of the SOI activities, and the impact of SOI activities on various horizons. At the European level, this research contributes with a completed green innovation ecosystem actor network from Marcon et al. (2021). At the regional level, the research combines SOI and OI to map the SOI activities and their value creation and capture pathways in the shared infrastructure. In addition, the impact pathways of the LL were identified. On the organisational level, a conceptual framework is created describing the drivers and barriers affecting the interest of companies to engage in OI for

sustainability in the shared infrastructure. In addition, a design science research artifact was created that allows every researcher to consider environmental sustainability in their daily work.

The delimitations of this work include the study of only one shared infrastructure in one location, industry and geography. In addition, only four European RTOs with microelectronics infrastructure were included in the study on the European level.

1.3 Structure of the thesis

This thesis is structured as follows: Chapter 2 presents the state of the art relevant for this thesis. The most central topics and concepts for the thesis are presented, including sustainability in the semiconductor industry, SOI and OI, shared infrastructures, green innovation ecosystems, value creation and capture from sustainability, and impact of sustainability activities.

Chapter 3 introduces the research approach and methods used for this research, starting from the research design and methodological approaches, research process and methods, data collection and analysis, and discussing the quality of the research.

Next, chapter 4 summarises the results of the publications included to this thesis, presenting the background and objectives, main findings and main contributions of each publication.

Chapter 5 discusses the various aspects of SOI in the shared infrastructure, thus addressing the sub-research questions and then discussing the main research question characteristics of SOI in the shared semiconductor infrastructure.

Finally, chapter 6 concludes the study by summarising the thesis, highlighting its theoretical contribution and managerial implications, and stating the limitations of research as well as bringing forward suggestions for further research.

2 Literature review

This literature review concentrates on introducing relevant literature findings for this research. First the research topics for the various levels are introduced along with the used concepts. After that, important literature findings for this research are introduced together with the concepts.

2.1 Introduction to the literature review

The literature review took advantage of the literature reviews done for the individual publications, as well as a literature search conducted in a continuous manner during the years 2023–2025. For identifying additional newer literature, the Scopus database was used. For identifying relevant literature for the concepts in connection to sustainability and the semiconductor field, the search words were always linked to sustainability and/or semiconductor industry and/or high technology industry.

On the European level, the most important research topics include sustainability in the semiconductor industry, SOIs, sharing infrastructure and sustainability, green innovation ecosystems, actors, activities and roles of green innovation ecosystems. These topics were studied by unstructured literature search of the concepts SOI and the green innovation ecosystem, as well as actors and roles of innovation ecosystems or LLs.

On the regional level, the most important research topics include sustainability in the semiconductor industry, SOI, OI, sharing infrastructure and sustainability, LLs, actors, activities and roles of green innovation ecosystems, value creation and capture, impact of SOI, and the impact of LLs. These topics were studied by an unstructured literature search of the concepts SOI, OI, sustainable value, LL, actors and roles.

On the organisational level, the most important research topics include sustainability in the semiconductor industry, SOI, and sustainability assessment. These topics were studied by an unstructured literature search of the concepts SOI, OI, green innovation (GI), and LCA.

In addition to these, different kinds of variations were used for the literature search. For SOI, variations using sustainable, eco-friendly, and GI were also used. Various forms of the word sustainability were also tried out, combined with sustainability of, or sustainability for; and for the combination SOI and OI, the variants sustainable open innovation and open sustainable innovation were also used. For shared infrastructures, LLs and testbeds were also used as search words. For green innovation ecosystems, sustainability ecosystem was also used as search words.

2.2 Sustainability in the semiconductor industry

The academic research related to sustainability in the semiconductor industry is scattered. The main research trends include the eco-efficiency of the industry (Ruberti, 2024, 2023), use of sustainable energy, i.e. renewable energy sources (Chanana et al., 2024), and water use efficiency (Lin et al., 2022; Liu et al., 2024). The energy efficiency research of semiconductors includes research into new materials (Ueda et al., 2025), architectures (Monakhov et al., 2024), and manufacturing methods (Mullen and Morris, 2021).

Supply chain management and optimisation for sustainability is an active research area (Chaudhuri et al., 2024; Lu et al., 2023; Mugoni et al., 2024), including research into downstream and upstream supply chain strategies (Almelhem et al., 2025). Other active research areas include efficient manufacturing (Hsieh et al., 2025; Qi et al., 2024; Venkataswamy et al., 2024), resource utilisation (Holdeman and Howarter, 2025), circularity (Kumar et al., 2025), and waste management (Shen et al., 2018).

The challenge of measuring sustainability has also gained attention in the literature, and various methods for measuring it with, e.g. sustainable balanced score cards have been suggested as a solution (Hsu et al., 2011; Kurrahman et al., 2024). Leading semiconductor firms prioritise sustainable development throughout the broader industry ecosystem, rather than limiting their efforts to internal sustainability practices (Yoo and Cho, 2024).

GI include the development of eco-friendly products and/or processes (Marco-Lajara et al., 2023). Both green and traditional technological innovations boost sustainable performance in the semiconductor field, but green innovation has a stronger effect on the sustainability performance of companies. Green technology also improves ESG ratings, which enhances sustainability and environmental outcomes, though it does not indirectly benefit financial results (Wang et al., 2025).

Life cycle assessments (LCAs) represent the primary method for assessing semiconductor sustainability (Boyd, 2012; Delhaye et al., 2021; Krishnan et al., 2008; Kuo et al., 2020, 2022). Various methods have been proposed to simplify the LCA process, including modular approaches (Kiemel et al., 2022). Additional LCA-based tools have also been introduced in the semiconductor sector, focusing primarily on the manufacturing process (Villard et al., 2015, 2012). In addition, other qualitative eco-tools have been suggested for, e.g. the printed electronics field (Hakola et al., 2023), which are based on evaluation.

2.3 Sustainability-oriented innovation and open innovation in the context of the research

SOI, either incremental or radical, involves developing products, processes, and organisational structures that balance ecological, social, and economic goals for lasting societal and environmental benefits along with economic gain. (Dőry, 2023; Varadarajan, 2017). SOIs can be categorised into operational optimisation, organisational transformation (Adams et al., 2016), and system building, as shown in Table 2.

Adams et al. (2016) developed their SOI framework, shown in Table 2, to analyse SOI activities across a spectrum from internally-focused and incremental to system-level and radical. The activities associated with SOI can be classified into those related to strategy, process, learning, linkages, and organisational innovation.

Table 2 Activities of SOI, after Adams et al. (2016).

	Operational Optimisation: doing more with less	**Organisational Transformation: doing good by doing new things**	**Systems Building: doing good by doing new things with others**
Strategy	Comply with regulations or pursue efficiency gain	Embed sustainability as a cultural and strategic norm in a shaping logic that goes beyond greening	Logic of wide collaborations and investing in systems solutions to derive new, co-created value propositions
Process	Focus on internal and incremental innovation facilitated by use of tools	Adopt new values and platforms (e.g. reverse innovation) and new ideation practices (e.g. biomimicry)	Adopt new collaborative process platforms with diverse stakeholders
Learning	Exploit existing knowledge management capabilities to identify and access relevant knowledge	Engage with key stakeholders of the firm – internal and external	Develop ambidextrous skills enabling 'shadow tracking' and learning from experimentation with multiple new approaches
Linkages	Recruit external domain experts for new knowledge	Shift focus from intra-firm linkages to collaborations with immediate stakeholders	Get the whole system in the room to diagnose problems, understand system complexity, build trust, and identify levers for change
Innovative organisation	Exploit existing innovation capabilities	Embed SOI culture through the organisation	Adopt new business paradigms (e.g. B-Corps)

Another relevant concept for this research is OI. OI refers to the process of taking advantage of inwards-coming and outwards-going knowledge to accelerate internal innovation and expand the market for external application of new solutions (Chesbrough, 2003).

Open eco-innovation can be defined as "*the use of purposive inflows and outflows of knowledge, resources and commercialization paths to develop and/or adopt innovations improving the environmental performance of firms*" (Chistov et al., 2021). Open SOI refers to the combination of open innovation, corporate sustainability, and engagement with external stakeholders (Ghassim and Foss, 2020).

Innovation in high technology sectors like semiconductors is typically open, occurring largely through inter-firm collaboration. This openness is vital due to the industry's dynamic nature and ongoing demand for improved outputs. In this context, OI usually involves roadmapping or extending existing paths, rather than creating entirely new ones. Outdated regulations, geopolitics, limited venture capital, weak immaterial properties (IP) protection, and challenges with scaling businesses are key barriers to open innovation in this field (Huggins et al., 2023).

The sharing economy represents a key aspect of OI. Sharing advanced fabrication infrastructure is particularly sustainable, as it enables an increased utilisation rate (Helman et al., 2021). Research infrastructure is crucial for advancing OI (Onoda and Ito, 2022). Interaction with external actors such as customers, authorities, and research institutes typically increase SMEs' capacity to generate SOIs (Klewitz and Hansen, 2014). Also, Bocken et al. (2014) already identified collaboration as a key component in the advancement of more sustainable business models.

SOI and OI are popular research topics and typically they are treated separately, though also scarce literature exists on their combination; recently, for example, Cammarano et al. (2024).

2.4 Shared high-technology infrastructure

Literature relevant for examining the regional ecosystem in and round the shared infrastructure provided by the Finnish RTO is presented next in the context of sustainability. As the infrastructure is studied also as an LL, relevant related research to LLs is also summarised.

2.4.1 Sharing infrastructure and sustainability

Sharing infrastructure is "*sharing free capacity of machines and equipment in order to increase their use and strengthen the economy towards sustainable development of industry*". Sharing of infrastructure allows for cost savings with regards to infrastructure, competence and skills, and is a sustainable option, as several users take advantage of the same infrastructure (Helman et al., 2021). Shared infrastructure provides a cost-effective and sustainable approach, and subsidies for their operation may be considered investments that support education and innovation (Bowen et al., 2022).

The European research infrastructure hosted by universities is typically a shared infrastructure. Its advanced technologies are offered to externals, and the universities

managing such infrastructure focus on scientific development and long-term sustainability (Jürgens et al., 2024). Investments in shared instrumentation facilities contribute to attracting talent, supporting sustained economic activity through start-up culture, training future professionals, and outreach. For effective operation, supportive policy, funding, networking, and initiatives are necessary (Strom et al., 2020).

There are various challenges and opportunities associated with open-access research facilities, such as microscopy centres. Access to the most recent technologies in these facilities is typically restricted to reduce the risk of equipment misuse or damage, which influences investment outcomes (Cartwright et al., 2024).

2.4.2 **Living labs**

In LLs, users are studied within actual environments instead of under controlled laboratory conditions (Ballon and Schuurman, 2015; Lakatos et al., 2024). LL activities involve multiple stakeholders and produce various outcomes. LL activities include a variety of stakeholders and results in outcomes (Hossain et al., 2019). Although the shared infrastructure under examination in this research has not been set up with the purpose of it to be an LL, it can be studied as such because it fulfils this typical characteristic.

LLs may be classified as utiliser-driven (led by companies developing products), enabler-driven (initiated by public or non-governmental actors for specific projects), provider-driven (conducted by research institutes or universities to support research, development, and knowledge creation), and user-driven (organised by users to address current issues) (Leminen et al., 2012). User involvement in LLs occurs through processes such as recruitment, motivation, co-creation, and relationship-building (Huang et al., 2024).

Innovation infrastructures may also serve as LLs, facilitating collaboration among companies and research organisations to achieve specific goals (Guzmán et al., 2013). An LL can function as an experimental environment for co-creation, leveraging open innovation to address defined challenges (Leminen et al., 2020). While their role in advancing scientific discoveries toward industrialisation is well recognised, the organisational structures of LLs differ in accordance with their value propositions and design elements. LLs may take on roles such as technology sponsor, opportunity spotter, network orchestrator, or community anchor (Abi Saad and Agogué, 2024).

LLs promote innovation and experimentation in the field of sustainability, offering potentially solutions to economic, environmental, and social challenges (Lakatos et al., 2024). LLs are actual open innovation ecosystems that use iterative feedback to promote the development of sustainable outcomes (Leminen et al., 2021). Funding is vital for LL functions and success, and sustainability should be a strategic priority rather than an additional outcome (Compagnucci et al., 2021). Participation in LLs boosts SMEs' sustainability innovation (Alexandrakis et al., 2022). Previous research has also examined LLs for sustainability (Beaudoin et al., 2022; Bulkeley et al., 2016; von Wirth et al., 2019).

The effectiveness of LLs is affected by several factors. Strong collaborative and iterative processes with established networks and partnerships facilitate successful LLs, while challenges include supporting technologies, the time and cost required for collaboration, and uncertainties about the lifespan of the LL (Berberi et al., 2023). Learning is a key motivator for users to engage in LLs (Stahlbrost and Kareborn, 2011).

LLs act as innovation orchestrators within regional innovation ecosystems (RIE), operating in the intersection of government, academia, industry, and society. They facilitate collaboration by connecting diverse stakeholders and harnessing their collective expertise, resources, and experience to coordinate initiatives across the RIE. Through structure, governance, and decision-making, LLs strive to align ecosystem outcomes with the needs and expectations of all stakeholders (Fauth et al., 2024).

Whether LLs actually drive innovation is still unproven; this is assumed from their definition, but clear evidence is lacking (Paskaleva and Cooper, 2021).

2.5 Green innovation ecosystems

On the European level, the ecosystem round RTOs is studied as a green innovation ecosystem including certain actors. On the regional level, the shared infrastructure is studied as part of the regional green innovation ecosystem, consisting of the infrastructure provider and infrastructure users, and including certain actors, activities and roles.

2.5.1 Concepts of green innovation and innovation ecosystems

The terms eco-innovation, environmental innovation, GI, and sustainable innovation are all used widely in the literature (Franceschini et al., 2016). The word GI is chosen for this thesis in context with the innovation ecosystem, as it best describes the environmental focus of the SOI activities within the shared semiconductor infrastructure, and seems to be a widely used concept in the literature.

GI refers to the development, adoption, or application of novel business practices that effectively reduce environmental risks. This process is inherently complex and multidimensional, involving product, process, and organisational aspects—each contributing distinct factors that impact organisational performance, operational efficiency, and sustainable development (Mukhopadhyay and Nayak, 2024).

There are business ecosystems, innovation ecosystems, knowledge ecosystems and entrepreneurial ecosystems (Cobben et al., 2022). Whereas business ecosystems mainly focus on capturing value, innovation ecosystems are focused on creating value (Gomes et al., 2018). "*An innovation ecosystem is the evolving set of actors, activities, and artifacts, and the institutions and relations, including complementary and substitute relations that are important for the innovative performance of an actor or a population of actors"* (Granstrand and Holgersson, 2020).

An innovation ecosystem facilitates collaboration on innovation between government, industry, universities, and research institutions (Li et al., 2024). Innovation ecosystems play an important role in generating technological innovations (Adner and Kapoor, 2010). The green innovation ecosystem evolves as effective green innovation strategies diffuse throughout a complex network (Zhang et al., 2024).

The shared infrastructure under study is an innovation ecosystem, as it creates value for its users. It is studied here as a green innovation ecosystem, as the aim is to study how it creates value mainly for the environmental good.

2.5.2 Actors and roles in green innovation ecosystems

Actors within green innovation ecosystems are, according to Marcon et al. (2021), suppliers, consultants and experts, universities, research and technology firms, complementors, class organisations, investors and shareholders, regulatory agencies, governments, innovation hubs, other parties and customers. Intermediaries facilitate connections and opportunities for interaction and cooperation among various stakeholders within an ecosystem, and in this way advance the diffusion of innovations to the ecosystem (Sultana and Turkina, 2023).

Roles of actors in LLs or innovation ecosystems are not tied to each other but co-evolve over time. Actor roles within innovation ecosystems are influenced by context and may not be easily generalised (Carrara and Freisinger, 2024). The roles of actors are determined on a case-by-case basis and depend on specific activities. For instance, roles identified in the context of ecosystem emergence (Dedehayir et al., 2022) differ from those observed in, e.g. (existing) agricultural LLs (Toffolini et al., 2021).

As an example, in LLs, user roles include informant, tester, contributor, and co-creator (Leminen et al., 2014). These are, however, always case- and LL-specific. Open innovation network roles have been identified more precisely and a bit differently. The most complete list identified relevant for this research is from Nyström et al. (2014): coordinator, builder, messenger, facilitator, orchestrator, integrator, informant, tester, contributor, co-creator, webber, instigator, gatekeeper, advocate, producer, planner, and accessory provider.

An additional classification of roles within gaming innovation ecosystems has been recognised, encompassing leadership, direct value creation, value support, and the promotion of entrepreneurship (Klimas and Czakon, 2022). Roles in humanitarian innovation ecosystems are defined simply as facilitator, provider, researcher, user, utiliser, enabler, champion, communicator, leader, and implementer (Darkwa, 2025).

Universities play a pivotal role in the co-evolution of green innovation ecosystems, serving as initiators, facilitators, coordinators, and stimulators (Amitrano and Bifulco, 2024). Multinational corporations (MNCs) can have either a focal or a participating role (Danko et al., 2023).

2.6 Value creation and capture from sustainability

Value creation refers to the development of products, services, or solutions that are considered useful by customers. Value capture involves obtaining a portion of the value generated through interactions with customers (Klingenberg et al., 2022). The term "sustainable value" describes economic, social, and environmental value (Evans et al., 2017), as shown in Figure 2 below.

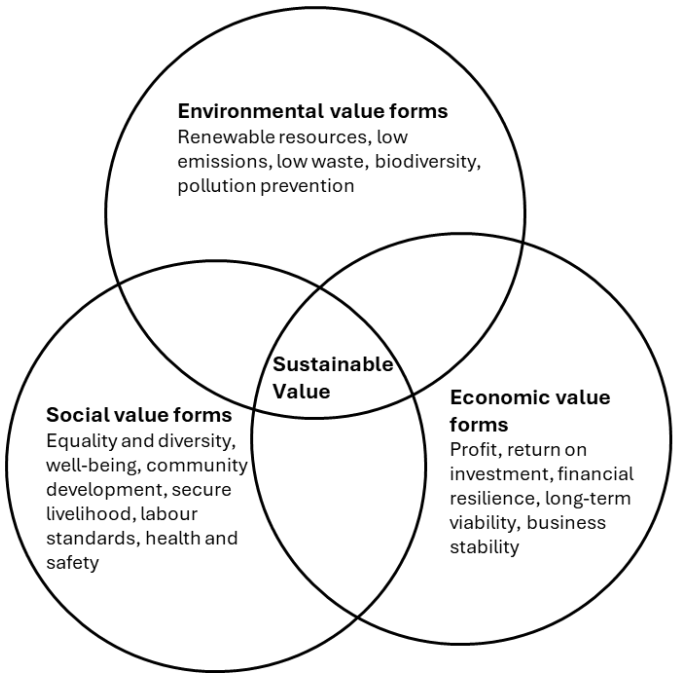


Figure 2 Sustainable value, after Evans et al. (2017).

Sustainable business models create value for customers and stakeholders whilst capturing economic benefits and preserving or enhancing natural, social, and economic capital (Lüdeke-Freund et al., 2019). Business model innovation is crucial for integrating sustainability into core business activities to create and capture value (Yang et al., 2017).

Sustainable business thinking requires creating value across social, environmental, and economic dimensions for all stakeholders (Bocken et al., 2015). This is challenging, because companies must benefit shareholders without disadvantaging other stakeholders. While supply chains have traditionally been evaluated by economic value, sustainable value also depends on managing environmental and societal impacts (Badurdeen et al., 2013; Lozano, 2008).

Companies typically pursue GI to address industry-specific challenges and enhance profitability by exploring new markets and improving service delivery, rather than focusing exclusively on reducing environmental impact (Abadzhiev et al., 2022). The

adoption of green innovations and products may provide a competitive advantage for firms (Al-Abdallah & Al-Salim, 2021), whilst initiatives related to environmental sustainability have been shown to positively influence company value (García-Sánchez et al., 2020; Geiszler et al., 2018).

Sustainable procurement benefits multiple stakeholders—such as firms, suppliers, clients, and communities—by contributing to economic, social, environmental, and ethical sustainability (Boruchowitch and Fritz, 2022). Active listening of customers' concerns can result in value co-creation of eco innovations (Martínez-Martínez et al., 2023).

Applying sustainable business models helps companies capture new opportunities, address compliance risks, and respond to competition from sustainable entrants (Ademi et al., 2024). For greater impact, these models should operate at the system or network level, ensuring that both stakeholder and broader system objectives are met for success (Dormeier et al., 2024). Whilst infrastructure-sharing supports sustainability, there are still few business models for sustainable sharing infrastructures (Helman et al., 2021).

Value is created collaboratively within ecosystems (Mbanefo and Grobbelaar, 2024). Innovation ecosystems should assess value in ways that address the interests of all participants for both collective management and ongoing exploration (Oskam et al., 2021). Creating and capturing value in open eco-innovation networks can be complex, due to typically low returns on investment (Garcia et al., 2019). Nevertheless, competing entities may work together in coopetition-based and value-oriented networks to jointly address challenges and advance sustainability (Rodríguez et al., 2024).

LLs play a pivotal role in fostering innovation, advancing sustainability, and facilitating value cocreation (Compagnucci et al., 2021). The business case for LLs relies on the benefits of participation and the upkeep of essential infrastructure (Burbridge et al., 2017).

2.7 Impact of sustainability activities

Whereas value creation and capture typically refer to the direct results of activities, impacts of actions refer to wider effects of activities during a typically longer time range (Churchill, 2012).

2.7.1 Impact of SOI

SOIs promote competitiveness by developing environmentally friendly products and services tailored to customer needs. They incorporate ecological and social considerations into products, processes, and organisational structures to minimise environmental impact and benefit communities. These innovations are designed to intentionally transform offerings to provide enduring environmental and social value whilst achieving economic benefits (Dőry, 2023). Through the implementation of effective strategies and advanced technologies, businesses and governments can foster sustainable growth and reduce environmental impacts (Wang et al., 2023).

Eco-innovations enhance the sustainability performance of companies (Eusebio, 2024). Eco-innovations also contribute to enhancing businesses' sustainability and competitivity in the digital era (Shafa Tiflis et al., 2024). Environmental regulations can drive the commercialisation of eco-innovations (Lu et al., 2025). The effectiveness of SOI commercialisation is evaluated with sustainability-oriented criteria, including the boost of corporate image and regulatory factors. The effectiveness of SOI commercialisation is assessed using sustainability-oriented criteria, including the enhancement of corporate image, whilst its efficiency is affected by a range of regulatory aspects (Kalmakova et al., 2021).

System level impacts are either intentional or unintentional (Dembek et al., 2023). The inclusion of external actors and openness to external opinions have been identified as drivers for the impact of SOI on a system level (Goodman et al., 2023). However, it is questioned whether SOI really affect the sustainability on a system level or whether the current discussion is too innovation-centric to really drive for transition (Hansen et al., 2022).

2.7.2 Impact of living labs

Key principles of LLs are value, sustainability, influence, realism and openness, and these can be used to evaluate the impact of LLs (Ståhlbröst, 2012). Evaluating isolated outcomes and indirect outcomes of LLs is challenging. One model suggests that the first dimension of the three-layered model is input, activity, and output, and then these are categorised into effects short-term, mid-term, and long-term. The second layer defines where the effects are seen: involved companies, consumers/users, society (Ballon et al., 2018).

Another way to evaluate the impact of LLs is round the questions who, what, why, how, where, when, and how effective (Beaudoin et al., 2022). A third suggested categorisation is a four-stage methodology (problem and ideation; development; implementation, testing and assessment; final proposal) to be evaluated with regards to feasibility impact; social impact; and spatial impact in a specific project (Aquilué et al., 2021).

The strength of the impact of the university-driven LL is mostly round visibility and participation in the public discussion of the topic (Molinari et al., 2023).

The success factors for LLs have been categorised into shared vision; interaction between partners; actors, resources, and activities; operational model and supporting structures. The framework for impact of collaborative innovation in LLs include impact on regional, national and global dimensions (Valkokari et al., 2024).

3 Research approach and methods

This chapter presents the methodological approaches, research design, research process and methods, as well as data collection and data analysis. In addition, the quality of the research is discussed.

3.1 Research design and methodological approaches

The research strategy can be a qualitative, quantitative or mixed methods approach. These methods define the way in which research data is collected. Whereas qualitative research seeks to explore and understand how individuals look at a problem, quantitative research is aimed at testing objective theories. In mixed methods research, both qualitative and quantitative methods are applied (Creswell, 2014; Saunders et al., 2009).

The choice of method depends on the research objective, as well as on the underlying research philosophy. The social *epistemology* view defines what the researcher considers as acceptable knowledge in a discipline: objective (*positivism, realism*) or also subjective (*interpretivism, pragmatism*) data (Bryman, 2012; Saunders et al., 2009). Moreover, the *positivist* looks for natural laws and relationships, whereas for the *anti-positivist* everything is relativistic and dependent on involved individuals (Burrell and Morgan, 1992).

The social *ontology* view defines the researchers' view on the nature of reality. Is reality objective, i.e., social entities existing external to social actors (*objectivism*), or is it subjective, i.e., social actors create social phenomena (*constructionism*) (Bryman, 2012; Saunders et al., 2009)? Additionally, the ontological view can be divided into *realism* and *nominalism*. The latter does not consider that the real world consists of anything else than names, labels and concepts, whereas the realist considers that the world exists also without these labels and without our acknowledgement of it (Burrell and Morgan, 1992). The axiology view reflects the researchers view of own-values in the research (Bryman, 2012; Saunders et al., 2009).

Sociologists differentiate between *determinist* views, where individuals are shaped by their environment, and *voluntaristic* views, which emphasise free will. Methodologically, the *ideographic* approach values first-hand insights to understand society, whilst the *nomothetic* approach relies on systematic methods akin to the natural sciences. These perspectives create four paradigms: *radical humanist*, *radical structuralist*, *interpretive*, and *functionalist*. The functionalist paradigm, prevalent in organisational studies, uses an objective, problem-solving approach aiming for practical outcomes, grounded in realism and positivism. In contrast, the interpretivist paradigm focuses on understanding reality through subjective experience and personal perception (Burrell and Morgan, 1992).

This research applies a constructionism ontological philosophy, as it aims to build theory from the viewpoints of individual participants. The research considers that the approach taken by the organisations depend on the opinions and actions of the individuals. The

epistemological orientation of the research is interpretivism, as it seeks to interpret the reality from the viewpoint of social actors. Sustainability cannot be treated only from an objectivistic viewpoint, as it is linked with values. This research hence mainly belongs to the interpretive paradigm.

The view on research theory can be either deductive, inductive or abductive (Bryman, 2012; Dubois and Gadde, 2002). In deductive theory, the theory and hypothesis come first and the hypothesis is then tested with empirical data. In inductive theory, the researcher pulls findings from the empirical data and feeds them back to a theory (Bryman, 2012). In abductive theory, or systematic combining, the constant interchange between theory and empirical observations is emphasised. The focus is on the generation of new concepts and refinement of existing theories: existing frameworks are typically modified owing from, typically, a combination of unintended empirical findings and further theoretical insights (Dubois and Gadde, 2002).

Exploratory research seeks new insight into what is happening and looks for shedding new light on phenomena. Exploratory research is typically conducted as literature search, expert interviews, or focus group interviews. Descriptive research, on the other hand provides an accurate picture of a person, event or situation, whereas explanatory research describes the connection between different kinds of variables in the context of a situation or problem (Saunders et al., 2009).

Depending on the research objective, the research can be designed as experiment, survey, case study, action research, grounded theory, ethnography or archival research. Timewise, research design can be either cross-sectional or longitudinal. In cross sectional design, data is collected from several cases at a single point of time and data variables are studied to detect association patterns. In longitudinal research, the samples are surveyed at several points of time (Saunders et al., 2009). A case study is considered a suitable research method when the purpose is to study a topical matter in an in-depth manner (Yin, 2018).

The aim of this research is to explore SOI in a new setting that has not been studied earlier in the academic research. Hence, a qualitative approach was chosen as the research method, as the aim was to study an emergent phenomenon and develop an understanding of a particular case rather than validate existing theories. To examine an emerging phenomenon in a different context, such as SOI in the semiconductor industry and at RTOs, a qualitative case study is considered a suitable methodology (Yin, 2018).

Table 3 summarises the research objectives, underlying reasoning logic and research method for the various publications. Publications I-IV were conducted as multiple-case studies. Publication V was completed as design science research. These will be introduced in detail in the next sections.

Table 3 Research objectives, reasoning logic and research method.

Publication	Research objective	Reasoning logic	Research method
I	Identify and categorise SOI activities at and round European RTOs and the actors driving those.	Abductive: application of prior research to the case under study and framework completion	Literature review Multiple case study Qualitative data analysis
II	Identify the role of the shared semiconductor research infrastructure for OI for sustainability activities at infrastructure user companies as well as the drivers and barriers at the user companies for engaging into SOI activities.	Inductive: framework development for case under study	Literature review Multiple case study Qualitative data analysis
III	Map what sustainable value the shared infrastructure provides for entrepreneurs as well as how in practice value is created and captured from SOIs by the users of the shared infrastructure.	Inductive: application of findings to theory	Literature review Multiple case study Qualitative data analysis
IV	Identify actors, roles and activities of the shared infrastructure users, and map the impact of the SOI activities on various levels.	Abductive: framework refinement for case under study	Literature review Multiple case study Qualitative data analysis
V	Create an approach for how and in which way the RTO, i.e. infrastructure provider, can consider SOI in all R&D projects.	Abductive: best practice and framework development based on findings	Literature review Design science research Workshops Surveys

3.2 Research process and methods

In this section, the research process and methods for the publications are presented as divided into case studies (publication I-IV) and design science research (publication V).

3.2.1 Case studies

Case study research is a qualitative approach. The typical case study design is an in-depth analysis of a single case in one setting (Yin, 2018). Typical data collection methods include participant observation and unstructured interviews. Multiple-case studies allow for comparison of collected data and include more than one case (Bryman, 2012). Single case studies are typically selected when the case represents a critical, extreme, unique or typical case. Multiple cases are typically used when there is a need to understand whether the same things occur in several cases, i.e. whether the findings can be generalised (Saunders et al., 2009). Case studies are typically used when the aim is to build theory from practice (Eisenhardt, 1989).

European level

For publication I, a multiple-case study was selected as the research method, as the aim was to explore SOI in a new context as well as refine the existing actor framework. The aim was to identify SOI activities at four European RTOs with dedicated semiconductor cleanrooms and to identify the actors round the RTOs participating in SOI activities. This mapping of SOI activities at RTOs in Europe provides a broader perspective into the state of practice and allows for comparison to the analysis on the regional level.

The selected RTOs are all established players and well-known in their field, as explained in Konstari and Valkokari (2025a), and the interviewees were all appointed by their organisations to be the best contacts for the study.

Regional level

For publications II, III and IV, a multiple-case study was selected as the research method, because the aim was to study SOI activities at the regional level in and round the shared semiconductor infrastructure as well as induce theory from practice or systematically combine findings.

The Otaniemi shared semiconductor infrastructure, Micronova, in Espoo, Finland and the company ecosystem round it were chosen for this study, due to their longstanding tradition and the possibility of access to the infrastructure to external companies. This characteristic establishes the infrastructure as an open innovation ecosystem that has given birth to several innovations and businesses. The forthcoming infrastructure expansion, Kvanttinova hub, is expected to further enhance capabilities for developing specialised microelectronics innovations in Finland. The Micronova shared cleanroom is jointly run by VTT and Aalto University, with both sides hosting their own equipment. Kvanttinova hub-shared cleanroom space will be run by VTT.

In total, the 14 companies were selected for this multiple-case study as explained in detail in Konstari and Valkokari (2025b, 2025c, 2024). The interviewed companies included both SMEs and large companies.

3.2.2 Design science research

Design science differs from both theory-building and theory-testing approaches, which are modelled after the natural sciences and focus on explanations based on observation. Design science can be defined with an emphasis on the process of exploration through design and is a more holistic process. Design science examines alternative approaches to problem solving and connects practical application with theoretical frameworks. Design science research focuses on identifying new ways to address problems, explaining these processes, and refining the methods for problem-solving. Design science research may be carried out through various approaches, such as action science, action research, action innovation research, participatory action research, participatory case studies, or academe-industry partnerships (Hevner et al., 2004; Holmström et al., 2009).

A key advantage of the design science approach is its clear emphasis on enhancing practical outcomes. However, a notable challenge lies in its capacity to generate novel theoretical insights. Design science primarily seeks to address specific problems rather than to produce explanatory or theoretical knowledge. As a result, design scientists may find that whilst their solutions effectively resolve the targeted issues, they do not necessarily contribute new understanding to the theoretical domain (Hevner et al., 2004; Holmström et al., 2009).

For publication V, a design science approach was chosen as the research method, due to its focus on identifying and addressing problems as well as integrating practice with theory (Holmström et al., 2009). This approach was selected because the Microelectronics and quantum technology research area at VTT Technical research Centre of Finland, where the research was carried out, aimed to address the topic collaboratively through discussion, utilising in-house multidisciplinary know-how and by taking an abductive approach. This department consists of approximately 230 researchers specialising in microelectronics and quantum technologies, along with about 20 managers. The aim of the research was to develop an artifact which enables cost-efficient evaluation of environmental sustainability topics in all microelectronics R&D projects in an RTO. The role of the author was to run this process as part of the research area management team.

3.3 Data collection and analysis

The research data was collected and analysed following a qualitative research approach. Data was collected through literature reviews (publications I-V), phone interviews and questionnaires (publication I), semi-structured interviews (publications I-IV), and through a design science participatory approach (publication V). The collected data was validated through member checking (publications I-IV), and triangulation (publications I-V). The data collection and data analysis methods for the various publications are summarised in Table 4.

Table 4 Summary of data collection and data analysis methods.

Publication	Data collection	Data analysis
I	1) Phone interview and questionnaire with four European RTOs with semiconductor infrastructure 2) Semi-structured interviews with the same RTO representatives Literature review	1) Qualitative content analysis, mapping of answers to the SOI framework by Adams et al. (2016), member checking 2) Qualitative data analysis, member checking
II	14 semi-structured interviews with infrastructure user companies Data from Orbis company information portal Literature review	Qualitative data analysis using NVivo 14 software tool for qualitative research, member checking
III	14 semi-structured interviews with infrastructure user companies Data from Orbis company information portal Literature review	Qualitative data analysis using NVivo 14 software tool for qualitative research, member checking Mapping of data into sustainable values after Evans et al. (2017) and SOI framework by Adams et al. (2016).
IV	14 semi-structured interviews with infrastructure user companies Data from Orbis company information portal Literature review	Qualitative data analysis using NVivo 14 software tool for qualitative research, member checking Mapping of qualitative data to Actors, resources activities (ARA) model after Håkansson H and Johanson J (1992) and impact framework adapted from Valkokari et al. (2024)
V	1) Research diary over a two-year period 2) 3 Workshop stages 3) 4 Anonymous questionnaires Literature review	Design science including workshops, triangulation Analysis of questionnaire results.

3.3.1 Data collection and analysis for case studies

European level

For publication I, the research was conducted in two stages, as described in Konstari and Valkokari (2025a). During the first stage, which took place from November to December 2023, data collection involved telephone interviews supplemented by a detailed email questionnaire. This approach was selected as the interviewees wanted to consult additional personnel at the RTOs for additional information. Interviewees provided initial responses during the telephone discussions, which were recorded on the questionnaire form by the corresponding author and subsequently shared with the participants. Afterwards, interviewees consulted their colleagues within their organisations to complete the survey. The final documents were returned by January 2024.

The second round consisted of semi-structured Teams interviews conducted in June and July 2024, which were recorded and transcribed. Prior to the interviews, participants were provided with a research information sheet, the interview questions, and a mapping of their first-round responses. During the interviews, first-round answers were reviewed and updated.

The literature review was completed both after the first interview and second interview rounds, using the Scopus database with targeted search words with the aim to identify the most relevant research related to sustainability in the semiconductor industry, SOI, green innovation ecosystems, as well as research infrastructures and sustainability.

The SOI framework suggested by Adams et al. (2016) and shown in Table 2 was used as an analytical framework for the first round. As analytical framework for the second round, the actor division presented by Marcon et al. (2021) was used – suppliers, consultants and experts, universities, research and technology firms, complementors, class organisations, investors and shareholders, regulatory agencies, governments, innovation hubs, other parties and customers – and applied to the specific case in question.

The research approach was abductive, and the findings evolved during the research process: the first stage empirical results combined with the preliminary literature review revealed new linkages and possibilities and gave rise to new inputs to the second stage, after which the framework presented by Marcon et al. (2021) was refined, thanks to the new findings.

Regional level

Publications II, III, and IV form a trilogy generated through a multiple-case study within the shared semiconductor infrastructure in Otaniemi, Finland.

The companies participating in the research were selected from the current users of the Micronova research infrastructure and potential new users that had expressed their interest in the infrastructure expansion to Kvanttinova. Fourteen companies were chosen

for the study, each of which was contacted regarding participation and to identify appropriate contacts for semi-structured interviews, as explained in Konstari and Valkokari (2025b, 2025c, 2024). The individuals selected for interviews held duties related to sustainability within their respective organisations, and were identified as suitable participants by their companies.

All fourteen semi-structured interviews were conducted in December 2023 via Teams, and were recorded, transcribed, and subsequently delivered to participants for validation as text documents. A total of twenty-three individuals participated in these interviews, with three additional contributors providing further information to address gaps in the transcripts. Company identities and corresponding verified answers were pseudonymised (Company A–N) and imported into the NVivo 14 tool for qualitative research. The company information was complemented by information from Orbis company portal. The data was analysed with NVivo 14, coded and summarised; as explained in more detail in Konstari and Valkokari (2025b, 2025c, 2024).

For publication II, a literature review was completed using the Scopus database, with the aim to identify the most relevant research for the topic in hands related to sustainability in the semiconductor industry, OI and SOI, sharing infrastructures and sustainability, as well as drivers and barriers for sustainability in various contexts using suitable search words and combinations of such. For the shared infrastructure literature search, LLs and testbeds were also used as search words. As no earlier framework was identified for the topic in hand, an inductive approach was used to derive a framework for drivers and barriers for OI for sustainability in shared-use infrastructures.

For publication III, a literature review was completed using the Scopus database to identify prior research most relevant for the study related to SOI and sustainable value, as well as value creation and capture from sustainability. Search words were used that included these and semiconductor industry, alternatively shared infrastructure or LL/ testbeds. The sustainable value that the infrastructure provides to its users was then analysed based on the definition by Evans et al. (2017) in Figure 2. The SOI activities in the shared infrastructure were then categorised after the Adams et al. (2016) framework presented in Table 2, and further categorised into value creation or value capture methods.

For publication IV, a literature review was completed using the Scopus database, searching for the most relevant prior research linked to the impact of SOI, characteristics of LLs, actor roles in LLs, and the impact of LLs. Used search words included variations of these, as well as urban LLs and success factors of LLs. For data analysis, the actors, resources and roles, activities (ARA) model (shown in Figure 3) that was originally proposed by Håkansson H and Johanson J (1992) and later used by Valkokari et al. (2016), was used as the analytical framework for analysing what roles exist in the LL for advancing SOI activities. This model was selected because it captures both the dynamics and relationships within an LL, as well as the evolving nature of collaboration among its actors.

Furthermore, the impact indicator framework of collaborative innovation proposed by Valkokari et al. (2024) was used as a basis, and modified in accordance with the abductive approach to suit the specific case of SOI impact analysis in the semiconductor industry. The adopted framework is shown in Figure 4.

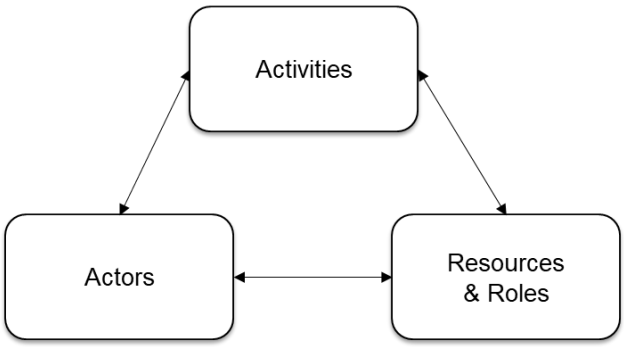


Figure 3 Framework for analysing actors, resources and roles, and SOI activities in the LL.

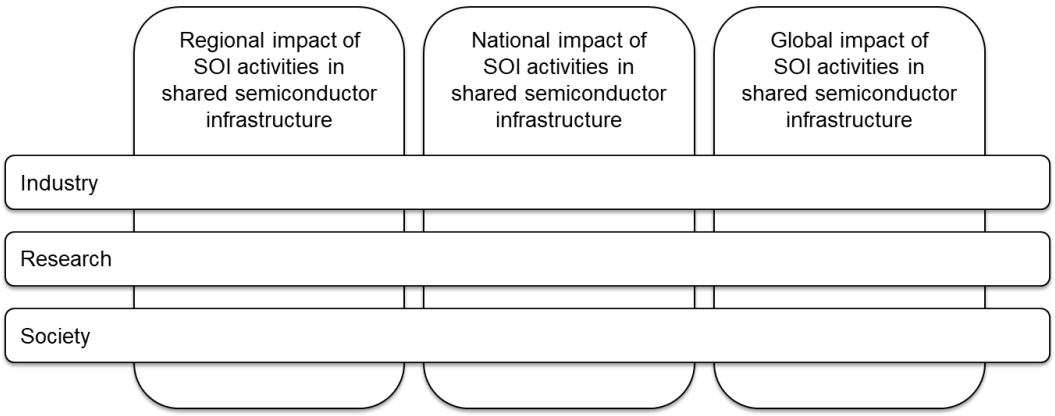


Figure 4 Framework for analysing SOI impact in a shared semiconductor infrastructure.

3.3.2 Data collection and analysis for design science research

For publication V, data was collected in three ways: (1) as a research diary of discussions, events and decisions affecting the research questions, (2) through engaging workshops, and (3) through anonymous surveys during bi-yearly department meetings. The research diary was collected by the corresponding author during the entire two-year period from May 2023 to April 2025. The collected data includes benchmarking data from the department meeting in May 2023 about how researchers think that sustainability should be considered in various research fields.

The environmental sustainability evaluation artifact was developed through workshops involving researchers from microelectronics and experts in sustainable electronics,

biodegradable materials, material design, and supply chains. The workshops were conducted in three stages, as explained below.

The first stage was from June 2023 to September 2023. The core development team included five people from the microelectronics department core management team. The target was to define a preliminary sustainability approach for the research area, based on the literature review and discussions. The outcome of this stage was understanding that the research area should consider sustainability on multiple levels: manufacturing, material selection, device design, system architecture, and choice of target application.

The second stage was from August 2024 to February 2025. About 15 scientists, including experts for microelectronics and electronics design and processing, chemists, material design and supply chain specialists, recycling generalists and innovation management specialists participated in the workshops. The aim was to adopt the green tool from Hakola et al. (2023) for the requirements of the microelectronics field. The outcome was that adoption of the green tool for microelectronics will not serve the research areas purposes as it is too time-consuming, and the life cycle data needed is unavailable; hence, the researchers cannot affect the categories in the tool.

The third stage was from March 2025 to April 2025. It included six people from the microelectronics department core management team. The target was to find a solution for how sustainability should be considered in the research areas' early-phase work without a digital tool, to increase sustainability awareness and make it a competitive advantage. The outcome was the decision to move the sustainability discussion to research projects with the help of an identified set of key questions and management sparring: project application, design, fabrication, lifecycle perspective, and raw materials.

During the two-year period, the literature was scanned continuously using the Scopus database, feeding the design science approach with new insights. The publication V presents the most relevant papers for the research about sustainability and sustainability assessment in the semiconductor industry including life cycle assessments (LCAs), as well as knowledge-sharing, knowledge exploitation and knowledge exploration.

Findings from the literature were used as input material for the workshops. Workshop results were shared twice a year with the microelectronics department. Feedback from the department was gathered via surveys during these meetings. The artifact was validated through investigator triangulation among the participants of the workshops.

During the research process, new results and angles to the research topic were continuously identified from the literature and from the on-going dialogue. The first framework was developed in the first stage, then the aim in the second stage was to change it, but the literature findings and dialogue within the workshop team as well as with department representatives proved that the first approach was finally better than the second one. Hence, in the third stage, the artifact became again to reassemble the first

stage version more. Through systematic combining of the upcoming results, the final artifact was created within the multi-disciplinary team.

3.4 Quality of the research

The quality of the qualitative research is evaluated through its reliability, replication and validity. Reliability deals with the repeatability of the results. Replicability deals with the possibility for others to repeat the study. Validity concerns the integrity of the conclusions that are drawn from the research. Internal validity deals with whether we interpret the findings correctly, whereas external validity deals with whether the findings are generalisable (Bryman, 2012).

Triangulation strengthens the study and can be done in four different ways: data triangulation is the use of several data sources, investigator triangulation is the use of several individual researchers, theory triangulation takes advantage of multiple perspectives in the data interpretation, and methodological triangulation uses several methods to study the same problem (Carter et al., 2014; Patton, 2002).

For publication I, the reliability of the research can be considered good in its own context. The interviewed people were appointed by the RTO departments to be the right contacts for the study. Participant checking was used for verification of the conclusions for internal validity. However, the external validity would require further research into various settings. The replicability of qualitative research is difficult due to its nature: case studies are context- and time-specific, and the results are of a subjective nature, even though there have been measures to increase reliability.

For publications II-IV, the reliability of the research can be considered good in its own context. The interviewed companies cover most of the active companies in the regional ecosystem, the people were appointed by the companies to be the right contacts for the study, the answers in the multiple cases started to repeat each other, and participant checking was used to verify the answers for internal validity. The multiple case study allowed for data triangulation and a multidisciplinary research team for investigator triangulation. However, the external validity would require further research into various settings. Replicating qualitative research is challenging, because case studies are context- and time-dependent, and findings remain subjective despite efforts to improve reliability.

For publication V, the reliability of the research can be considered good in its own organisational context. The artifact is the result of longitudinal work within a multi-disciplinary team. Hence, the artifact has been created in collaboration with experts from various disciplines in the specific research organisation. The research was done as longitudinal participatory research, removing the risk of wrong interpretations from isolated events. However, the external validity would require further research into different kinds of settings. Replicability of the design science research is difficult due to its nature of being the result of a collaborative effort.

4 Results

In this chapter we present the individual publications, their context, research gaps, research questions, findings, and contributions. Table 5 summarises the research gaps and research questions of the publications.

Table 5 Research gaps and questions of the individual publications.

Publi-cation	Research gap	Research questions in the publication
I	Lack of research about SOI activities at RTOs in general	RQ1: What kind of SOI activities are the RTOs engaged in and what are the driving factors behind these engagements? RQ2: What are the green innovation ecosystem actors around the RTOs?
II	Lack of case studies about drivers and barriers for open innovations for sustainability in shared research infrastructures with multiple user organisation.	RQ1: What does sustainability mean and include for the case companies at the shared research infrastructure? RQ2: What are the drivers and barriers at the case companies for engaging in open innovation for sustainability related activities in the shared research infrastructure?
III	Lack of case studies that combine several disciplines to analyse execution, practices, and behaviours of SOI in a shared semiconductor infrastructure.	RQ1: What sustainable values does shared semiconductor infrastructure represent for user companies? RQ2: How can value from SOI actions be created and captured by the actors in the innovation ecosystem under study?
IV	Lack of research on actors, roles and activities for SOI activities in LLs. Lack of research on impact of SOI actions in LLs on various horizons.	RQ1: What roles are there in the LL for advancing sustainability-oriented innovation activities? RQ2: What is the impact of the sustainability-oriented innovation activities in the shared semiconductor infrastructure?
V	Lack of research and solutions on how environmental sustainability can cost-efficiently be addressed in microelectronics R&D phase at an RTO.	RQ1: How can environmental sustainability be considered at an RTO during the R&D phase of microelectronics devices? RQ2: What aspects affect the efficient multi-disciplinary environmental sustainability knowledge integration into microelectronics R&D at an RTO?

4.1 Publication I

Green innovation ecosystems in the semiconductor industry - the role of European research and technology organisations (Konstari and Valkokari, 2025a)

4.1.1 Background and objectives

RTOs collaborate in public and private R&D projects at the national, European, and international scales. These R&D activities impact innovation activities and the progression of the global electronics industry. RTOs participate in initiatives related to sustainability and technological advancement within their organisations and the broader sector as they develop new technologies.

This paper examines how four European RTOs with microelectronics departments with in-house semiconductor research infrastructure approach the topic of sustainability and which SOI activities they prioritise, the drivers for the SOI activities, and the function and role of the RTO for SOI activities in the green innovation ecosystem surrounding the RTO. Additionally, the study aims to identify other actors involved in the green innovation ecosystems associated with the RTOs.

4.1.2 Main findings and contributions

The main findings of this paper include the state-of-practice of the SOI activities that the four RTOs undertake for advancing sustainability in the semiconductor field. These are summarised in Table 6. The main motivators or drivers for the RTOs to engage in SOI activities include regulations and funding requirements, but also political pressure and image, customer requirements, and energy savings. The role of the RTOs in the green innovation ecosystem was found out to be the innovator, initiator, information provider, disseminator, role model or solution provider - the orchestrator of the green innovation ecosystem. The green innovation ecosystem actors round the RTOs were mapped and summarised.

The research provides insight of SOI activities at European RTOs and the drivers for those. In addition, the research maps the actors of the green innovation ecosystem round the RTOs and identifies the RTOs' role for driving the SOI activities in those.

The principal academic contribution of this research is the development of a complemented framework for green innovation ecosystem actors round microelectronics RTOs based on previous research done by Marcon et al. (2021). The framework suggested by Marcon et al. (2021) was complemented by grouping the actors, adding expanding the "other parties" category with central actors for this context: service providers, SMEs, large companies, local municipality, and public opinion. The complemented framework is shown in Figure 5.

Table 6 Summary of the RTO's SOI activities.

Operational optimisation	**Organisational transformation**	**Systems building**
Focus on following regulations and legislation, monitoring and measurement Focus on supply chain, scope 1, 2 and 3 emissions, infrastructure updates Sustainability awareness building	Sustainability is included in the RTO corporate strategy Strong management support for transition Creation or use of new operational models, products, infrastructure, technology or equipment, alternative products in-house or by external parties	Co-creation of new products and services with external partners Value capturing through R&D projects Influencing – ecosystem, government, funding agencies

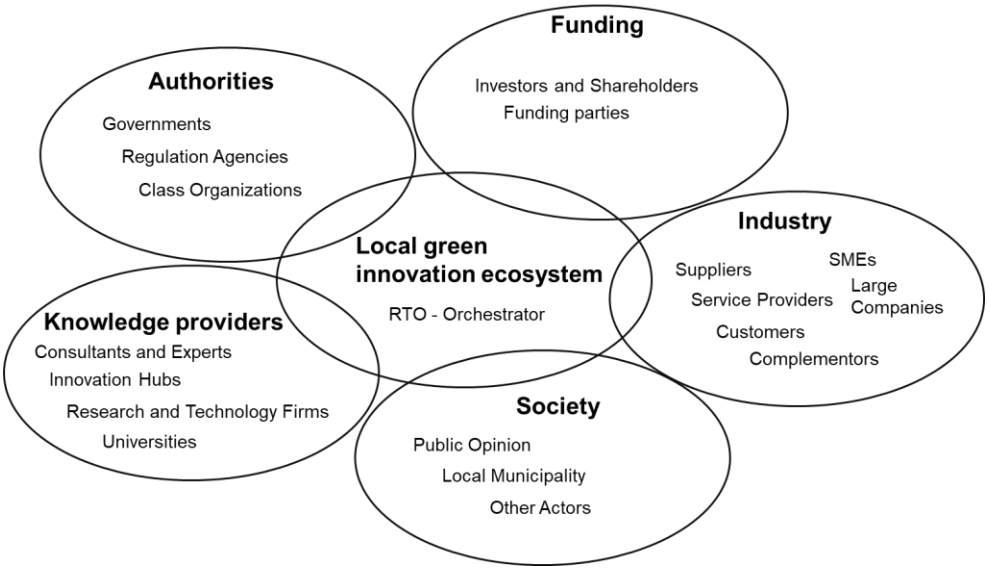


Figure 5 Green innovation ecosystem actor framework.

The findings may be useful for managers in industry and academia to identify relevant actors within their local green innovation ecosystems related to SOI advancement. Government representatives may also use this study to gain insight into the complexity of the subject and the importance of adequate funding as well as a multidisciplinary approach for promoting sustainability in the European semiconductor sector through collaboration.

4.2 Publication II

Drivers and barriers for open innovation for sustainability in a shared semiconductor infrastructure (Konstari and Valkokari, 2024)

4.2.1 Background and objectives

A shared semiconductor infrastructure is a collaborative innovation ecosystem where users access both the common infrastructure and common fabrication equipment. This arrangement forces the users to have some degree of collaboration. Companies vary in their approach to technology development; some maintain strict confidentiality, whilst others view openness and knowledge sharing as advantageous for innovation. The users' perspectives on sustainability also differ, affecting the extent of their engagement in OI activities for sustainability.

This study examines a shared-use semiconductor research infrastructure as a local innovation ecosystem, focusing on the interplay between the operating company and user companies in enabling OI for sustainability. The user companies are profiled, ant their interest to engage in OI for sustainability mapped. Addressing this research gap is relevant to gain insight into the drivers and barriers within organisations to engage with OI for sustainability.

4.2.2 Main findings and contributions

The characteristics of infrastructure user companies were classified into two categories: SMEs and large companies. These groups have distinct objectives related to open innovation for sustainability within the infrastructure.

SMEs are frequently established as spin-offs or start-ups for commercialising technologies initially researched and developed at RTOs or universities, representing the outcomes of outbound open innovation activities.

The SMEs need the research infrastructure daily for operative activities like fabrication and R&D. As they grow, SMEs may invest in limited proprietary infrastructure for back-end processes while relying on shared research infrastructure for capital-intensive semiconductor processing. Consequently, they depend on inbound open innovation activities within the shared research infrastructure and may undertake smaller investments into critical equipment within the shared infrastructure. The sustainability practices and environmental measures implemented by the shared research infrastructure are particularly significant for SMEs.

The large companies involved in the shared infrastructure typically maintain their own cleanrooms in Finland for volume manufacturing and R&D. These companies engage in inbound open innovation activities, such as assessing new technical capabilities and acquiring knowledge from the shared infrastructure. Parent companies of acquired SMEs

act alike and participate in these activities, seeking expansion opportunities, i.e. for inbound open innovation activities. Additionally, large companies may use some shared equipment as alternatives to their own tools. Large companies focus on learning about sustainability and on transferring this expertise internally through inbound open innovation efforts.

Hence, the IP strategy of SMEs can be considered to typically involve greater reliance on open innovation within shared research infrastructures, whilst large companies generally utilise their own infrastructure and conduct manufacturing processes in-house, resulting in a more closed approach to IP management.

The study shows that interviewees' knowledge of sustainability varied widely depending on their position in the organisation. The understanding of what sustainability means varies among the companies, based on factors like strategy, size, focus, industry, technology, available resources, funding, and company origin.

Sustainability reporting requirements have led some user companies to concentrate on actions within their supply chains, with less emphasis on R&D partners. This indicates a current focus on monitoring and operational activities rather than on SOI. The findings also suggest that companies may view sustainability as a collaborative factor rather than a source of competitive advantage. Nevertheless, some companies have identified opportunities to position sustainability in ways that could provide a competitive edge.

The primary theoretical contribution of this study is the development of a conceptual framework summarising the key drivers and barriers influencing the user companies' interest in engaging in OI for sustainability within shared research infrastructure, divided into company internal and company external factors, as shown in Table 7. This framework integrates two fields—OI and SOI—and identifies central factors that facilitate or hinder progress in both areas simultaneously. The study also links the semiconductor industry with innovation management. It contributes to the academic discussion by addressing OI with a focus on sustainability within shared research infrastructures and local ecosystems.

Depending on context, many factors can act as both drivers and barriers for OI for sustainability. Whilst some have been discussed in prior research, this framework also highlights the influence of company origin and shareholder sustainability reporting requirements. Key internal drivers include value proposition, innovation and IP strategy, branding, effective management and communication, corporate responsibility, and advanced technology. Network-related drivers involve owners, stakeholders, and individual interests. Internal barriers are weak management, poor communication, and lack of expertise, while external barriers include limited funding and outdated infrastructure.

From a managerial perspective, the study provides insights into OI activities related to sustainability in local ecosystems, such as shared semiconductor infrastructure. It also highlights the differing interests of various user company groups in the shared

semiconductor infrastructure - SMEs and large companies - and that they have varying needs and hence differing expectations on the shared infrastructure OI for sustainability activities.

Table 7 The conceptual framework for case company internal and external factors affecting the possibilities for initiating OI for sustainability-related activities in the shared semiconductor cleanroom environment.

Category	**Case company internal factors**	**Network related, Case company external factors**
Company strategy	Strategic goals Innovation strategy IP strategy Management Communication Value proposal Branding	Shareholders, Company owners Effect of company origin
Operations management	Sustainability reporting	Stakeholders - Suppliers, Customers, Partners
Social behaviour		Individual interest
Knowledge management	Learning	Education
Technological aspects	Technology	Shared infrastructure and available equipment
Finance	Own financing	External funding
Policy and regulatory	Corporate responsibility Company operational profile (manufacturing/R&D)	Laws and regulations

The results demonstrate the complexity of OI for sustainability within the semiconductor industry. They also indicate the need for local ecosystems to address sustainability concerns at the local level and suggest that the shared infrastructure operator has a role in educating stakeholders, defining criteria, and facilitating OI activities focused on sustainability. Managers may reference these findings when initiating SOI actions and identifying related factors in their organisations.

4.3 Publication III

Value creation and capture from sustainability-oriented innovations in a shared semiconductor infrastructure (Konstari and Valkokari, 2025b)

4.3.1 Background and objectives

This study explores value creation and capture from SOIs within the Finnish semiconductor innovation ecosystem, as well as entrepreneurial opportunities associated

with SOI activities. The shared semiconductor infrastructure is an OI environment where personnel work next to each other, which is less common at this scale in the semiconductor sector, and serves as an example of an LL in this industry context. Users share the facility and the fabrication equipment and may interact with each other during their work, enabling both planned and unplanned information exchange.

The infrastructure signifies different things to various users, as well as provides different kinds of sustainable value for the users. This study identifies SOI activities and develops further understanding of the implications of these in the shared infrastructure for entrepreneurs. The study examines first what sustainable value the shared infrastructure provides to its users and then studies the practical value creation and capture methods of SOIs in shared infrastructure.

4.3.2 Main findings and contributions

The main findings of this research include understanding of what sustainable value the shared semiconductor infrastructure provides to its users, mapped after Evans et al. (2017). The shared infrastructure was found to provide economic, environmental and social value to its users. It was described as an open-access facility that supports the development of businesses aiming to minimise environmental impact, serves as focal point, a knowledge resource, and a centre for innovation in the local industry, and it links users to the broader semiconductor community.

Hence, the LL definition in this specific context and this specific case can be expanded to include sustainable value: *an open-access infrastructure that supports business growth whilst focusing on reducing environmental burdens, acting as a focal point, knowledge source, and innovation centre for the local industry, and connecting users to the wider semiconductor ecosystem*.

The value creation for SOI actions in the shared semiconductor infrastructure were identified both for the user companies as well as for the shared infrastructure provider. These were divided according to Adams et al. (2016) to SOI activities for (1) operational optimisation, (2) organisational transformation and (3) systems building. The user companies focused on value creation through (1) optimisation of their operational model, (2) through development of new processes and technologies either alone or in collaboration, and (3) through participation in R&D projects, as well as through collaborating, networking, and learning. The shared infrastructure provider, on the other hand, should focus on (1) setting up the infrastructure, tools and recycling services; as well as providing joint solutions for the infrastructure users to (2) evaluate new ways to minimise the environmental burden of operations and measure consumptions, as well as (3) collaborate with the ecosystem through networking and teaching.

User companies in addition to the shared infrastructure provider were found out to be able to capture value from SOI activities in the shared infrastructure. The user companies capture the value through increase in company value (shareholders), business growth

(customers), business expansion through open innovation, knowledge development of personnel, and increased operational efficiency. The shared infrastructure provider, on the other hand, can capture value through providing open-access shared infrastructure services, measuring consumption, and providing user company-specific consumption data as a service, best practice dissemination, knowledge development and teaching, and innovations as well as IP creation.

This study combines multiple theoretical perspectives to outline forms of sustainable value in shared semiconductor infrastructures and maps how value is created and captured from SOIs. Findings show that shared infrastructures offer environmental, social, and economic benefits, supporting sustainability and entrepreneurship. Addressing the needs of ecosystem actors enables value creation and entrepreneurial opportunities for all parties. The results help managers initiate SOI activities and guide entrepreneurs in developing sustainable business models.

4.4 Publication IV

Roles for and impact creation of sustainability-oriented innovations in a shared semiconductor infrastructure (Konstari and Valkokari, 2025c)

4.4.1 Background and objectives

A shared semiconductor infrastructure can be studied as a provider driven LL. The infrastructure hosts several actors, both companies and individuals, that undertake various activities in the infrastructure, and play a variety of roles. The shared infrastructure provider plays several active roles for SOI in the LL. The user companies take an either active or passive role for SOI. In addition, based on their personal interests, the user-company employees take their own roles for advancing SOI in the shared infrastructure.

This study identifies and maps the actors, resources and roles as well as activities of the shared semiconductor infrastructure. Based on these, the impact of SOI activities in the shared semiconductor infrastructure is analysed on regional, national, and global horizons.

4.4.2 Main findings and contributions

The facility and the semiconductor equipment can be identified as actors, as their status and properties widely affect what activities can be undertaken in the infrastructure. Within the shared infrastructure, multiple organisations are active, and within these organisations various individuals affect the SOI activities. Additionally, national, European, and global legislation and regulations play a role in shaping the SOI activities in the shared infrastructure. Funding parties determine which SOI activities receive financial support. The supply chain as well as industry standards and requirements also contribute to the

ways in which SOI activities are carried out. The full analysis of the actors is available in Konstari and Valkokari (2025c).

The activities carried out by participants in the shared semiconductor infrastructure involve both individual efforts by organisations and collaborative initiatives among the users, as explained in detail in Konstari and Valkokari (2025c). The facility, semiconductor infrastructure provider, semiconductor infrastructure user companies, and universities have individual activities in the infrastructure. These are linked to the infrastructure, infrastructure services or the tools, or then to teaching, business, R&D and expertise, piloting and production. The collaborative activities are linked to engaging into collaborative R&D among the users, engaging into collaborative other efforts between users, engaging in best practice sharing and training, engaging in collaboration with wider ecosystem, taking part in talent development, and sharing information in meetings, as well as engaging in sporadic meetings in the cleanroom.

Based on the actors and activities, the roles for driving SOI in the shared semiconductor infrastructure were identified. There are parties taking more active roles, whereas there are others being more passive, mainly wishing to benefit from other people's work. The infrastructure provider and semiconductor equipment operator were recognised as the SOI sponsor, advocate, innovator, educator, informant, and facilitator. Individuals served as sustainability advocates. Some of the identified roles have been previously identified as explained in Konstari and Valkokari (2025c), whereas some are newly identified. The newly identified roles are benefiter, educators, exploiter, and innovator. The roles in this LL differ from those found in previous literature, as each LL is unique and its roles depend on its objectives.

Some user companies identified as SOI advocates, whilst others viewed themselves as exploiters or beneficiaries. None of the interviewees referenced an ecosystem or LL orchestrator, indicating that this role was not present within the shared infrastructure. The infrastructure provider was primarily perceived as a source of expertise and technology, rather than as an ecosystem builder. The absence of a defined LL orchestrator may contribute to the limited collaborative SOI activities.

Based on the actors, activities and roles within the shared semiconductor infrastructure, the framework originally suggested by Valkokari et al. (2024) was adapted for the impact of SOI activities in the shared semiconductor infrastructure, according to Figure 4. The full impact framework can be found in Konstari and Valkokari (2025c).

SOIs in shared infrastructure become integral to user companies' operations and products. These activities impact the regional industry by generating local IP and shaping the area's reputation. Nationally, SOIs spread through collaborative R&D, supporting new applications and long-term competitiveness though IP creation to Finland. For user companies owned by global firms, SOI benefits extend internationally, enhancing global parent companies' competitiveness, supporting net-zero goals, improving sustainability in the semiconductor sector, and advancing SDGs.

SOI activities within shared infrastructure influence long-term research at regional, national, and global levels. The shared semiconductor infrastructure determines R&D fabrication capabilities and which SOIs can be pursued in various research projects. Through research activities, SOIs adopted in the shared infrastructure operations diffuse geographically, also enhancing know-how and expertise across multiple areas.

SOI activities in shared semiconductor infrastructure impact regional, national, and global ecosystems on a societal level. Regionally, they support local sustainability transfer; nationally, they also influence public funding decisions; globally, they promote SOI adoption and raise awareness across networks, affecting the implementation of SOIs in the global semiconductor industry. These actions contribute to achieving UN SDGs worldwide.

The theoretical contributions include defining the actors and roles for SOI activities in an LL context and presenting a framework for understanding the impact pathways of these activities in a technology-focused environment. The findings expand the existing discussion on LL impacts to include deep technology sectors and illustrate the complexity of SOI impact pathways in technology-intensive industries, with implications for SDGs.

The managerial implications of this research offer insights into the various roles of LL actors for SOI and how SOI activities generate impact. The results may assist managers in evaluating their activities in LLs, help RTOs understand and analyse their SOI-related impacts, enable funding organisations to better assess the effects of supporting SOI activities, and provide the research community with a deeper understanding of the impact of SOIs.

4.5 Publication V

Integration of multi-disciplinary environmental sustainability aspects into early-phase microelectronics research and development (Konstari and Valkokari, 2025e)

4.5.1 Background and objectives

Multi-disciplinary RTOs participate in public and private R&D projects both nationally and globally. Through innovation activities, RTOs with microelectronics departments affect and contribute widely to the development of the electronics industry. Hence, RTOs are in a situation to promote sustainability through next-generation technologies. To make the industry more sustainable, it is important to raise sustainability awareness among RTO researchers and ensure that all microelectronics R&D projects consider environmental impacts cost-effectively, already during an early phase.

This research creates a cost-effective approach for incorporating environmental sustainability consideration into early-phase microelectronics R&D at an RTO, despite limited information on the product, no LCA funding, and strict technical performance

requirements. It also examines factors impacting effective environmental sustainability knowledge-sharing between RTO departments.

4.5.2 Main findings and contributions

The main finding of this study is the design science artifact presented in Figure 6 for environmental sustainability evaluation during early phase microelectronics R&D. First, it is essential to clearly define the objective of the R&D activities and the application itself, along with its significance, as well as the potential impact on the future digital society. Secondly, it is important to consider the product's lifecycle as thoroughly as possible, evaluating whether the ongoing project can influence or extend the lifespan of the final product in any way.

Furthermore, researchers must make various decisions during microelectronics R&D regarding materials selection, device layout, fabrication methods, and testing procedures. Each of these choices influences factors such as device energy consumption, the likelihood of meeting technical performance requirements, energy use during manufacturing and testing, materials utilised, and quantities required for fabrication. These should be carefully assessed to minimise environmental impact whilst ensuring that the device meets the technical requirements.

Evaluation of the categories in Figure 6 were found out to require multi-disciplinary know-how from chemistry, electronics, materials sciences, semiconductor technology and sustainability fields. Knowledge related to these fields and sustainability was found to be to some degree siloed within various departments of the RTO.

Different kinds of aspects affect efficient knowledge integration from various RTO departments. These aspects were found out to be individual (personal interest, **degree of specialisation**); organisational (Leadership, Organisational goals, Organisational structure, Organisational culture, Time, resources and funding, Physical location); knowledge-related (Available knowledge within own organisation, Available knowledge elsewhere, Possibilities for interactive knowledge sharing, Terminology, **Multi-disciplinarity**, Knowledge silos); or technologically related (**Device performance requirements**, **Available infrastructure and equipment**). Of these, the newly identified ones are **bolded**, whereas the others had been previously identified.

The principal theoretical contribution of this study is the design science artifact, along with the identified aspects influencing effective sustainability knowledge integration from various RTO departments. These findings provide academics with insights into the practical challenges faced by researchers in early-phase microelectronics R&D projects when incorporating environmental sustainability at an operational level.

Managers can utilise these results for promoting sustainability awareness in their R&D departments and to identify key considerations for enhancing knowledge utilisation within their organisations. The proposed approach aims to integrate environmental

sustainability into the daily activities of researchers and foster greater awareness. However, the findings also underscore the importance of strong leadership and ongoing coaching to achieve sustainability objectives.

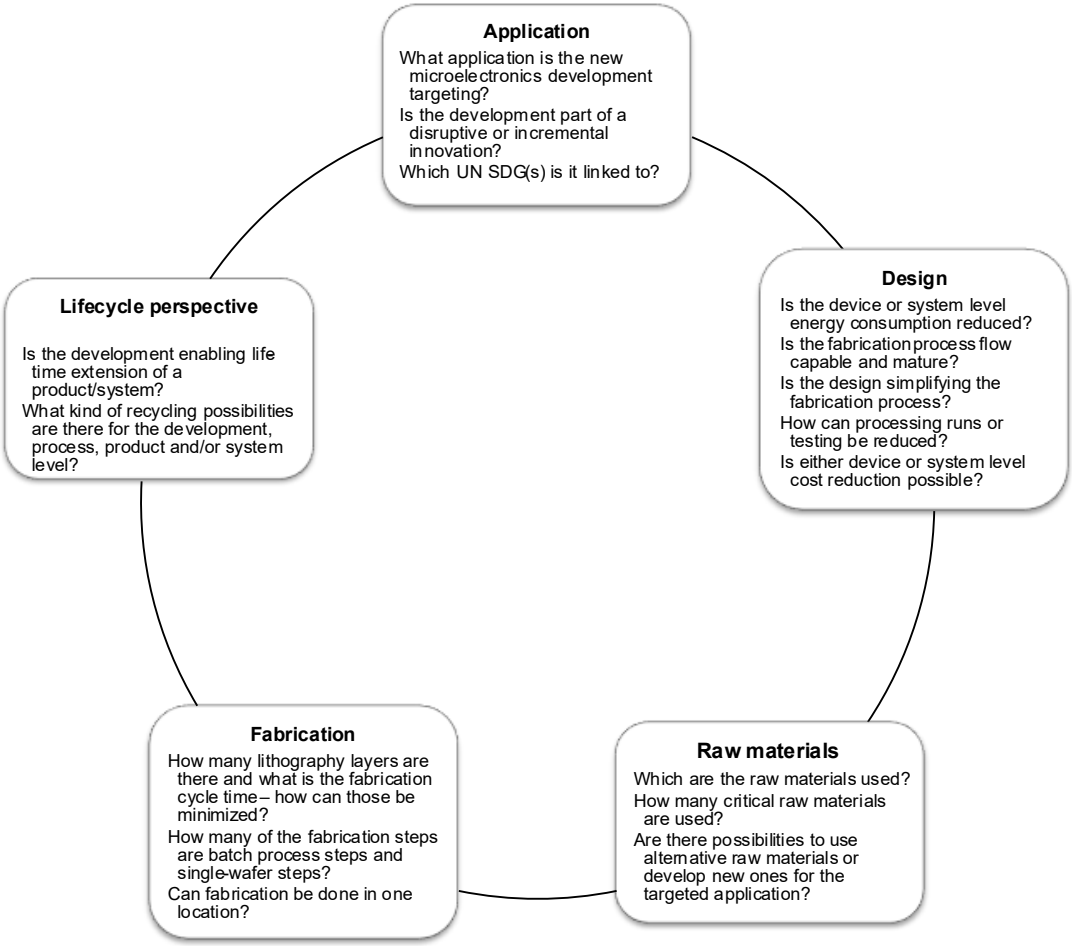


Figure 6 The design science artifact for how environmental sustainability can be evaluated in early phase microelectronics R&D at an RTO. After Konstari and Valkokari (2025e).

5 Discussion

The aim of this thesis was to study aspects of SOI in a shared semiconductor infrastructure in Finland. This was done on three levels, as shown in Figure 1. The answer to the main RQ "*What characterises SOI in an RTO driven shared semiconductor infrastructure?*" is built through the sub-RQs presented in Table 1.

5.1 Various aspects of SOI in a shared semiconductor infrastructure

This section addresses the sub-RQs, outlining the key characteristics of SOI in an RTO-driven shared semiconductor infrastructure.

5.1.1 Who are the actors for SOI?

On the European level, the parties of the green innovation ecosystem round RTOs are grouped in Figure 5 as authorities, funding parties, industry, societal parties, and knowledge providers. Compared to previous mapping done by Marcon et al. (2021), these actors are complemented in this specific setting with service providers, SMEs, large companies, local municipality, and the public opinion. In a high technology field, it is important to differentiate between SMEs and large companies, as those have different kinds of internal know-how and capabilities available for advancing SOI, and these should hence be considered as various actor groups.

Within the shared semiconductor infrastructure on a regional level, the companies active in the shared infrastructure are either SMEs or large companies. The company actors for SOI in the shared infrastructure are organisations, individuals, legislation and regulations, funding parties, supply chain and industry requirements.

On the organisational level, the organisational actors of a shared semiconductor infrastructure constitute technology and facility providers and users. Also, the funding and legislative parties are actors, as they exert a large impact on what kind of SOI activities can be initiated in the infrastructure.

The individual actors for SOI in the shared infrastructure are facility management, facility maintenance personnel, management, R&D personnel, maintenance personnel, quality personnel, management, operative personnel, sustainability and quality personnel, shareholders/owners, teaching personnel, students. Advancing SOI in R&D projects at RTOs should be on all researchers' tables.

Individual actors at RTOs for advancing SOI in green innovation ecosystems include more widely operative people, sustainability directors, procurement, top management, top R&D management, the CEO.

5.1.2 What are the concrete SOI activities?

On a European level, the concrete activities for advancing SOI include joint research projects, the co-creation of new products and services between many partners, and influencing activities. These are often driven by RTOs. In addition, the RTOs also have individual activities in-house for advancing SOI, as summarised in Table 6.

On the regional level, there are both joint and company individual activities for SOI in the shared infrastructure. The individual activities at the companies often are such that they aim at creating value for the organisation in question. The collaborative activities, on the other hand, aim more at advancing topics that are not competitive or do not concentrate on the core business of the actors but rather aim at a wider impact. The concrete SOI activities are such that they create value for the user companies through (1) optimisation of their operational model, (2) through development of new processes and technologies either alone or in collaboration, and (3) through participation in R&D projects, as well as via collaborating, networking, and learning.

The facility provider, semiconductor infrastructure provider, user companies, and universities each carry out their own SOI activities related to infrastructure, services, tools, teaching, business, R&D, piloting, and production. Collaborative efforts include joint R&D, best practice sharing, training, ecosystem partnerships, talent development, information exchange in meetings, and occasional cleanroom gatherings.

On the organisational level, the RTOs engage in SOI activities related to operational optimisation, organisational transformation and systems building. Environmental sustainability can be considered in early phase microelectronics R&D projects by evaluating aspects related to the application, lifecycle perspective, design, and raw materials, as well as fabrication of the device under development.

The findings are in line with the earlier findings by Abadzhiev et al. (2022) that companies pursue green innovation mainly to address industry challenges and secure profitability through new markets and increased service delivery, rather than solely to reduce environmental impact. The findings are also in line with the ones from Al-Abdallah and Al-Salim (2021) that green innovations and products can give companies a competitive advantage, and as García-Sánchez et al. (2020) and Geiszler et al. (2018) pointed out, that environmental sustainability-related initiatives positively affect company value.

5.1.3 Which roles are there for advancing SOI?

The role of the RTO for SOI activities in green innovation ecosystems in Europe is to be the innovator, initiator, information provider, disseminator, role model or solution provider: the orchestrator. The RTO is the orchestrator of the green innovation ecosystem, a central resource for advancing SOI activities within the green innovation ecosystem around it. The RTO plays an important role in the green innovation ecosystem around it

as the RTO drives for next generation technologies and innovation. The green innovation ecosystem round the RTO frequently expects the RTO to set the barrier and show what is possible and meaningful to do related to sustainability. This puts the RTO in a responsible position for advancing SOI within Europe.

The company roles for advancing SOI on a regional level in a shared infrastructure include the advocate, contributor, facilitator, informant, integrator, messenger, provider, sponsors, user, benefiter, exploiter. The individual roles for advancing SOI in a shared infrastructure are somewhat more numerous and include the advocate, contributor, expert, facilitator, informant, integrator, messenger, provider, researcher, sponsors, user, benefiter, educators, exploiter, and innovator.

It is of interest that roles for advancing SOI often seem to go down to the individual level. Companies can have a strategy or a policy, but at the end it is always individuals who drive the topic. Individuals may have roles related to their job description, or then they may take a role due to personal interest. In the latter case, their activity is often more intense, and they have a personal interest in sustainability.

Compared to previous academic literature, this research identified additional role descriptions for advancing SOI activities in an LL than what the earlier literature had identified. The newly identified roles were the benefiter, educators, exploiter, and innovator. This coincides well with the earlier finding by Carrara and Freisinger (2024) that actor roles within innovation ecosystems are case- and context-specific.

5.1.4 How and why do the actors engage in SOI?

On a European level, actors engage in SOI through collaborative projects, as well as through orchestrating, influencing and driving innovation. The drivers for engaging in SOI activities at RTOs include regulations and funding requirements, but also political pressure and image, customer requirements and energy savings. RTOs and other parties engage in collaborative efforts for SOI to create impact and future value. The aim is to include several actors from the society and utilise available funding.

Regionally, the infrastructure provider and users engage in SOI activities by being in the shared infrastructure and collaborating with others there. Alternatively, the organisations individually engage in activities that advance sustainability within their companies or through individual actions. The value is created through individual and collaborative activities and captured through entrepreneurial opportunities. The reasons for SMEs and large companies to engage in OI for sustainability differ.

The user companies create value by optimising their operations, developing new processes and technologies, and engaging in R&D and information sharing. The shared infrastructure provider adds value by establishing infrastructure and services, finding ways to reduce environmental impact and monitor consumption, and collaborating through networking and education.

User companies capture value through higher company worth, customer growth, open innovation, personnel development, and improved efficiency. The shared infrastructure provider benefits by offering open-access services, tracking and reporting usage data for each user, sharing best practices, developing knowledge, and creating innovations and IP.

The facility, semiconductor infrastructure provider and users as well as universities each conduct SOI activities in the infrastructure that are linked to the infrastructure services or tools, teaching, business, R&D, piloting, and production. These groups also collaborate within the shared infrastructure, engaging in joint R&D, sharing best practices, training, ecosystem partnerships, talent development, and regular information exchanges, including cleanroom meetings.

There are various reasons for the user companies to engage in SOI activities in the shared infrastructure. The internal and external factors at companies affecting their interest to engage in OI for sustainability in a shared infrastructure. Internal drivers motivating companies to pursue open innovation for sustainability include value proposition, innovation and IP strategies, branding, management and communication practices, corporate responsibility, and advanced technology. Network-related drivers consist of ownership structures, stakeholder involvement, and individual interests. Internal barriers comprise management practices, communication issues, and expertise gaps, whilst external challenges encompass funding limitations and outdated infrastructure.

At the organisational level, European RTOs engage in SOI activities through various efforts focusing on operational efficiency, organisational transformation, and systems building. The RTO engages in SOI to provide added value and create impact. Another reason for the infrastructure provider to consider SOI is to include consideration on it in all R&D projects.

The findings are in line with the previous finding by Klewitz and Hansen (2014) that Interaction with external actors like customers, authorities, and research institute typically increase SMEs' capacity to generate SOIs. However, this research did not find support for the finding by Abadzhiev et al. (2022) that companies engaged in green innovation only to increase efficiency or to change how they operate; rather, the results showed that the companies engage to, e.g. also collectively improve the environmental footprint. The findings hence complete the previous understanding of the topic.

5.1.5 What is the impact of SOI activities?

The impact of SOI activities in the shared infrastructure, studied as a LL, is wide, thanks to the wide user group of the infrastructure. The developed SOI affects industry or businesses, academia and society on various geographical dimensions from regional, to national to global. At best, the SOI activities affect the sustainability of the entire semiconductor industry when diffused to global semiconductor giants. A lot of the impact comes indirectly, through improved image or increased regional attractiveness.

On a European or even global level, the SOI activities support the global semiconductor industry by facilitating knowledge diffusion and technology transfer into multinational companies, thereby enhancing their long-term competitiveness and aligning with net-zero and sustainability targets. The capabilities of shared infrastructure influence the range and scope of international R&D collaborations, shaping the type of SOI initiatives advanced globally. Additionally, SOI activity dissemination fosters global awareness of sustainable best practices in the semiconductor sector, positions Finland and Europe as leaders in sustainability, and contributes to achieving the UN SDGs, supporting the broader sustainable development of the digital society.

On the regional level, the SOI activities in the shared semiconductor infrastructure are integrated into user companies' products and services, strengthening the region's industrial competitiveness and reputation. The technologies and operational models available dictate the region's capacity to engage into collaborative microfabrication R&D. This has long-term implications for the inclusion of sustainability in R&D, development of regional expertise, and the diffusion of SOI within the industry. The infrastructure serves as a regional role model for sustainability, setting the barrier for others, guiding future directions, and sharing best practices, thus supporting the region's transition towards sustainability.

On the organisational level, the SOI activities in the shared semiconductor infrastructure are integrated into the user companies' products and services, strengthening the competitiveness of these local businesses. They become integrated into R&D activities at the RTO and the universities, and affect the sustainability awareness at the organisations.

The findings are in line with previous findings by Dembek et al. (2023) that system level impacts are either intentional or unintentional. The intention of the concrete SOI activities is not, for example, to improve the image or attractiveness of the region, but this is the impact of these activities.

This research, on the other hand, tends to contradict the criticism by Hansen et al. (2022) as to whether SOI really affects the sustainability on a system level or whether the current discussion is too innovation-centric to really drive for transition. Our findings clearly show that when first thoroughly analysing the actors, activities and roles in the shared infrastructure for SOI activities, the industry-specific impact framework can be created. This framework shows that when SOI is considered in a proper industry context as part of other technology development, SOI activities do have system level impact.

It is arguable that should all semiconductor technology that advances UN SDGs be considered innovations done with sustainability in mind, i.e. SOIs, and not only those developments with the very purpose and scope of advancing green technologies. This thesis tends towards suggesting the first approach. In this way, the impact of SOI becomes more concrete, and the discussion is no longer excessively innovation process-centric but rather focuses on outcomes.

5.2 Characteristics of SOI in the shared semiconductor infrastructure

The main research question for this thesis was "*What characterises SOI in an RTO driven shared semiconductor infrastructure?*" From the sub-RQs, it is possible to draw conclusions of what are the characteristics of SOI in an RTO driven shared semiconductor infrastructure. Next, we summarise the answer to the main RQ and discuss it.

5.2.1 Answer to the main research question

In a shared semiconductor infrastructure, the SOI activities are done in a multi-actor environment. The organisational- and individual actors have their own goals, targets and strategies for SOI. Based on their internal aims, they take various roles for advancing SOI.

There are activities at a variety of levels, both separately at organisations and collaboratively. The SOI activities in the shared infrastructure can be categorised as operational optimisation, organisational transformation and systems building activities. Typical for collaborative activities is that those are not part of the core business of the organisations but value adders. These activities rather create long term than short term impact. Available funding affects the collaborative activities.

The user companies individually tend to focus on economic sustainability. The focus of the collaborative activities in the green ecosystem round the RTO is typically on environmental sustainability. The European or wider ecosystem focuses both on environmental and social sustainability for our future prosperity and well-being.

The value of the SOI activities is created through the SOI advancing activities within the shared semiconductor infrastructure and captured through the individual organisations' business activities.

The impact of SOI activities is more widespread on various geographical levels and linked to industry, research and society in general. On a regional level, the SOI activities in the shared infrastructure typically set the level of where the regional players aim related to sustainability. On a wider horizon, the SOI activities also affect the UN SDGs.

5.2.2 Discussion around the main research question

The SOI activities in the shared semiconductor aim at varying sustainability dimensions at various levels. The shared infrastructure itself provides sustainable value – economic, environmental and social – to its users. This finding is in line with Helman et al. (2021), who underlined that advanced infrastructure sharing in itself is already highly sustainable. The existence of these sustainable values lay the basis for sustainable business thinking, as was highlighted by Bocken et al. (2015).

The focus of the infrastructure user companies is on their own business, i.e. the economic sustainability, and they focus on capturing the value of the SOI activities in the shared infrastructure. Different kinds of internal and network related factors affect their strategy and interest to engage into OI for sustainability. As Lüdeke-Freund et al. (2019) pointed out, a sustainable business models must create value for customers and stakeholders whilst capturing economic benefits and preserving or enhancing natural, social, and economic capital. The findings of this research show that the user companies are not all yet there on all the sustainability dimensions.

The findings show that SMEs and large companies have varying aims and needs in the shared semiconductor infrastructure. SMEs are more dependent on the shared infrastructure than the large companies. Klewitz and Hansen (2014) earlier highlighted that SMEs' SOI activities benefit from interaction with external parties. Our findings are in line with this. Danko et al. (2023), on the other hand, highlighted that MNCs either take a focal or a more participatory role. Our findings are also in line with this: many of the larger companies were more interested in following the topic and moving the best practices to their own companies through inbound open innovation, hence taking a more participatory than driver role in the SOI activities. Earlier, Rodríguez et al. (2024) also said that competitors can collectively promote sustainability through co-opetition-based networks. The results are aligned with these, as the infrastructure users were widely of the opinion that sustainability is not a competitive topic.

The infrastructure provider, on the other hand, is an RTO, and also focuses in addition to the economic side on caring for the environment, as the RTO is the one running the infrastructure. Previous it has been identified by Oskam et al. (2021) that it is important that value is evaluated in ecosystems, so that the need of all actors is satisfied. The findings are in line with this - it is important that all users understand the needs of the various actors in the shared infrastructure.

On the regional level, the focus of the collaborative SOI activities in the green innovation ecosystem is on the environmental part of sustainability. The available funding affects this direction, as well as the feeling of social responsibility: the RTOs feel that they are responsible for showing an example. The SOI activities have regional impact, and they lay the basis for future regional value creation of SOI activities.

The findings are in line with Mbanefo and Grobbelaar (2024), who wrote that value is co-created in ecosystems. However, the research findings are also in line with Garcia et al. (2019), who highlighted that it is difficult to create and capture value in open eco-innovation networks, as there is a low return on investment. Hence, the findings show that funding is necessary in green innovation ecosystems to achieve the wider impact. This is also in line with Dormeier et al. (2024), who highlighted the importance of the system level approach for ensuring that both the stakeholder's and the broader system's objectives are met. Zhang et al. (2024), on the other hand, discovered that the green innovation ecosystem evolves as effective green innovation strategies diffuse throughout a complex network. This is also in line with our findings on the impact of SOI activities:

they affect and impact the ecosystem round the shared infrastructure in a multitude of ways.

On the European and wider level, the focus of the SOI activities is environmental and social. Funding is provided to develop SOIs that ensure the long-term competitiveness and well-being. On this level, the basis is laid for future value creation of SOI, and the SOI activities in the shared infrastructure are diffused to the wider ecosystem and hence create impact on a wider scale. This finding is in line with Bowen et al. (2022) who found out that supporting shared infrastructure should be considered an investment to education and innovation, hence hinting on the wider impact of the activities in the shared infrastructure.

Yoo and Cho (2024) also underlined that high-performing semiconductor companies emphasise sustainable development across the entire industry ecosystem, rather than focusing solely on internal sustainability aspects. Consequently, the shared infrastructure may be considered to play a role in the picture on the European level. The findings also support Wang et al. (2023), who argued that the government can effectively advance sustainable growth whilst reducing environmental impact through effective strategies and innovative technologies.

Figure 7 shows the sustainability focus areas, at what levels value is created and captured, and at what levels the impact of the SOI activities can be encountered. This explains the importance of studying the topic on various levels. It is characteristic for SOI in a multi-user infrastructure that the value creation and capture mechanisms are complex, and the impact of the actions can be seen on a much wider horizon than the infrastructure itself.

Sustainability is a multi-disciplinary topic, and experts often approach it through their own expertise. Hence, bridgebuilding between various disciplines is important to explain the value creation and capture as well as impact mechanisms of the SOI activities from one stakeholder to another. To advance SOI in the semiconductor field, knowledge sharing and bridge building between various disciplines is of outermost important.

Only by explaining what the actual SOI activities are, how they can be advanced, and by showing how various user groups can benefit out of those is it possible to advance sustainability in a shared infrastructure setting. It is possible to conclude that it is also characteristic for SOI activities in an RTO-driven, shared infrastructure that they are dependent on multi-disciplinary knowledge of the topic. This specific aspect constitutes an interesting addition to the other aspects identified in this research.

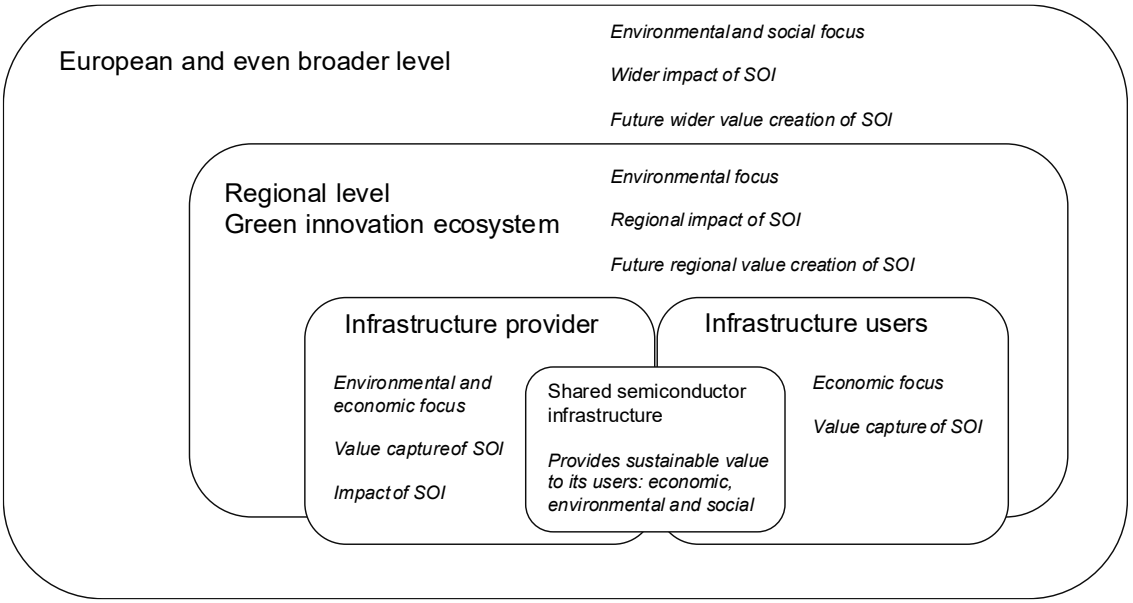


Figure 7 Refined research framework showing at which levels value is created and captured from SOI and which levels the SOI activities impact, as well as what sustainability dimensions the activities primarily addresses at the various levels.

6 Conclusions

This chapter summarises and concludes the thesis, discusses the limitations of the research, and provides suggestions for further research.

6.1 Summary of the thesis

The purpose of this thesis was to create new knowledge about SOI activities in the context of a shared semiconductor infrastructure, also studied as an LL, the drivers and barriers for engaging into SOI activities, the value creation and capture pathways of SOI activities, and the wider impact of SOI activities in the shared infrastructure. The study looked to integrate SOI with industry-specific technological expertise to develop a deeper understanding of SOIs in the semiconductor field.

First, a literature review of important topics for this research were presented in chapter 2. Then, the research approach and methods were presented in chapter 3. Chapter 4 summarised the findings, and chapter 5 discussed the research questions and compared them to previous findings.

The SOI topic was studied from the point of view of the main shared infrastructure user groups: user companies and infrastructure provider. The research method was selected as qualitative multiple case studies and design science research. The research topic was studied on three levels: (1) the European level, (2) the regional level, and (3) the organisational level of the infrastructure actors, as was shown in Figure 1.

The RQs were presented in Table 1. The sub-RQs covered understanding of who, what, which, how and why SOI activities in the shared infrastructure, as well as what the impact of these SOI activities are on different horizons. With the help of these, understanding was built to answer the main research question of what characterises SOI in the selected specific environment and industry of a shared semiconductor infrastructure.

The answer to the main RQ can be summarised as following:

SOI activities within a shared semiconductor infrastructure occur in a complex, multi-actor environment where both organisations and individuals pursue their own objectives and adopt various roles to advance sustainability. These activities operate at varying levels—some are undertaken separately by companies, whilst others are collaborative, often contributing to long-term value rather than immediate gains. Funding availability influences the scope and nature of joint initiatives. Individually, companies tend to prioritise economic sustainability, whilst collaborative efforts in the green ecosystem surrounding the RTO focus on environmental sustainability. At the European and broader level, attention shifts to both environmental and social sustainability, aiming to support collective prosperity and well-being. The value generated by SOI activities is realised through operational optimisation, organisational transformation, and systems building, and is ultimately captured by the business activities of participating organisations. The

impact of SOI initiatives extends across different regions, influencing industry, research, and society – locally by setting standards, and globally by contributing to the achievement of UN SDGs.

With the help of this outcome, the research framework was refined to include the sustainability dimensions and focus areas of the various levels, as shown in Figure 7.

This thesis meets well its research objectives, i.e. to identify SOI activities in a shared semiconductor infrastructure and the value creation and capture as well as their impact. The research fills the identified research gaps in its specific context and in this way contributes to the lack of qualitative case studies in this field as well as to the identified academic research need. In addition, the research brought technical understanding from the semiconductor industry to the SOI discussion, successfully going deeper in the analysis of the practical SOI activities and making the SOI discussion in question industry-specific.

The findings of this thesis introduce a new comprehension of the topics under study, in addition to strengthening previous findings whilst validating and completing them in this specific setting and context. The research responds to earlier identified research gaps and contributes to the on-going academic discussion. The research shows the complexity of the sustainability topic and the need to combine various disciplines and make the topic industry-specific in order to understand it thoroughly.

6.2 Theoretical contributions

On the European level, the academic discussion was advanced by developing an expanded framework for green innovation ecosystem actors in microelectronics RTOs, building on Marcon et al. (2021). The revised framework grouped actors and broadened the "other parties" category to include service providers, SMEs, large companies, local municipalities, and public opinion. Additionally, it identified key pain points and drivers for SOI in the green innovation ecosystem round semiconductor RTOs.

On the regional level, several theoretical perspectives were combined to describe forms of sustainable value in shared semiconductor infrastructures and mapped the processes for creating and capturing value from SOIs. The findings indicate that shared infrastructures may provide environmental, social, and economic effects relevant to sustainability and entrepreneurship.

On the regional level, the actors and roles involved in SOI activities were identified within the LL context, and a framework to describe the impact pathways on various horizons of these activities in technology-focused settings was introduced. The results broaden the analysis of LL impacts to include deep-tech sectors and demonstrate the complexity of SOI impact pathways in technology-intensive industries, with reference to potential relevance for SDGs.

On the organisational level, a conceptual framework was introduced that highlighted the main drivers and barriers for companies pursuing OI for sustainability in shared research infrastructures. Integrating OI and SOI, it identified factors that facilitate or hinder both, emphasising company origin and shareholder sustainability reporting requirements. Internal drivers include value proposition, innovation and IP strategy, branding, effective management and communication, corporate responsibility, and advanced technology; whilst network drivers are owners, stakeholder, and individual interests. Internal barriers are weak management, poor communication, and lack of expertise; external barriers are limited funding and outdated infrastructure.

On the organisational level, an environmental sustainability artifact was introduced. This artifact helps researchers to consider various SOI dimensions in their work and to look for alternatives. In addition, factors affecting knowledge use in specific contexts and disciplines were identified. The results offer insights into the practical challenges researchers face when integrating environmental sustainability into microelectronics R&D projects at an operational level.

The main theoretical contribution of the entire thesis is the combination of several disciplines and concepts to define the SOI context on three levels in a shared semiconductor infrastructure, as shown in Figure 7. By its aid, characteristics of SOI activities within that shared infrastructure could be conceptualised. The focus of SOI activities on an organisational level is very much economic and aims at capturing value. In the case of RTOs, the aim may also be to create environmental value. The focus of SOI activities on the regional level is environmental, aiming at future value creation. Finally, the focus on the European level is environmental and social, aiming at future value creation. The SOI activities result on all levels in research, business and societal impact.

6.3 Managerial and policy implications

The practical implications of this dissertation address similar topics as the theoretical contributions, but from a different angle. The results are relevant for the growing semiconductor industry in general. The thesis combines and explains sustainability in practice in the semiconductor field, and demonstrates how the various aspects of SOI in practice are encountered in a shared semiconductor infrastructure or in the wider ecosystem round the same. This information is valuable for managers for guiding their organisations.

First, the findings help managers in industry and academia identify key players in local green innovation ecosystems for SOI advancement. Government officials can also use these results to better understand the complexity of sustainability in the European semiconductor sector as well as the need for multidisciplinary collaboration.

Meeting the needs of ecosystem participants can contribute to value generation and entrepreneurial prospects. The findings offer information for managers evaluating SOI

activities and provide guidance for entrepreneurs developing business models oriented toward sustainability.

Furthermore, this research describes the various roles of LL actors for SOI and the ways SOI activities create impact. The findings may help managers review their activities in LLs, support RTOs in measuring SOI-related impacts, assist funding organisations in assessing the effects of SOI activities, and provide researchers with information about SOI's impact.

The findings offer valuable insights into OI activities concerning sustainability within local ecosystems, such as shared semiconductor infrastructure. They highlight the complexity inherent in this topic across the semiconductor industry and clarify its intermediary function between organisational units. Furthermore, the results emphasise the importance of proactively integrating sustainability considerations into the local ecosystem, particularly through OI. These insights may assist managers in initiating SOI initiatives and in identifying related factors within their organisations. The research also highlights for policymaker the positive impact of sharing infrastructure on sustainability, and OI for sustainability.

Additionally, managers can use the results to guide conversations about sustainability awareness in R&D departments and to identify factors relevant to improving knowledge use within organisations. The suggested approach is intended to incorporate environmental sustainability into researchers' daily work and increase awareness. The findings also indicate that effective leadership and continuous coaching are significant means for meeting sustainability goals.

The research also highlights the importance of the requirements of available funding for R&D activities directed towards SOI for policymakers and funding parties. For example, the requirements of the kinds of organisations participating in R&D projects shape the possible ambition level of the R&D project: SMEs and large companies do not always have, for example, the same prerequisites to contribute to the requirements of the semiconductor industry. The available funding for SOI activities and how it is directed will exert long-term impact on sustainability on different horizons.

6.4 Limitations of research and suggestions for future research

There are limitations of research linked to all three levels of study. The qualitative research on European level cover only four RTOs during a short period of time in a specific setting. Although the RTOs covered are well known in their field, there are several other RTOs in Europe active in the microelectronics field that are not addressed. However, the organisations were carefully selected for this study and are good representants for typical European RTOs. Hence, it can be assumed that the results are similar in other RTOs, even though the results require validation. However, the results are preliminary, not generalisable, and open possibilities for further research.

The qualitative case study on the regional level is based on empirical research in the semiconductor industry over a short period of time, with the focus on one shared infrastructure that constitutes an innovation ecosystem and incorporates a specified set of companies. The companies studied represent the participants of the shared infrastructure well, but from a larger perspective they constitute only a small group of business enterprises in Finland. The results are hence preliminary and not yet generalisable. Instead, they indicate avenues for further research into other shared infrastructures in various industries and geographical locations.

The design science artifact is the result of work within one RTO. It has not yet been tested in practice, even though it is the result of longitudinal research. The artifact has been preliminary tested, and further testing is planned in new R&D projects. However, further research is also needed for practical use cases, where it can be applied and possibly tuned.

In addition, the literature review completed for this thesis was not a systematic one, but was performed in a continuous manner with selected search words, due to the breadth of the research topic and the large number of concepts to be covered. Consequently, this represents a research limitation. Nevertheless, previous research was not identified with the key words applied on the same topic as described in earlier chapters.

This thesis identifies six potential future research directions, comprising the three levels examined in this study. First, on the European level, further research is required into the roles the actors take for advancing SOI in the green innovation ecosystem, as well as on the value creation and capture and impact pathways of the SOI activities in the green innovation ecosystem.

Second, more attention should be given to mapping how the SOI activities in the shared semiconductor infrastructure affect various environmental, social and economic factors on different horizons. The research should be moved to different settings, and the results could be compared to other regional companies not active within the shared infrastructure.

Third, more understanding is needed of the decision-making criteria of the various actors in the shared infrastructure, i.e. when and with whom they are ready to collaborate for SOI. What activities are the actors ready to collaborate on, which activities do they not want to collaborate on, and are there any differences between SMEs and large corporations on the matter?

Fourth, the angle of co-opetition of the actors in the shared semiconductor infrastructure should be studied on various levels: regional and European. This research found that all actors in the shared infrastructure do not consider sustainability to be a competitive topic, and hence they would be ready to collaborate on this, even though the companies are competitors. Further research is needed in this area. In addition, the internal dynamics and co-evolution of the innovation ecosystem constitute an interesting further research angle.

Fifth, an interesting further research field would also be to study the system level impacts of the SOI activities in the shared semiconductor infrastructure, which of them are intentional and which are unintentional, and who at the end identifies these.

Finally, the design science artifact should be tested further in practice and validated through practical use cases.

References

Abadzhiev, A., Sukhov, A., Sihvonen, A., Johnson, M., 2022. Managing the complexity of green innovation. European Journal of Innovation Management 25, 850–866. https://doi.org/10.1108/EJIM-02-2022-0098

Abi Saad, E., Agogué, M., 2024. Living Labs in science-industry collaborations: Roles, design, and application patterns. Technovation 135, 103066. https://doi.org/10.1016/j.technovation.2024.103066

Adams, R., Jeanrenaud, S., Bessant, J., Denyer, D., Overy, P., 2016. Sustainability-oriented Innovation: A Systematic Review. International Journal of Management Reviews 18, 180–205. https://doi.org/10.1111/ijmr.12068

Ademi, B., Sætre, A.S., Klungseth, N.J., 2024. What do established companies do to factor in sustainability into their business models? Bus Strategy Environ. https://doi.org/10.1002/bse.3980

Adner, R., Kapoor, R., 2010. Value creation in innovation ecosystems: how the structure of technological interdependence affects firm performance in new technology generations. Strategic Management Journal 31, 306–333. https://doi.org/10.1002/smj.821

Al-Abdallah, G.M., Al-Salim, M.I., 2021. Green product innovation and competitive advantage: an empirical study of chemical industrial plants in Jordanian qualified industrial zones. Benchmarking: An International Journal 28, 2542–2560. https://doi.org/10.1108/BIJ-03-2020-0095

Alexandrakis, J., Hein, J., Kratzer, J., 2022. Living Labs and Small and Medium-Sized Enterprises: A Symbioses Propelling Sustainable Innovation. Sustainability 14, 12729. https://doi.org/10.3390/su141912729

Almelhem, M., Buics, L., Süle, E., 2025. Comparison of sustainability and circularity indicators: downstream vs. upstream supply chain strategies. Discover Sustainability 6, 302. https://doi.org/10.1007/s43621-025-01158-0

Amitrano, C.C., Bifulco, F., 2024. The co-evolution of ecosystem and university's roles: a focus on the integration of technologies and cultural heritage. J Technol Transf. https://doi.org/10.1007/s10961-024-10127-0

Aquilué, I., Caicedo, A., Moreno, J., Estrada, M., Pagès, L., 2021. A Methodology for Assessing the Impact of Living Labs on Urban Design: The Case of the Furnish Project. Sustainability 13, 4562. https://doi.org/10.3390/su13084562

Badurdeen, F., Goldsby, T.J., Iyengar, D., Jawahir, I.S., 2013. Transforming Supply Chains to Create Sustainable Value for All Stakeholders, in: Treatise on Sustainability Science and Engineering. Springer Netherlands, Dordrecht, pp. 311–338. https://doi.org/10.1007/978-94-007-6229-9_18

Ballon, P., Schuurman, D., 2015. Living labs: concepts, tools and cases. info 17.

Ballon, P., Van Hoed, M., Schuurman, D., 2018. The effectiveness of involving users in digital innovation: Measuring the impact of living labs. Telematics and Informatics 35, 1201–1214. https://doi.org/10.1016/j.tele.2018.02.003

Baxter, D., Chipulu, M., 2023. Developing a new scale for measuring sustainability-oriented innovation. J Clean Prod 429, 139590. https://doi.org/10.1016/j.jclepro.2023.139590

BCC Research, 2025. Semiconductor Chips: Applications and Impact of Shortage. BCC Research. Copyrighted Material. All rights reserved.

Beaudoin, C., Joncoux, S., Jasmin, J.-F., Berberi, A., McPhee, C., Schillo, R.S., Nguyen, V.M., 2022. A research agenda for evaluating living labs as an open innovation model for environmental and agricultural sustainability. Environmental Challenges 7, 100505. https://doi.org/10.1016/j.envc.2022.100505

Berberi, A., Beaudoin, C., McPhee, C., Guay, J., Bronson, K., Nguyen, V.M., 2023. Enablers, barriers, and future considerations for living lab effectiveness in environmental and agricultural sustainability transitions: a review of studies evaluating living labs. Local Environ. https://doi.org/10.1080/13549839.2023.2238750

Bocken, N.M.P., Rana, P., Short, S.W., 2015. Value mapping for sustainable business thinking. Journal of Industrial and Production Engineering 32, 67–81. https://doi.org/10.1080/21681015.2014.1000399

Bocken, N.M.P., Short, S.W., Rana, P., Evans, S., 2014. A literature and practice review to develop sustainable business model archetypes. J Clean Prod 65, 42–56. https://doi.org/10.1016/j.jclepro.2013.11.039

Bodtker, T.E., Riley, R.A., Ozer, S., Gardner, S.K., Russell, R.J., Birdsall, J., Johnson, S.P., 2024. Leading Sustainability Applications for More Responsible Logic Technology Development. IEEE Transactions on Semiconductor Manufacturing 37, 428–432. https://doi.org/10.1109/TSM.2024.3438098

Boruchowitch, F., Fritz, M.M.C., 2022. Who in the firm can create sustainable value and for whom? A single case-study on sustainable procurement and supply chain stakeholders. J Clean Prod 363, 132619. https://doi.org/10.1016/j.jclepro.2022.132619

Bowen, S.K., Kigyeni, J., Constable, S., Mundoma, C., 2022. A Shift in Our Thinking: Reframing Shared Research Resources as Investments in Education and Innovation, Not Subsidized Science. Journal of Biomolecular Techniques 33. https://doi.org/10.7171/3fc1f5fe.f1e46498

Boyd, S.B., 2012. Semiconductor LCA: The Road Ahead, in: Life-Cycle Assessment of Semiconductors. Springer New York, New York, NY, pp. 109–112. https://doi.org/10.1007/978-1-4419-9988-7_8

Bryman, A., 2012. Social Research Methods, Fourth Edition. ed. Oxford University Press, Oxford.

Bulkeley, H., Coenen, L., Frantzeskaki, N., Hartmann, C., Kronsell, A., Mai, L., Marvin, S., McCormick, K., van Steenbergen, F., Voytenko Palgan, Y., 2016. Urban living labs: governing urban sustainability transitions. Curr Opin Environ Sustain 22, 13–17. https://doi.org/10.1016/j.cosust.2017.02.003

Burbridge, M., Morrison, G.M., van Rijn, M., Silvester, S., Keyson, D. V., Virdee, L., Baedeker, C., Liedtke, C., 2017. Business Models for Sustainability in Living Labs, in: Living Labs. Springer International Publishing, Cham, pp. 391–403. https://doi.org/10.1007/978-3-319-33527-8_30

Burrell, G., Morgan, G., 1992. Sociological Paradigms and Organisational Analysis. Elements of the Sociology of Corporate Life, 1st ed. Ashgate Publishing Limited, Aldershot.

Cabral, N.G.C., Gohr, C.F., 2023. Sustainable value creation in sharing economy: Conceptual framework proposition and application in Brazilian offline communities. Technol Forecast Soc Change 186, 122124. https://doi.org/10.1016/j.techfore.2022.122124

Cammarano, A., Aquilone, G., Varriale, V., Michelino, F., Caputo, M., 2024. The potential of open innovation platforms: driving sustainable development goals through digital collaboration. Innovation 1–24. https://doi.org/10.1080/14479338.2024.2421015

Carrara, F., Freisinger, E., 2024. Actors, activities, and interactions in innovation ecosystems: A systematic literature review and typology. International Journal of Innovation Management 28. https://doi.org/10.1142/S1363919624300022

Carter, N., Bryant-Lukosius, D., DiCenso, A., Blythe, J., Neville, A.J., 2014. The Use of Triangulation in Qualitative Research. Oncol Nurs Forum 41, 545–547. https://doi.org/10.1188/14.ONF.545-547

Cartwright, H.N., Hobson, C.M., Chew, T.-L., Reiche, M.A., Aaron, J.S., 2024. The challenges and opportunities of open-access microscopy facilities. J Microsc 294, 386–396. https://doi.org/10.1111/jmi.13176

Chanana, G., Palia, N., Sharma, R., 2024. Energy Efficiency and Sustainability Initiatives in the Semiconductor Industry, in: 2024 2nd International Conference on Advancements and Key Challenges in Green Energy and Computing (AKGEC). IEEE, pp. 1–5. https://doi.org/10.1109/AKGEC62572.2024.10868430

Chaudhuri, R., Singh, B., Agrawal, A.K., Chatterjee, S., Gupta, S., Mangla, S.K., 2024. A TOE-DCV approach to green supply chain adoption for sustainable operations in the semiconductor industry. Int J Prod Econ 275, 109327. https://doi.org/10.1016/j.ijpe.2024.109327

Chesbrough, H.W., 2003. The era of open innovation. MIT Sloan Manag Rev 44, 35–41.

Chistov, V., Aramburu, N., Carrillo-Hermosilla, J., 2021. Open eco-innovation: A bibliometric review of emerging research. J Clean Prod 311, 127627. https://doi.org/10.1016/j.jclepro.2021.127627

Churchill, E.F., 2012. Impact! Interactions 19, 12–15. https://doi.org/10.1145/2168931.2168936

Cobben, D., Ooms, W., Roijakkers, N., Radziwon, A., 2022. Ecosystem types: A systematic review on boundaries and goals. J Bus Res 142, 138–164. https://doi.org/10.1016/j.jbusres.2021.12.046

Compagnucci, L., Spigarelli, F., Coelho, J., Duarte, C., 2021. Living Labs and user engagement for innovation and sustainability. J Clean Prod 289, 125721. https://doi.org/10.1016/j.jclepro.2020.125721

Congressional Research Service Report R47508, 2023. Semiconductors and the Semiconductor Industry.

Cotterlaz-Rannard, G., Ferrary, M., 2025. Exploring the virtuous circle of societal value creation and capture by non-profit organizations from a Bourdieusian perspective. Public Management Review 27, 2172–2193. https://doi.org/10.1080/14719037.2024.2402373

Creswell, J.W., 2014. Research Design. Qualitative, Quantitative, and Mixed Methods Approaches, Fourth edition. ed. Sage Publications, Inc., Thousand Oaks.

Danko, T., Krasnokutska, N., Shyriaieva, N., 2023. Mapping the European innovation ecosystems for renewable energy: the role and impact of MNCs, in: 2023 IEEE International Conference on Technology and Entrepreneurship (ICTE). IEEE, pp. 20–25. https://doi.org/10.1109/ICTE58739.2023.10488535

Darkwa, I., 2025. Innovation: actor heterogeneity and linkages in humanitarian innovation ecosystems. Innovation and Development 15, 63–89. https://doi.org/10.1080/2157930X.2023.2234222

Dedehayir, O., Mäkinen, S.J., Ortt, J.R., 2022. Innovation ecosystems as structures: Actor roles, timing of their entrance, and interactions. Technol Forecast Soc Change 183, 121875. https://doi.org/10.1016/j.techfore.2022.121875

Delhaye, T.P., Brun, G. Le, Flandre, D., Raskin, J.-P., 2021. Bottom-Up Life-Cycle Assessment of MEMS Piezoresistive Pressure Sensors, in: 2021 Symposium on Design, Test, Integration & Packaging of MEMS and MOEMS (DTIP). IEEE, pp. 1–6. https://doi.org/10.1109/DTIP54218.2021.9568683

Dembek, K., Lüdeke-Freund, F., Rosati, F., Froese, T., 2023. Untangling business model outcomes, impacts and value. Bus Strategy Environ 32, 2296–2311. https://doi.org/10.1002/bse.3249

Dormeier, C., Mindt, N., Niemeyer, J.F., Asghari, R., Mennenga, M., 2024. Review and framework for the engineering of Business Models for Sustainability: A System of Systems perspective. Sustain Prod Consum 51, 1–22. https://doi.org/10.1016/j.spc.2024.08.030

Dőry, T., 2023. Key Factors of Sustainability-Oriented Innovation on Competitiveness of SMEs: A Review. Chem Eng Trans 107, 31–36. https://doi.org/10.3303/CET23107006

Dubois, A., Gadde, L.-E., 2002. Systematic combining: an abductive approach to case research. J Bus Res 55, 553–560. https://doi.org/10.1016/S0148-2963(00)00195-8

Eisenhardt, K.M., 1989. Building Theories from Case Study Research, Source: The Academy of Management Review.

Eusebio, E.J.G., 2024. How eco-innovation affects sustainable performance: A systematic review. Multidisciplinary Reviews 8, 2025166. https://doi.org/10.31893/multirev.2025166

Evans, S., Vladimirova, D., Holgado, M., Van Fossen, K., Yang, M., Silva, E.A., Barlow, C.Y., 2017. Business Model Innovation for Sustainability: Towards a Unified Perspective for Creation of Sustainable Business Models. Bus Strategy Environ 26, 597–608. https://doi.org/10.1002/bse.1939

Fauth, J., De Moortel, K., Schuurman, D., 2024. Living labs as orchestrators in the regional innovation ecosystem: a conceptual framework. J Responsible Innov 11. https://doi.org/10.1080/23299460.2024.2414505

Franceschini, S., Faria, L.G.D., Jurowetzki, R., 2016. Unveiling scientific communities about sustainability and innovation. A bibliometric journey around sustainable terms. J Clean Prod 127, 72–83. https://doi.org/10.1016/j.jclepro.2016.03.142

Garcia, R., Wigger, K., Hermann, R.R., 2019. Challenges of creating and capturing value in open eco-innovation: Evidence from the maritime industry in Denmark. J Clean Prod 220, 642–654. https://doi.org/10.1016/j.jclepro.2019.02.027

García-Sánchez, I., Gallego-Álvarez, I., Zafra-Gómez, J., 2020. Do the ecoinnovation and ecodesign strategies generate value added in munificent environments? Bus Strategy Environ 29, 1021–1033. https://doi.org/10.1002/bse.2414

Geiszler, M., Muenzen, J., Lippitt, J., 2018. The Effect of Environmental Sustainability Initiatives on Firm Value. The International Journal of Sustainability in Economic, Social, and Cultural Context 14, 21–31. https://doi.org/10.18848/2325-1115/CGP/v14i03/21-31

Ghassim, B., Foss, L., 2020. How Do Leaders Embrace Stakeholder Engagement for Sustainability-Oriented Innovation?, in: New Leadership in Strategy and Communication. Springer International Publishing, Cham, pp. 63–80. https://doi.org/10.1007/978-3-030-19681-3_6

Gomes, L.A. de V., Facin, A.L.F., Salerno, M.S., Ikenami, R.K., 2018. Unpacking the innovation ecosystem construct: Evolution, gaps and trends. Technol Forecast Soc Change 136, 30–48. https://doi.org/10.1016/j.techfore.2016.11.009

Goodman, J., Halme, M., Juntunen, J.K., 2023. Sustainability-Oriented Innovation for System-Level Impact. Academy of Management Proceedings 2023. https://doi.org/10.5465/AMPROC.2023.141bp

Granstrand, O., Holgersson, M., 2020. Innovation ecosystems: A conceptual review and a new definition. Technovation 90–91. https://doi.org/10.1016/J.TECHNOVATION.2019.102098

Guzmán, J.G., del Carpio, A.F., Colomo-Palacios, R., de Diego, M.V., 2013. Living Labs for User-Driven Innovation: A Process Reference Model. Research-Technology Management 56, 29–39. https://doi.org/10.5437/08956308X5603087

Håkansson H, Johanson J, 1992. A Model of Industrial Networks, in: B Axelsson, G Easton (Eds.), Industrial Networks. Routledge.

Hakola, L., Smolander, M., Orko, I., Sokka, L., Välimäki, M., 2023. Development of a Qualitative Tool for Sustainability Assessment and Application of the Tool to Benchmark Electronic Smart Labels. Circular Economy and Sustainability. https://doi.org/10.1007/s43615-023-00280-3

Hansen, E., Korhonen, J., Panwar, R., Hakovirta, M., 2022. The Quandary of Sustainability-Oriented Innovations, in: The Role of Business in Global Sustainability Transformations. Routledge, London, pp. 185–200. https://doi.org/10.4324/9781003003588-15

Harsanto, B., Kumar, N., Michaelides, R., 2024. Sustainability-oriented innovation in manufacturing firms: Implementation and evaluation framework. Bus Strategy Environ 33, 5086–5108. https://doi.org/10.1002/bse.3740

Harsanto, B., Mulyana, A., Faisal, Y.A., Shandy, V.M., Alam, M., 2023. Sustainability Innovation in Small Medium Enterprises (SMEs): A Qualitative Analysis. Qualitative Report 28, 3257–3271. https://doi.org/10.46743/2160-3715/2023.6193

Helman, J., Rosienkiewicz, M., Molasy, M., Cholewa, M., 2021. Infrastructure Sharing Model as a Support for Sustainable Manufacturing, in: Smart Innovation, Systems and Technologies. pp. 71–80. https://doi.org/10.1007/978-981-15-8131-1_7

Hermundsdottir, F., Aspelund, A., 2021. Sustainability innovations and firm competitiveness: A review. J Clean Prod 280, 124715. https://doi.org/10.1016/j.jclepro.2020.124715

Hevner, March, Park, Ram, 2004. Design Science in Information Systems Research. MIS Quarterly 28, 75. https://doi.org/10.2307/25148625

Holdeman, C.J., Howarter, J.A., 2025. Benchmarking Energy, Emissions, and Resource Sustainability in Semiconductor Manufacturing, in: Minerals Metals and Materials Series. pp. 17–25. https://doi.org/10.1007/978-3-031-80688-9_2

Holmström, J., Ketokivi, M., Hameri, A., 2009. Bridging Practice and Theory: A Design Science Approach. Decision Sciences 40, 65–87. https://doi.org/10.1111/j.1540-5915.2008.00221.x

Hossain, M., Leminen, S., Westerlund, M., 2019. A systematic review of living lab literature. J Clean Prod 213, 976–988. https://doi.org/10.1016/j.jclepro.2018.12.257

Hsieh, C.-C., Rachmawati, N.L., Lin, Y.-C., 2025. Coordinating remanufacturing efforts for sustainable chemical supply in semiconductor supply chains. Comput Ind Eng 201. https://doi.org/10.1016/j.cie.2025.110895

Hsieh, S., Lin, P.-Y., Lin, I.-H., Beck, D.E., Lin, C.-H., 2023. Assessing the contribution of semiconductors to the sustainable development goals (SDGs) from 2017 to 2022. Heliyon 9, e21306. https://doi.org/10.1016/j.heliyon.2023.e21306

Hsu, C.-W., Hu, A.H., Chiou, C.-Y., Chen, T.-C., 2011. Using the FDM and ANP to construct a sustainability balanced scorecard for the semiconductor industry. Expert Syst Appl 38, 12891–12899. https://doi.org/10.1016/j.eswa.2011.04.082

Huang, J.H., Iakovleva, T.A., Bessant, J., 2024. FOSTERING USER INVOLVEMENT IN COLLABORATIVE INNOVATION SPACES: INSIGHTS FROM LIVING LABS. International Journal of Innovation Management 28. https://doi.org/10.1142/S1363919624500324

Huggins, R., Johnston, A., Munday, M., Xu, C., 2023. Competition, open innovation, and growth challenges in the semiconductor industry: the case of Europe's clusters. Sci Public Policy 50, 531–547. https://doi.org/10.1093/scipol/scad005

Hung, H.-C., Chiu, Y.-C., Wu, M.-C., 2017. Analysis of Competition Between IDM and Fabless–Foundry Business Models in the Semiconductor Industry. IEEE Transactions on Semiconductor Manufacturing 30, 254–260. https://doi.org/10.1109/TSM.2017.2699739

Iliopoulos, C., Theodorakopoulou, I., Giotis, T., Brunori, G., 2025. Perceptions of costs and benefits of farm digitalization in Europe. International Food and Agribusiness Management Review 28, 543–564. https://doi.org/10.22434/ifamr.1274

Jakobs, L., Salamanca Cano, A.K., Rauch, E., 2024. Sustainability in SMEs: A Comparative Study to Assess Current Status and Setting Targets for Action. IFAC-PapersOnLine 58, 836–841. https://doi.org/10.1016/j.ifacol.2024.09.188

Jürgens, A., Tedeschi, G., D'Errico, G., Kilian, K., Zawadzki, K., Daniel, O., Leibfried, A., Poschet, G., Lau, L., Helm-Petersen, N., 2024. Navigating the frontier: research infrastructures, core facilities and a new paradigm at European Universities. Cogent Education 11. https://doi.org/10.1080/2331186X.2024.2365613

Kalmakova, D., Bilan, Y., Zhidebekkyzy, A., Sagiyeva, R., 2021. Commercialization of conventional and sustainability-oriented innovations: a comparative systematic literature review. Problems and Perspectives in Management 19, 340–353. https://doi.org/10.21511/ppm.19(1).2021.29

Kiemel, S., Rietdorf, C., Schutzbach, M., Miehe, R., 2022. How to Simplify Life Cycle Assessment for Industrial Applications—A Comprehensive Review. Sustainability 14, 15704. https://doi.org/10.3390/su142315704

Klewitz, J., Hansen, E.G., 2014. Sustainability-oriented innovation of SMEs: a systematic review. J Clean Prod 65, 57–75. https://doi.org/10.1016/j.jclepro.2013.07.017

Klimas, P., Czakon, W., 2022. Gaming innovation ecosystem: actors, roles and co-innovation processes. Review of Managerial Science 16, 2213–2259. https://doi.org/10.1007/s11846-022-00518-8

Klingenberg, C.O., Valle Antunes Júnior, J.A., Müller-Seitz, G., 2022. Impacts of digitalization on value creation and capture: Evidence from the agricultural value chain. Agric Syst 201, 103468. https://doi.org/10.1016/j.agsy.2022.103468

Konstari, P., Valkokari, K., 2025a. Green innovation ecosystems in the semiconductor industry - the role of European research and technology organisations. Sustainable Futures 10, 101127. https://doi.org/10.1016/j.sftr.2025.101127

Konstari, P., Valkokari, K., 2025b. Value creation and capture from sustainability-oriented innovations in a shared semiconductor infrastructure. Sustainable Technology and Entrepreneurship 4, 100104. https://doi.org/10.1016/j.stae.2025.100104

Konstari, P., Valkokari, K., 2025c. Roles for and impact creation of sustainability-oriented innovations in a shared semiconductor infrastructure. International Journal of Innovation Management 29. https://doi.org/10.1142/S1363919625400201

Konstari, P., Valkokari, K., 2025d. Impact of sustainability-oriented innovations in a shared semiconductor infrastructure, in: XXXVI ISPIM Innovation Conference. Bergen.

Konstari, P., Valkokari, K., 2025e. Integration of multi-disciplinary environmental sustainability aspects into early-phase microelectronics research and development. Discover Sustainability 6, 1089. https://doi.org/10.1007/s43621-025-01980-6

Konstari, P., Valkokari, K., 2024. Drivers and barriers for open innovation for sustainability in a shared semiconductor infrastructure. Journal of Open Innovation: Technology, Market, and Complexity 10, 100395. https://doi.org/10.1016/j.joitmc.2024.100395

Krishnan, N., Boyd, S., Somani, A., Raoux, S., Clark, D., Dornfeld, D., 2008. A hybrid life cycle inventory of nano-scale semiconductor manufacturing. Environ Sci Technol 42. https://doi.org/10.1021/es071174k

Kumar, A., Thorbole, A., Gupta, R.K., 2025. Sustaining the future: Semiconductor materials and their recovery. Mater Sci Semicond Process 185, 108943. https://doi.org/10.1016/j.mssp.2024.108943

Kuo, C.-H., Hu, A.H., Hung, L.H., Yang, K.-T., Wu, C.-H., 2020. Life cycle impact assessment of semiconductor packaging technologies with emphasis on ball grid array. J Clean Prod 276, 124301. https://doi.org/10.1016/j.jclepro.2020.124301

Kuo, T.-C., Kuo, C.-Y., Chen, L.-W., 2022. Assessing environmental impacts of nanoscale semi-conductor manufacturing from the life cycle assessment perspective. Resour Conserv Recycl 182, 106289. https://doi.org/10.1016/j.resconrec.2022.106289

Kurrahman, T., Tsai, F.M., Jeng, S.-Y., Chiu, A.SF., Wu, K.-J., Tseng, M.-L., 2024. Sustainable development performance in the semiconductor industry: A data-driven

practical guide to strategic roadmapping. J Clean Prod 445, 141207. https://doi.org/10.1016/j.jclepro.2024.141207

Lakatos, E.S., Pacurariu, R.L., Bîrgovan, A.L., Cioca, L.I., Szilagy, A., Moldovan, A., Rada, E.C., 2024. A Systematic Review of Living Labs in the Context of Sustainable Development with a Focus on Bioeconomy. Earth 5, 812–843. https://doi.org/10.3390/earth5040042

Leminen, S., Nyström, A.-G., Westerlund, M., 2020. Change processes in open innovation networks – Exploring living labs. Industrial Marketing Management 91, 701–718. https://doi.org/10.1016/j.indmarman.2019.01.013

Leminen, S., Rajahonka, M., Westerlund, M., Hossain, M., 2021. Collaborative innovation for sustainability in Nordic cities. J Clean Prod 328, 129549. https://doi.org/10.1016/j.jclepro.2021.129549

Leminen, S., Westerlund, M., Nyström, A.G., 2014. On becoming creative consumers - user roles in living labs networks. International Journal of Technology Marketing 9, 33. https://doi.org/10.1504/IJTMKT.2014.058082

Leminen, S., Westerlund, M., Nyström, A.-G., 2012. Living Labs as Open-Innovation Networks. Technology Innovation Management Review 2, 6–11. https://doi.org/10.22215/timreview/602

Li, Q., Gao, Q., Zhang, Y., Gou, C., 2024. How Can Small and Medium-Sized Manufacturing Enterprises Improve Green Innovation Performance through Innovation Ecosystems? Sustainability 16, 2519. https://doi.org/10.3390/su16062519

Lin, Y.-S., Chien, C.-F., Chou, D., 2022. UNISON decision framework for hybrid optimization of wastewater treatment and recycle for Industry 3.5 and cleaner semiconductor manufacturing. Resour Conserv Recycl 182, 106282. https://doi.org/10.1016/j.resconrec.2022.106282

Liu, Y.-Z., Lu, W.-M., Tran, P.P., Pham, T.A.K., 2024. Sustainable Energy and Semiconductors: A Bibliometric Investigation. Sustainability 16, 6548. https://doi.org/10.3390/su16156548

Lozano, R., 2008. Envisioning sustainability three-dimensionally. J Clean Prod 16, 1838–1846. https://doi.org/10.1016/J.JCLEPRO.2008.02.008

Lu, H., Zhang, Y., Jiang, J., Cao, G., 2025. Do market-based environmental regulations always promote enterprise green innovation commercialization? J Environ Manage 375, 124183. https://doi.org/10.1016/j.jenvman.2025.124183

Lu, W., Lo, S., Hung, S., Yo, J., 2023. Semiconductor industry supply chain productivity changes: Incorporating corporate green performances. Managerial and Decision Economics 44, 4232–4247. https://doi.org/10.1002/mde.3945

Lüdeke-Freund, F., Schaltegger, S., Dembek, K., 2019. Strategies and drivers of sustainable business model innovation. Handbook of Sustainable Innovation 101–123. https://doi.org/10.4337/9781788112574.00012

Marco-Lajara, B., Zaragoza-Saez, P., Martínez-Falcó, J., 2023. Green Innovation, in: Research Anthology on Business Law, Policy, and Social Responsibility. IGI Global, pp. 916–931. https://doi.org/10.4018/979-8-3693-2045-7.ch048

Marcon, A., Ribeiro, J.L.D., Dangelico, R.M., Fraccascia, L., 2021. Green Innovation Ecosystems: An Exploratory Study of the Involved Actors, in: Springer Proceedings in Mathematics and Statistics. pp. 585–595. https://doi.org/10.1007/978-3-030-78570-3_45

Martínez-Martínez, A., Cegarra-Navarro, J.-G., Garcia-Perez, A., De Valon, T., 2023. Active listening to customers: eco-innovation through value co-creation in the textile industry. Journal of Knowledge Management 27, 1810–1829. https://doi.org/10.1108/JKM-04-2022-0309

Martín-García, A.V., Gutiérrez-Pérez, B.M., Aceros, J.C., 2021. Living Senior Labs, ecosistemas de co-creación e innovación abierta con personas mayores: revisión sistemática de la literatura en Ciencias Sociales. Interface - Comunicação, Saúde, Educação 25. https://doi.org/10.1590/interface.210399

Marwala, T., 2023. Semiconductor Chips for Sustainable Development. United Nations University.

Mbanefo, C.C., Grobbelaar, S.S., 2024. Unveiling the core elements of platform ecosystem development: a systemic lens for value co-creation in small and medium enterprises and orchestrators. Management Review Quarterly. https://doi.org/10.1007/s11301-024-00416-1

McKinsey & Company, 2023. Beyond the fab: Decarbonizing Scope 3 upstream emissions.

McKinsey & Company, 2022. Keeping the semiconductor industry on the path to net zero.

Molinari, M., Anund Vogel, J., Rolando, D., Lundqvist, P., 2023. Using living labs to tackle innovation bottlenecks: the KTH Live-In Lab case study. Appl Energy 338, 120877. https://doi.org/10.1016/j.apenergy.2023.120877

Monakhov, K.Yu., Meinecke, C., Moors, M., Schmitz-Antoniak, C., Blaudeck, T., Hann, J., Bickmann, C., Reuter, D., Otto, T., Schulz, S.E., Parala, H., Devi, A., 2024. Molecular approach to semiconductors: a shift towards ecofriendly manufacturing and neuroinspired interfaces. Pure and Applied Chemistry 96, 1313–1331. https://doi.org/10.1515/pac-2024-0242

Mugoni, E., Kanyepe, J., Tukuta, M., 2024. Sustainable Supply Chain Management Practices (SSCMPS) and environmental performance: A systematic review. Sustainable Technology and Entrepreneurship 3, 100050. https://doi.org/10.1016/j.stae.2023.100050

Mukhopadhyay, N., Nayak, N.C., 2024. Examining the relationship between green innovation dynamics and firm performance: a comparative study of BRICS and G7 countries. Cogent Business & Management 11. https://doi.org/10.1080/23311975.2024.2364836

Mullen, E., Morris, M.A., 2021. Green nanofabrication opportunities in the semiconductor industry: A life cycle perspective. Nanomaterials 11. https://doi.org/10.3390/nano11051085

Narayanaswamy, V., Muthusamy, K., 2011. Sustainability Index Benchmarking in a Semiconductor Manufacturing Environment. Adv Mat Res 383–390, 3377–3381. https://doi.org/10.4028/www.scientific.net/AMR.383-390.3377

Neri, A., Cagno, E., Trianni, A., 2021. Barriers and drivers for the adoption of industrial sustainability measures in European SMEs: Empirical evidence from chemical and metalworking sectors. Sustain Prod Consum 28, 1433–1464. https://doi.org/10.1016/j.spc.2021.08.018

Nyström, A.-G., Leminen, S., Westerlund, M., Kortelainen, M., 2014. Actor roles and role patterns influencing innovation in living labs. Industrial Marketing Management 43, 483–495. https://doi.org/10.1016/j.indmarman.2013.12.016

Onoda, T., Ito, Y., 2022. On the boundary of services and research collaborations in Japanese state-of-the-art academic research infrastructures. Sci Public Policy 49, 488–498. https://doi.org/10.1093/scipol/scac002

Oskam, I., Bossink, B., de Man, A.-P., 2021. Valuing Value in Innovation Ecosystems: How Cross-Sector Actors Overcome Tensions in Collaborative Sustainable Business Model Development. Bus Soc 60, 1059–1091. https://doi.org/10.1177/0007650320907145

Paskaleva, K., Cooper, I., 2021. Are living labs effective? Exploring the evidence. Technovation 106, 102311. https://doi.org/10.1016/j.technovation.2021.102311

Patton, M.Q., 2002. Qualitative Research & Evaluation Methods, Third Edition. ed. Sage Publications, Inc., Thousand Oaks.

Pei, P., Chang, X., 2025. Corporate social governance ESG policies and energy efficiency in G20 countries: The impact of policy coherence on environmental sustainability. Energy & Environment. https://doi.org/10.1177/0958305X251349469

Pushpananthan, G., Elmquist, M., 2022. Joining forces to create value: The emergence of an innovation ecosystem. Technovation 115, 102453. https://doi.org/10.1016/j.technovation.2021.102453

Qi, E., Luo, T., Wick, M., Armer, H., Raiford, M., Marteniz, T., Mittal, S., 2024. Sustainability Model for Semiconductor Manufacturing, in: 2024 35th Annual SEMI Advanced Semiconductor Manufacturing Conference (ASMC). IEEE, pp. 1–4. https://doi.org/10.1109/ASMC61125.2024.10545500

Rodríguez, A., Alcalde-Heras, H., Iñigo, E.A., 2024. Exploring coopetition and value-based networks in business models for sustainability—A case study of the specialty coffee industry in Colombia. Bus Strategy Environ. https://doi.org/10.1002/bse.3878

Rodríguez-Espíndola, O., Cuevas-Romo, A., Chowdhury, S., Díaz-Acevedo, N., Albores, P., Despoudi, S., Malesios, C., Dey, P., 2022. The role of circular economy principles and sustainable-oriented innovation to enhance social, economic and environmental performance: Evidence from Mexican SMEs. Int J Prod Econ 248, 108495. https://doi.org/10.1016/j.ijpe.2022.108495

Ruberti, M., 2024. Environmental performance and trends of the world's semiconductor foundry industry. J Ind Ecol 28, 1183–1197. https://doi.org/10.1111/jiec.13529

Ruberti, M., 2023. The chip manufacturing industry: Environmental impacts and eco-efficiency analysis. Sci Total Environ 858, 159873. https://doi.org/10.1016/j.scitotenv.2022.159873

Saunders, M., Lewis, P., Thornhill, A., 2009. Research methods for business students, Fifth edition. ed. Pearson Education Limited, Essex.

Schöggl, J.-P., Baumgartner, R.J., O'Reilly, C.J., Bouchouireb, H., Göransson, P., 2024. Barriers to sustainable and circular product design – A theoretical and empirical prioritisation in the European automotive industry. J Clean Prod 434, 140250. https://doi.org/10.1016/j.jclepro.2023.140250

Semi, 2023. Scope 3 Category 1 GHG assessment guideline for the semiconductor sector. Semi-Semiconductor Climate Consortium (SCC). Semiconductor Climate Consortium Report .

Shafa Tiflis, A., Nemtsova, E., Paytaeva, K., 2024. Eco-innovations in the digital transformation of enterprises: Sustainability and competitiveness. BIO Web Conf 140, 01007. https://doi.org/10.1051/bioconf/202414001007

Shen, C., Tran, P.P., Minh Ly, P.T., 2018. Chemical Waste Management in the U.S. Semiconductor Industry. Sustainability 10, 1545. https://doi.org/10.3390/su10051545

Ståhlbröst, A., 2012. A set of key principles to assess the impact of Living Labs. International Journal of Product Development 17, 60. https://doi.org/10.1504/IJPD.2012.051154

Stahlbrost, A., Kareborn, B.B., 2011. Exploring users motivation in innovation communities. Int J Entrep Innov Manag 14, 298. https://doi.org/10.1504/IJEIM.2011.043051

Strom, T.A., Haugstad, G., Shu, J., Seshadri, R., 2020. Shared instrumentation facilities: Benefiting researchers and universities, and sustaining research excellence. MRS Bull 45, 331–335. https://doi.org/10.1557/mrs.2020.130

Sultana, N., Turkina, E., 2023. Collaboration for Sustainable Innovation Ecosystem: The Role of Intermediaries. Sustainability 15, 7754. https://doi.org/10.3390/su15107754

Teece, D.J., 2010. Business Models, Business Strategy and Innovation. Long Range Plann 43, 172–194. https://doi.org/10.1016/j.lrp.2009.07.003

Toffolini, Q., Capitaine, M., Hannachi, M., Cerf, M., 2021. Implementing agricultural living labs that renew actors' roles within existing innovation systems: A case study in France. J Rural Stud 88, 157–168. https://doi.org/10.1016/j.jrurstud.2021.10.015

Tura, N., Hanski, J., Ahola, T., Ståhle, M., Piiparinen, S., Valkokari, P., 2019. Unlocking circular business: A framework of barriers and drivers. J Clean Prod 212, 90–98. https://doi.org/10.1016/j.jclepro.2018.11.202

Ueda, A., Akinaga, H., Agarwal, S., Hagmann, J.A., Das, S., Marinella, M.J., Chen, A., 2025. Green materials in semiconductors: perspective from the IRDS beyond-CMOS roadmap. Nanotechnology 36. https://doi.org/10.1088/1361-6528/ADB041

Valkokari, K., Hyytinen, K., Leväsluoto, J., 2024. Living Labs as Enablers for Collaborative Innovation – Exploring Success Factors and Impacts. Journal of Innovation Management 12, 158–174. https://doi.org/10.24840/2183-0606_012.003_0007

Varadarajan, R., 2017. Innovating for sustainability: a framework for sustainable innovations and a model of sustainable innovations orientation. J Acad Mark Sci 45, 14–36. https://doi.org/10.1007/s11747-015-0461-6

Venkataswamy, R., Trimble, L., McDonald, A., Nevers, D., Bengochea, L.V., Carswell, A., Rossner, A., Seo, J., 2024. Environmental Impact Assessment of Chemical Mechanical Planarization Consumables: Challenges, Future Needs, and Perspectives. ACS Sustain Chem Eng 12, 11841–11855. https://doi.org/10.1021/acssuschemeng.4c03195

Villard, A., Lelah, A., Brissaud, D., 2015. Drawing a chip environmental profile: environmental indicators for the semiconductor industry. J Clean Prod 86, 98–109. https://doi.org/10.1016/j.jclepro.2014.08.061

Villard, A., Lelah, A., Brissaud, D., Mantelli, M., 2012. An eco-design tool for manufacturers of semiconductor technologies: Looking for environmental opportunities in the design phase, in: 2012 IEEE International Symposium on Sustainable Systems and Technology (ISSST). IEEE, pp. 1–6. https://doi.org/10.1109/ISSST.2012.6228013

von Wirth, T., Fuenfschilling, L., Frantzeskaki, N., Coenen, L., 2019. Impacts of urban living labs on sustainability transitions: mechanisms and strategies for systemic change through experimentation. European Planning Studies 27, 229–257. https://doi.org/10.1080/09654313.2018.1504895

Voytenko, Y., McCormick, K., Evans, J., Schliwa, G., 2016. Urban living labs for sustainability and low carbon cities in Europe: towards a research agenda. J Clean Prod 123, 45–54. https://doi.org/10.1016/j.jclepro.2015.08.053

Wang, F., Wong, W.-K., Wang, Z., Albasher, G., Alsultan, N., Fatemah, A., 2023. Emerging pathways to sustainable economic development: An interdisciplinary exploration of resource efficiency, technological innovation, and ecosystem resilience in resource-rich regions. Resources Policy 85, 103747. https://doi.org/10.1016/j.resourpol.2023.103747

Wang, Y., Liu, Y., Chen, X.H., 2025. Green technology innovation, ESG ratings and corporate sustainable performance: Empirical evidence from listed semiconductor companies in China. International Review of Economics & Finance 99, 104061. https://doi.org/10.1016/j.iref.2025.104061

Yang, M., Vladimirova, D., Evans, S., 2017. Creating and Capturing Value Through Sustainability. Research-Technology Management 60, 30–39. https://doi.org/10.1080/08956308.2017.1301001

Yin, R.K., 2018. Case study Research and Applications, Sixth Edition. ed. SAGE Publications, Inc.

Yoo, Y., Cho, K., 2024. Key Traits of Leading Sustainable Firms in the Semiconductor Industry. Sustainability 16, 4563. https://doi.org/10.3390/su16114563

Zhang, R.-J., Tai, H.-W., Cao, Z.-X., Wei, C.-C., Cheng, K.-T., 2024. Green innovation ecosystem evolution: Diffusion of positive green innovation game strategies on complex networks. Journal of Innovation & Knowledge 9, 100500. https://doi.org/10.1016/j.jik.2024.100500

Publication I

Konstari, P., and Valkokari, K.
Green innovation ecosystems in the semiconductor industry - the role of European research and technology organisations

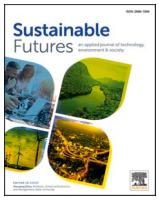
Reprinted with permission from
Sustainable Futures
10, 101127

Sustainable Futures 10 (2025) 101127

Contents lists available at ScienceDirect

Sustainable Futures

journal homepage: www.sciencedirect.com/journal/sustainable-futures



Green innovation ecosystems in the semiconductor industry - the role of European research and technology organisations

Piia Konstari [a,*], Katri Valkokari [b]

[a] Microelectronics and quantum technology, VTT Technical Research Centre of Finland, PO Box 1000, FI-02044 VTT, Finland
[b] Foresight and data economy, VTT Technical Research Centre of Finland, PO Box 1300, FI-33101, Tampere, Finland

ARTICLE INFO

Keywords:
Sustainability-oriented innovation
Semiconductor infrastructure
Green innovation ecosystem
Ecosystem actor
Research and technology organisation

ABSTRACT

Most of the research and technology organizations (RTOs) with semiconductor technology departments also host semiconductor research infrastructure. The outcome of public and private research projects, to which these organizations participate, has a wide impact on the development of the electronics industry. This study focuses on understanding how RTOs advance sustainability and sustainability-oriented innovations (SOI) within their organisation as well as in the local ecosystem. This study also looks for understanding what kind of actors the RTOs identify in their local green innovation ecosystem. The research is done as a qualitative multiple-case study with four selected European RTOs. The study provides evidence that the level of SOI engagement at the four different RTOs vary, but all are active in SOI through operational optimization especially in the semiconductor infrastructure side, organizational transformation and systems building. We also find out that the driver for sustainability related research activities is managerial or governmental pressure and available funding. In addition, we propose a green innovation ecosystem actor framework specific for the green innovation ecosystem around semiconductor RTOs complemented with the actors: public opinion, the local municipality, different kind of companies, and a strong orchestrator. We contribute to the current discussion on green innovation ecosystems and highlight the complexity of the topic in the semiconductor industry.

1. Introduction

Semiconductors contribute widely to the United Nation's (UN) sustainable development goals (SDGs) [1]. The transition towards a more sustainable semiconductor industry, or electronics industry, is topical [2–5]. The semiconductor industry consumes large amounts of energy, electricity and water and generate hazardous waste and greenhouse gas (GHG) emissions [6]. Green technology innovation hence is in the focal point to create sustainable semiconductor business [7,8]. Green technology innovation is affected by many factors, such as leadership and the organizational environment [9], human resources management approaches [10,11], as well as environmental regulations [12].

Reaching SDGs require not only good alignment of strategic management [13], but multi-stakeholder engagement and collaboration in innovation ecosystems among various actors [14,15]. The "triple-helix" of university-industry-government is often referred to as the recipe for our knowledge-based society and of the innovation ecosystem [16]. In this, along universities [17], research and technology organisations (RTO) play a central role [18,19].

RTOs coordinate and participate in public and private research and development (R&D) projects at national, European, and global levels, hence having a large impact on innovation activities and the advancement of the global electronics industry. RTOs are pivotal in fostering sustainability and innovation within both their organizations and the broader ecosystem as they develop next-generation technologies. Therefore, increasing sustainability awareness among RTO researchers is essential for enhancing the sustainability of the semiconductor and electronics industry.

The current academic discussion on sustainable business practices is vivid [8,20]. The discussion around sustainability in the semiconductor industry is focused on green supply chains [21], green energy [22], efficient manufacturing [23,24], waste management [25], sustainability balanced scorecards [26]. High-performing semiconductor companies emphasize sustainable development across the entire industry ecosystem, rather than focusing solely on company internal sustainability aspects [27]. There is research about sustainability efforts at universities [20,28], but research on sustainability at RTOs seems to be lacking. Likewise, the research about living labs as regional innovation

* Corresponding author.
E-mail address: piia.konstari@vtt.fi (P. Konstari).

https://doi.org/10.1016/j.sftr.2025.101127
Received 13 September 2024; Received in revised form 3 June 2025; Accepted 4 August 2025
Available online 7 August 2025

ecosystem orchestrators [15] is also nascent, lacking deeper analysis about the role of RTOs as innovation ecosystem orchestrators in the semiconductor industry.

Most European RTOs have own corporate sustainability goals and programs, but little can be found online about what the RTOs do in practice to advance sustainability-oriented innovations (SOI) within their organisations and departments. Most RTOs with semiconductor or microelectronics related R&D also host semiconductor research infrastructure [29,30]. This semiconductor infrastructure is used in public and private R&D projects. Hence, the sustainability related activities undertaken in these infrastructures widely affect the sustainability of the next-generation products of the R&D project partners, as well as the sustainability of the innovation ecosystem around the RTOs. Understanding the type of SOI activities undertaken at the RTOs as well as the constitution of the green innovation ecosystem around the RTO can be considered crucial for understanding the role of RTOs in the sustainability transition of the semiconductor industry.

This research focuses on investigating how four European RTO microelectronics departments with semiconductor research infrastructure address sustainability as a topic and what kind of sustainability-oriented innovation activities they prioritize. In addition, this study looks for understanding the actors of green innovation ecosystems around these RTOs. The main research questions for this study are:

RQ1: What kind of SOI activities are the RTOs engaged in and what are the driving factors behind these engagements?
RQ2: What are the green innovation ecosystem actors around the RTOs?

The research is done as multiple-case study qualitative research among four selected European RTOs with in-house semiconductor research infrastructure. The data was collected in two rounds first in end of 2023 and then in mid-2024. Data collection methods was first phone discussion followed with an email survey based on the phone discussion and questions, and then in the second phase through semi-structured follow-up interviews over Teams.

For the research, we use the following definitions:

- SOI when talking about the innovations aiming at benefits for the environment
- green innovation ecosystem when we talk about the ecosystem around the RTOs that participate in generating SOI i.e. “green” innovations, as it seems to be the most used terminology for that in the literature.

The main findings of this paper include evidence of the concrete actions that RTOs take for advancing sustainability in the semiconductor field i.e. the state-of-practice. Secondly, based on our findings, this paper presents a complemented framework for green innovation ecosystem actors around microelectronics RTOs based on previous research done by Marcon et al. [31].

This paper is structured as follows: Section 2 presents the most relevant literature for this research. Section 3 presents the research methodology. Section 4 brings forward the findings and discusses them. Section 5 concludes the study and gives suggestion for further research.

2. Literature review

In this chapter we summarize the most relevant previous research for this study related to sustainability in the semiconductor industry, SOI, green innovation ecosystems, as well as research infrastructures and sustainability.

2.1. Sustainability in the semiconductor industry

Leading consulting firms’ analyses on sustainability within the semiconductor sector emphasize supply chain management and the decrease of greenhouse gas (GHG) emissions across scope 1, 2, and 3 categories [2–4,32].

The academic discussion related to sustainability in the semiconductor industry is rather fragmented, and there is little discussion about SOI in the semiconductor industry. SOI activities in shared semiconductor infrastructures of RTOs, however, has lately gained some attention [29,30].

There is active discussion about the operational and technical topics with regards to reducing the environmental burden of the manufacturing, as well as on sustainability reporting. The prospects of the European semiconductor industry have been studied, and the importance of collaborative efforts among various organizations was highlighted as key success factor. Such collaboration is crucial due to the dynamic nature of the industry and the continuous improvement of products [33].

A methodology for assessing both the commercial and sustainability efficiency of semiconductor process steps has recently been proposed [23]. Ways to optimize wastewater treatment in semiconductor cleanrooms has been studied [34], as well as the direct emissions (scope 1) and energy-related emissions (scope 2) of greenhouse gases within the semiconductor sector [35]. That fabless semiconductor companies have an advantage in product innovation when they can focus all their efforts on that and leave the process innovation to their manufacturing/foundry partner has been pointed out [36].

The environmental impact of semiconductors has been evaluated through various life cycle assessments [36–38]. In addition, a framework for assessing the environmental indicators in microelectronics, pinpointing the most significant environmental effects of the industry, has been proposed [39,40]. The environmental impact and eco-efficiency in the semiconductor sector have been analysed [6,41], and the efficiency of semiconductor manufacturing investigated [42], along with environmental concerns related to the semiconductor industry [43].

2.2. Sustainability-oriented innovations in different contexts

Sustainable development has three cornerstones: environmental, social, and economic benefit [44]. SOI are innovations for environmental, social, and economic benefit. These have been presented in the academic literature in depth [45,46].

SOI at small- and medium sized companies (SMEs) has gained attention lately [46–48]. The latter one concluded that the studied SMEs mainly focused on the more environmentally friendly raw materials and packaging materials. Sustainability-oriented open innovations in SMEs have also been researched [49].

Recently, a six-dimensional high-level SOI approach for manufacturing companies was presented [50], and a scale for measuring SOI adoption in organisations has been presented [51]. Whether open innovation promotes sustainable value creation in companies and the link between open innovation and sustainability has also been studied [52]. A conceptual framework to analyse the benefits of openness for SOI has been presented [53].

The benefits of university-industry collaboration for environmental sustainability have been studied [54], and several other studies have been done about sustainability within universities or higher education [55,56].

Ways for companies to implement SOI as a business strategy through systems building in the Indonesian e-bus industry has been analysed [57]. That study highlighted the importance for further research into how companies co-create value in ecosystems, as well as the need of a change leader. It also underlined the importance of close relationship to governmental and regulatory actors., and universities and research institutes were considered strategic partners for learning.

Some ecosystem related SOI research has so far been done [58–60], but the authors have not identified any prior research for SOI in the green semiconductor innovation ecosystems.

2.3. Green innovation ecosystems

The main types of ecosystems are business ecosystems, innovation ecosystems, knowledge ecosystems and entrepreneurial ecosystems [61], and these have been analysed in detail by several authors [62]. A collaborative model for innovation ecosystems including main actors, resources and key activities has been presented [63], and different places and spaces for collaborative R&D divided into physical and virtual spaces has been studied [64]. A framework comprising of nine lower order ecosystem features and three higher order dimensions was earlier presented as: roles (self-organization, non- linearity, shared vision), structures (complementarity, modularity, coupling) and processes (emergence, co-opetition, co-evolution) [65].

The value creation in different innovation ecosystems has been studied through multiple case studies [66], as well as how values effect SOI in collaboration ecosystems [67]. Recently also the links between co-innovation behaviour, sustainable innovations, absorptive capacity, and competitive intensity have been mapped [68], as well as how and why collaborations between businesses and non-profit organizations work in SOI [69].

Actors in green innovation ecosystems have been named as suppliers, consultants and experts, universities, research and technology firms, complementors, class organizations, investors and shareholders, regulation agencies, governments, innovation hubs, other actors, and customers [31]. The role of universities to the co-evolution of ecosystems was recently studied and defined as initiator, facilitator, coordinator, and stimulator [70].

Ways for how SDGs can be reached through collaborative innovation in multi-stakeholder partnerships in four European countries was recently studied. The partnerships were metagoverned by non-profit organizations. One recent paper presented a conceptual model of collaborative innovation for sustainability and SDGs [18]. In a recent study, SDG platforms and why private companies use such as strategic tools for achieving their goals has also been addressed [71].

The role of multinational corporations (MNCs) on the European innovation ecosystem for renewable energy showed that there are two types of MNCs: focal and participating MNCs [72] . Green innovation ecosystems are effective ways for small and medium sized manufacturing enterprises for implementing green innovation projects with government-industry-university-research institution [73]. The role of intermediaries for collaboration for sustainable innovation ecosystems is central [74].

Different actors in knowledge ecosystems generate SOI in different ways [75]. A study on the role of different actors for implementing sustainable innovations in the Dutch asphalt paving sector showed that specific innovation process was slow due to lack of collaborative environment (i.e. coordinators) and pressure for change - a lack of system level perspective on the topic [76]. In a different study on how purpose ecosystems achieve the UN's SDGs, the actors in those were named as capacity builder, communicator, collaborator, enabler, change maker, influencer [77].

On a more general level, research on the critical sustainability factors of SMEs on a regional level, a study concluded that the local community is a very important stakeholder for SMEs for achieving sustainable development [77].

The authors did not manage to locate any previous study on actors in green innovation ecosystems around research organisations in the semiconductor field.

2.4. Research infrastructure and sustainability

RTOs with semiconductor departments most often also host semiconductor research infrastructure i.e. semiconductor cleanrooms that they use for their R&D activities. Sometimes also external users like SMEs have the chance to use this infrastructure [78]. SOI activities in such shared semiconductor infrastructures have recently been studied [29,30].

Three areas of SDGs in research infrastructures have been identified earlier: economic sustainability, technical sustainability, and network sustainability. The need of supporting policy, funding, contacts and initiatives has been underlined in a study on shared instrumentation facilities [79]. The benefit of sharing infrastructure with respect to sustainability, as sharing of infrastructure allows for cost savings with regards to infrastructure, competence and skills, has been highlighted [80,81]. Also, a framework for actor roles and their innovation potential in digital ecosystems has been presented with the categorization to specialists and orchestrators [82].

Although the previous research addresses SOI, sustainability of infrastructures, green innovation ecosystems and sustainability in the semiconductor industry, it does not directly address the topic we have under study: SOI in RTOs with semiconductor infrastructure, as well as the actors of the green innovation ecosystem around the RTOs. Hence, there is a clear research gap to be tackled.

3. Methodology

As prior research in the exact same field has not been identified, a qualitative research approach was chosen as this study aims at creating new understanding of a particular case and not at proving already existing theories. To study an emerging phenomenon, such as SOI in the semiconductor industry and at RTOs, a qualitative case study is an appropriate methodology [83]. The entire research cycle is described in Fig. 1.

Four European RTOs with in-house semiconductor cleanrooms were selected for this study. Organizational guidelines were followed for obtaining consent for the research. Management of the RTO's microelectronics departments were consulted for the correct contact persons for this research. All RTOs have long traditions in Europe in microfabrication activities and are important players among the European RTOs. They employ hundreds of people in microfabrication related fields. To keep their anonymity, more details cannot be given about the departments as the interviews are confidential. Table 1 summarizes the titles of the participating people from the RTOs, as well as shows what other personnel was consulted during the process. The same people were involved in the first and second round. Research consent was received from the participating persons and their organizations for both rounds.

The research was conducted in two parts. In the first part, in November-December 2023, telephone interviews combined with a more detailed e-mail questionary was selected as the information collection method due to the complexity of the topic. A research information sheet and the interview questions were shared in advance of the telephone interview with the interviewees by e-mail. The questions covered topics from corporate sustainability and sustainability goals, operational sustainability-oriented actions in the research infrastructure, SOI, and the role of the RTO for the sustainability of the ecosystem. The interviewees either answered themselves the questions during the phone call, and the corresponding author wrote their preliminary answers down to the questionnaire form and shared with the interviewees after the call. The interviewees then consulted additional people inside their organisations and completed the survey. They returned the documents to the corresponding author by January 2024. The responses were then pseudonymised and analysed.

For the analysis, a slightly modified SOI framework suggested by Adams et al. [84] was used that includes categorisation of the activities to (1) Operational optimisation SOI (often incremental), (2) organisational transformational SOI (somewhere in between incremental and radical), and (3) system level SOI (highly radical).

Admas et al. [84] suggested, that the activities for SOI can be analysed through the Framework in Table 2. As this is one of the best known and complete frameworks for SOI, we selected it for our analysis of the state-of-practice of SOI at RTOs. We then mapped the survey answers into the framework presented in Table 2 separately for each RTO. Each

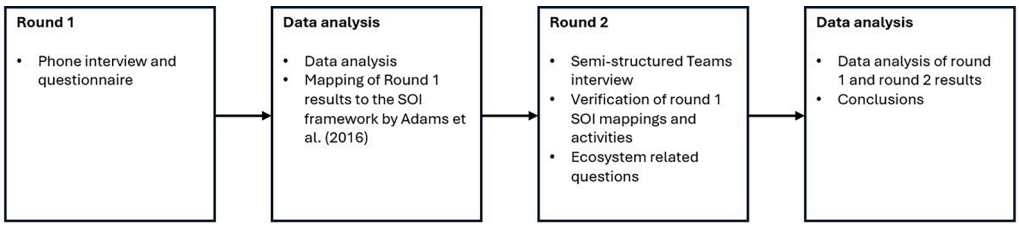


Fig. 1. Study flow of the research.

Table 1
The interviewed people from the four European RTOs.

RTO	Interviewees during first and second round	Internal consultation on first round	Duration of second round interview
RTO A	Fab manager, Quality manager, Sustainability manager	Microelectronics lead	34min
RTO B	Project manager, Scientific Associate	Fab management	53min
RTO C	Microsystems group manager, Chief Safety Officer, EU program lead		26min
RTO D	Sustainable electronics program director		29min

mapping was returned to the first-round participants in June 2024 for verification and completion be the interviewees. In this way best possible reliability of the research was ensured. Due to the complexity with some of the answers due to scattered understanding of the topic and the mapping to the framework presented in Table 2, the authors decided to do a follow-up study with the same people on the topic to gain additional information and verification to the first-round questions, as well as ask more about the green innovation ecosystem actors.

The second study round was conducted as semi-structured interviews over Teams in June and July 2024, recorded and transcribed. A research information sheet was shared with the participants in advance together with the interview questions and the mapping of their first-round answers into the framework presented in Table 2. The length of the interviews can be seen in Table 1. During the interviews, the framework was verified and corrected. In addition, the participants answered questions about whether they had started new SOI related activities since the last discussion, as well as about the green innovation ecosystem actors and drivers and barriers for green innovations in the ecosystem around their RTOs.

The second-round data was then pseudonymised and analysed. Based on the raw data we developed a framework for the green innovation ecosystem around the RTOs. The framework is a complemented version of the actors identified earlier by Marcon et al. [31], adapted to the case in our hands.

The reliability of this study can be considered good in its specific context, as the selected RTOs are central players in the field and the interviewed people were appointed by the RTO department management to be the right people for the study, and the interviewees requested additional information from their organizations when needed.

4. Findings and discussion

In this chapter we present the findings from this two-phased research and discuss the research questions.

4.1. SOI activities at RTOs

4.1.1. State of practice

The mappings of SOI activities per RTO are presented in Tables A.1, A2, A3, A.4 in Appendix A. The level of SOI related initiatives seems to vary a lot between these four RTOs. Two of the RTOs have very little activities in total, whereas one has activities in all the fields.

All four RTOs have SOI activities related to operational optimisation, and there the activities are mostly aligned. The activities concentrate on actions in the semiconductor research infrastructure i.e. in the cleanroom. Especially, all RTOs are trying to minimise energy and water consumption in the infrastructure and trying to minimize exhaust. Two RTOs are sending out newsletters related to sustainability to raise awareness. And three mention that they are focusing on following regulations.

On the organisational transformation side, we start to see more variation in the activities. All RTOs mention that sustainability is implemented into the strategic level. Only two out of four mention that there is a heavy push from top management side for advancing sustainability. All RTOs mentioned here research projects as the means for advancing the topic, mostly on the cleanroom operational side and related to fabrication. Only two RTOs also mention that other than cleanroom related R&D projects have sustainability focus. Two RTOs mention recycling.

Table 2
Activities of SOI.

	Operational Optimization: doing more with less	Organizational Transformation: doing good by doing new things	Systems Building: doing good by doing new things with others
Strategy	Comply with regulations or pursue efficiency gain	Embed sustainability as a cultural and strategic norm in a shaping logic that goes beyond greening	Logic of wide collaborations and investing in systems solutions to derive new, co-created value propositions
Process	Focus on internal and incremental innovation facilitated by use of tools	Adopt new values and platforms (e.g. reverse innovation) and new ideation practices (e.g. biomimicry)	Adopt new collaborative process platforms with diverse stakeholders
Learning	Exploit existing knowledge management capabilities to identify and access relevant knowledge	Engage with key stakeholders of the firm – internal and external	Develop ambidextrous skills enabling 'shadow tracking' and learning from experimentation with multiple new approaches
Linkages	Recruit external domain experts for new knowledge	Shift focus from intra-firm linkages to collaborations with immediate stakeholders	Get the whole system in the room to diagnose problems, understand system complexity, build trust and identify levers for change
Innovative organisation	Exploit existing innovation capabilities	Embed SOI culture through the organization	Adopt new business paradigms (e.g. B-Corps)

On the systems building side, collaborative research projects seem to be in the focus, as well as education and communication to the ecosystem. Also recycling method development with other companies is mentioned by two of the RTOs. One highlights the important role of the RTO for the ecosystem for driving sustainability.

Based on Tables A.1–A.4, we can say that RTO A and RTO B have the least activities related to SOI. These were also the two RTOs that mentioned that they had started new SOI related activities during the period between the first and the second round of this study, whereas RTO C and RTO D had mainly continued execution on the existing activities and started only few new ones.

What is visible from the answers, is that the RTOs come from different European countries, and hence follow different legislations. There are also differences in the available funding and governmental incentives in the different countries. In countries with strict requirements and quota on reducing energy consumption, the departments also seem to have received funding for making that happen.

The sustainability program director at RTO D stated it like this: *"[The motivation to start taking sustainability into account came] from many things: 1) The geopolitics in Ukraine and the global energy crisis in Europe. 2) The … government requests all national entities to reduce energy consumption. … 3) Motivation is also coming from people in the fab, especially related to materials recycling and consumption. 4) We have a strong management commitment, … CEO has a clear message on engaging in sustainability topics, new engineers want to have more sense in the R&D they do.*"

Based on Tables A.1–A.4 we summarised the answers. The summary of the SOI activities at the RTOs are shown in Table 3.

4.1.2. Driving factors for SOI at RTOs

Table 4 summarizes the most important drivers for SOI activities according to the interviews. All the interviewees mentioned funding as a driving factor – money they receive for research projects. Two mentioned political pressure. Then the other factors were mentioned only by one RTO: cost savings, image and the local environment.

The scientific associate from RTO B said: "*The biggest reason is political pressure, of course. Pressure on the customers, on the industry. All this product passports, PFAS regulations, the more and more tighter getting restrictions on every chemistry we are importing into EU, all this pressure on industry is indirectly increasing.*"

And the sustainability program director from RTO D said: "*A combination of (1) regulations and (2) local impact of industry implantation. When* e.g. *huge fab is planned/built that will capture water etc. – local society can be worried of this kind of implantation. Local society pushes the industry to have activity on sustainability*."

The fab manager from RTO A said: "*Personal interest is not enough for driving the change, it is only facilitating. Financial incentive is needed – customers, funding requirements."* And the microsystem group manager from RTO C said: "*It's the trend, we have to act according to the trend. You need to show example as an RTO…*"

Table 3
Summary of the RTO's SOI activities.

Operational optimisation	Organisational transformation	Systems building
Focus on following regulations and legislation, monitoring and measurement	Sustainability part of corporate strategy	Co-creation of new products and services with external partners
Focus on supply chain, scope 1,2 and 3 emissions, infrastructure updates	Strong management support for transition	Value capturing through R&D projects
Sustainability awareness building	Creation or use of new operational models, products, infrastructure, technology or equipment, alternative products in-house or by external parties	Influencing – ecosystem, government, funding agencies

Table 4
Most important drivers for SOI related activities from the RTOs perspective.

	Drivers for SOI
RTO A	Upcoming regulations, funding requirements, customer requirements
RTO B	Political pressure on customers and industry, funding
RTO C	Image, go green, governmental funding, energy cost savings
RTO D	Regulations, local impact of industry implantation

4.1.3. Discussion related to the first research question

The authors have not managed to identify any other case studies for what kinds of SOI activities RTOs with semiconductor departments are engaged in i.e. the only other state-of-practice mapping seems to be the one by [76]. However, the focus of that study was on the general practices and not on specific SOI activities at RTOs. Hence, our study is among the first to show what concrete SOI actions are taken within RTOs with microelectronics departments to advance green technology.

According to [33], innovation in high tech industries, like the semiconductor industry, typically emerge from collaboration between different organizations. And this can clearly be seen from our research results – the RTOs are focal points for R&D project collaboration.

According to our study, the biggest driver for SOI activities at RTOs is political and regulatory pressure along with available funding. These both factors drive effectively the R&D focus of the RTOs. Drivers and barriers for companies to engage into sustainable open innovation activities in shared semiconductor infrastructures were earlier studied by Konstari and Valkokari [29]. However, these cannot directly be compared to the RTO case now in our hands.

Danko et al. [72] earlier concluded that there are two types of MNCs in SOI activities: focal and participating MNCs – the latter one becoming a SOI driver. MNCs are large companies, and they have the capability tackling new topics in house. Our study confirms the need of such large companies for the semiconductor field for effectively driving SOI forward together with RTOs as the SMEs does not seem to always have the know-how to engage in driving and creating solutions for high tech industries like the semiconductor industry without thorough guidance and training. Or the other way around, RTOs can act as educators for the SMEs for driving sustainability topics forward, but adequate funding is required for that.

We conclude, that the answer to our first research question is presented in Tables 3 and Table 4.

4.2. Actors in the green innovation ecosystem around the RTOs

4.2.1. RTO green innovation ecosystem actors

In the first research round, the view on the role of the RTO for the ecosystem sustainability differed at the different RTOs. The EU program lead at RTO C stated "*We do not think that we are a driver for this. The sustainability comes via the research projects we do.*" On the other hand, the sustainable electronics program director at RTO D said: "*We have to play a major role in this. … R&D community has to share the results with the industry community. The industry community should support our work for sustainability. Funding should then be generated, and money should be raised related to the sustainability topic."* And the quality manager at RTO A stated that *"Our research cleanroom facility should be an example and pilot for sustainable and environmentally friendly cleanroom."*

In the second study round, we asked more about the actors in the green innovation ecosystem around the RTOs – on one hand participating companies and organisations, on the other hand participating roles/functions. The answers are summarized in Table 5. Table 5 shows that the view of the actors in the green innovation ecosystem around the RTOs vary a lot between the RTOs, underlining the complexity of the topic, the impact of different geographical, economic and political environments, and the difference in understanding of the topic at the

Table 5
(a) RTOs view of their own role in the green innovation ecosystem. Ecosystem (b) functions/roles and (c) actors according to the RTOs for driving SOI activities.

	(a) RTO's role in the green innovation ecosystem	(b) Functions/Roles of the green innovation ecosystem	(c) Green innovation ecosystem actors
RTO A	Innovator, initiator	RTO internal and external decision makers with influence on research topics, legislative authority, operational level at RTO for execution, procurement	Customers, Joint R&D project consortium members, Funding party, Regulatory party, public opinion
RTO B	Disseminator, information spreader	Evaluators of new risky technology (RTO), educators, consultants, communicators, facilitators	Large companies, SMEs, governmental funding bodies, standardization consortium
RTO C	Role model and solution provider	Top management, top R&D management, operational people (infrastructure manager, quality and safety manager, sustainability manager)	RTO, government, companies, R&D projects, regulatory party
RTO D	Innovation driver	CEO, sustainability director, operative people	Abatement company, filtration company, recycling company, sensing/monitoring companies, semiconductor companies, end users, materials providers

interviewees.

All RTOs agree that external companies are part of the ecosystem, as well as funding bodies. And all the RTOs view on their own role in the ecosystem was rather coherent – innovator, role model, solution provider, disseminator.

The RTO B scientific associate highlighted an interesting dilemma: "*What I think we would need for the ecosystem are SMEs, but there are not many SMEs that can be included into projects which are funded. And on one hand we need SMEs in projects, but on the other hand there are not many tackling the sustainability topics because they do not have the size and the money to tackle these semiconductor needed certifications. So, on one hand there are innovative ideas coming from SMEs, and that is why we need them, and we need them in project applications. On the other hand, they often don't meet the requirements form the semiconductor industry. So, there is a bit of a gap between the technical requirements, and the ideas which they have.*"

On the question of what is lacking in the ecosystem to capture the value from SOI, the sustainability director from RTO D said that *"[what is lacking is] real RTO alliance on sustainability, where we combine efforts. Sustainability is not a competitive area. We have to do more.*" The microsystem group manager from RTO C analysed that "*Need high performing green products* i.e. *performing as good as non-green products – a less performing one will not be used."* The fab manager from RTO A said "*A strong leader/pusher would be needed – initiatives are now coming through individual funding opportunities* e.g. *EU calls. There is one call, and one huge consortium – everybody wants to position themselves there – this shows that there would be much more initiatives need both on national an EU level."* The project manager and scientific associate from RTO B saw the lack of money even for basic education as a blocking item, as well as the misinformation around sustainability: *"There is a really big network of misinformation even in research areas and scientific levels… I would name here lack of money, I know it is not an actor, but we have lot of options and ideas, but it is not spread into the world for the moment."*

4.2.2. Discussion around the second research question

Li et al. [73] earlier concluded that green innovation ecosystems are effective ways for SMEs for implementing green innovation projects with government-industry-university-research institution. Also, Rodriguez-Espindola et al. [58] highlighted the need of governmental support for advancing SOI at SMEs. Our findings elaborate on these earlier results and highlight at the same time the challenge with SMEs in advanced technology industries and in including them in collaborative R&D projects.

Our findings indicate that a mechanism would be needed for effectively educating SMEs about the standards of the semiconductor industry to effectively include them into R&D projects. In addition, consideration should be put on what is the goal – to engage SMEs or to generate SOI. If the latter one, requirements for how to include SMEs in collaborative R&D projects could be reconsidered in critical technologies like the semiconductor field to accelerate development.

The role of intermediaries was studied by Sultana et al. [74]. We can see this need as well – there is a clear need for "bridge builders", for people that have a multidisciplinary understanding of both sustainability and circular economy related topics as well as of the semiconductor industry and its specific technological needs. Amir and Prabawani [57] highlighted the need of a change leader. Our results indicate that such a change leader would be needed. Or, more precisely, a collaborative organization for advancing SOI along with a change leader.

Ruiz et al. [76] earlier highlighted the lack of coordinators for creating a collaborative environment in the Dutch asphalt paving industry and the lack of pressure for change. Our findings indicate that in the semiconductor industry there is a huge pressure for change, and some level of coordination, but the coordination is here as well on project level. Hence, our results indicate that also the semiconductor industry would benefit from a system-level approach for advancing the SOI topic.

The earlier publication with the most complete green innovation ecosystem actor mapping is the one from Marcon et al. [31]. The named actors were suppliers, consultants and experts, universities, research and technology firms, complementors, class organizations, investors and shareholders, regulation agencies, governments, innovation hubs, other actors, customers. We use this as a starting point, and evolve it based on our findings to fit the case in our hands.

We can identify all the previously mentioned actors in our study. However, based on our study, the category "other actors" should in the case of a green innovation ecosystem around an RTO with semiconductor department and research infrastructure be complemented with a couple of crucial actors. Hence, we suggest that based on our findings, the actors in green innovation ecosystems around RTOs should be complemented as we present in Fig. 2, and grouped into five categories: authorities, funding, industry, society and knowledge providers.

The green innovation ecosystem around an RTO is local. Hence, the local authorities or the municipality plays a role here, especially due to that semiconductor R&D activities requires expensive and environmentally burdening infrastructure and that depends often on the local authorities or the municipality.

According to our findings, image and the public opinion influences what kind of R&D projects the RTOs engage into. The public opinion and the societal discussion affect also the opinions and interests of several other actors, not only the RTO. It can therefore be seen as an independent actor.

In addition, our framework considers that SMEs and large companies play different kinds of roles in the ecosystem due to their differing capabilities and resources. SMEs often lack resources and know-how from fields that are not their core business. On the other hand, they are quick decision makers and can quickly decide on the direction. For large companies, on the other hand, it is much easier to e.g. build new teams with internal resources and quickly ramp new capabilities. Large companies also have resources for new investments. However, they tend to

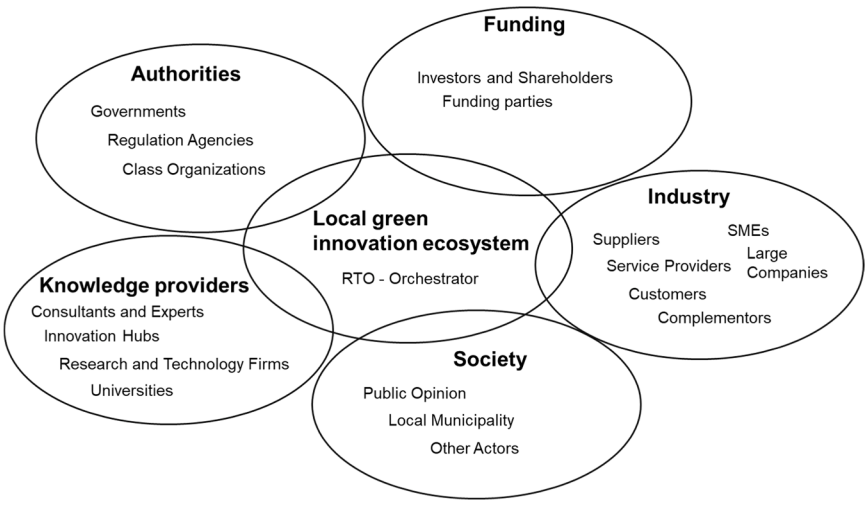


Fig. 2. Framework for the actors of the local green innovation ecosystem around RTOs.

be slower in their movements and consider more the next moves.

The RTOs described their own role as innovators, initiators, disseminator, role models and solution providers as well as innovation drivers. Amitrano and Bifulco [70] called the universities initiators, facilitators, coordinators and stimulators. We chose to use the word *orchestrator* for the RTO in the green innovation ecosystem, as it more strongly implies that the RTO actively drives the ecosystem thanks to its engagement and the research infrastructure it hosts, as well as initiates and disseminates the green innovation topic in the local ecosystem. Our framework underlines the role of the RTO in the focal point of the green innovation ecosystem as the orchestrator of the green innovation activities thanks to the infrastructure and the participation in the joint R&D projects.

5. Conclusions

5.1. Contribution

This research has focused on mapping the state of practice for what kind of SOI activities four European RTOs are engaged in, the drivers for these activities, as well as on analysing the actors of the green innovation ecosystem around the RTOs' microfabrication departments.

The summary for the answer to the first research question was presented in Table 3 and Table 4. We conclude that the level of engagement in SOI varies at the different RTOs, but all the four RTOs had engagement in the different areas: operational optimization especially in the semiconductor infrastructure, organizational transformation and systems building. The main drivers for SOI engagement at RTOs were found to be top management push, governmental pressure and available funding.

The answer to the third research question was shown in Fig. 2– a framework for green innovation ecosystem actors around RTOs that take into consideration as well the public opinion, the local municipality, the complexity of the industry through mentioning different kinds of companies, as well as the need of a strong orchestrator to advance the topic.

The main academic contribution of this research is the local green innovation ecosystem actor framework. In addition, this research serves as a mapping of the state-of-practice of SOI activities at RTOs and the driving factors for advancing those activities.

5.2. Practical implications

Managers of industry and academia can use our findings to understand what actors are important in their local green innovation ecosystems for advancing SOI. Governmental representatives can take advantage of our study to understand the complexity of the topic and need of multidisciplinary approach to advance sustainability in the European semiconductor industry through collaboration.

5.3. Limitations of research and suggestions for further research

Regarding its research limitations, this empirical research is based on a multiple case study of four RTOs with semiconductor departments. Thus, the empirical findings are tentative and in line with the purpose of our research, but they are not generalisable. Instead, they open avenues for further studies. Therefore, further research is needed to better understand the actors of green innovation ecosystems to prove generalisable actor roles. Interesting topics for further research include also continued mapping of how SOI activities evolve at the four RTOs, how SOI activities differ between RTOs in different parts of the world, how the RTOs extract value from SOI either alone or in the ecosystem around them, as well as more detailed studies of the green innovation ecosystem actors.

Ethical statement

The research plan and dataprotection plan for the research was reviewed together with the Ethics Officer of the authors' organization prior to starting the research.

Consent to the research was received from all participants.

This research did not require institutional review board approval because it does not deal with patient information neither with animal testing.

The authors do not have conflict of interests related to this study, neither have they received funding or the study.

CRediT authorship contribution statement

Piia Konstari: Writing – original draft, Methodology, Formal analysis, Conceptualization, Visualization, Investigation, Data curation. **Katri Valkokari:** Supervision, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors have no acknowledgements to make.

Appendix A

Table A.1
Sustainability-oriented innovation activities at RTO A.

RTO A	Operational optimisation	Organisational transformation	Systems building
Strategy	Follows regulations, aims at reducing energy consumption	Sustainability implemented in strategy, aim to be carbon neutral in 2030	Aim is that sustainability should be considered in every research project
Process	Optimisation of energy usage, exhaust and waste minimisation. Water based scrubbers to exhaust system, catalytic scrubbers to water pumps, motion detectors for lighting, recycling metal, quartz, silica, glass. Chemical process optimisation, increasing neutralization capacity.	Data platform planning for collecting data and optimising tool usage. Working out possible advanced recycling options for materials used in the cleanroom.	New shared-use infrastructure planned
Learning			Plan to share best practices in new infrastructure.
Linkages		In research projects companies developing new recycling methods.	Our cleanroom user companies that focus on processing and materials drive for sustainability-oriented innovations while using the cleanroom and also in joint research projects.
Innovative organisation		Multi-level sustainability goal presented to be considered in R&D. Sustainable material development focus in research project. Processing excellence focus including processing optimisation.	

Table A.2
Sustainability-oriented innovation activities at RTO B.

RTO B	Operational optimisation	Organisational transformation	Systems building
Strategy	Energy efficiency target, reduction of energy usage, green energy. Analysis of what is the biggest problems.	Sustainability implemented in RTO strategy, aim to be carbon neutral in 2030. Sustainability management and certification.	
Process	Minimise fab related energy and water use, green energy use, reduce exhaust, replace old equipment with newer, heat capture and heat coupling, solar system, gas scrubbers, turn down ventilation during closure hours, turn off light during closure time	control of particle limits to minimize ventilation, CMR material replacement (carcinogen), CMP slurry recycling methods	New research projects with partners for sustainability related projects, Green ICT validation project within Germany
Learning	Communication from main institute about learnings on sustainability – newsletter distributing learnings about building etc. Individual contacts and learnings from other cleanrooms (motion control, digital twin for cleanroom)	LCA calculation for research projects to be developed.	
Linkages			Evaluating how to recycle wastewater on CMP
Innovative organisation		Research on how to replace and reduce gases	

Table A.3
Sustainability-oriented innovation activities at RTO C.

RTO C	Operational optimisation	Organisational transformation	Systems building
Strategy	Following legislation, energy efficiency target, reduction of energy and water usage	CEO is pushing heavily for sustainability.	Participating in EU projects focusing on R&D around sustainability related projects
Process	Optimising and renewing tools and equipment, frequent changes of DI water, gas scrubbers, chemical disposal, exhaust air heat recapture, use of natural water for cooling, photovoltaic facade on building, motion detectors for lighting, water heater upgrade, air recycling optimization, cooling unit upgrade	LCA analysis of research projects, choice of research topics, material replacement with more sustainable options, PFAS replacement development, holistic approach	collaborative R&D projects with sustainability topic
Learning	internal sustainability newsletter, staff take e.g. only train when travelling, less email attachments	employee-to-employee education	industry talks on sustainability

(*continued on next page*)

Table A.3 (*continued*)

RTO C	Operational optimisation	Organisational transformation	Systems building
Linkages		Collaboration with recycling companies in the ecosystem	collaboration between different business units and organizations
Innovative organisation	Wet bench in idle mode outside of operating hours	Sustainability advanced through the research projects	

Table A.4
Sustainability-oriented innovation activities at RTO D.

RTO D	Operational optimisation	Organisational transformation	Systems building
Strategy	Following regulations and demands from government, strong demand to reduce electricity, energy and water consumption, reduction of waste	Heavy push from CEO and management due to geopolitics, actively looking for new ways and methods to advance sustainability	Government is demanding all parties to collectively reduce electricity consumption with quotas. RTO should share best practices with industry to spread the knowledge. Participation in EU projects with sustainability focus to get funding to drive for sustainability.
Process	Minimise fab energy and water consumption, minimise exhaust and waste, reduce energy consumption when facilities not used, water recycling in cleanroom, gas scrubbers	segregating as much materials as possible from DI water, storing valuable waste materials that do not yet have recycling methods, PFAS engagement	Pulling together new collaborative programs to advance recycling and development of new chemistries. Starting new cleanroom facility where sustainability is driving factor for building operation with humidity and temperature regulation for energy savings.
Learning	employees motivated to recycle materials	Especially need to motivate and educate the older researcher generation within the company - give methods disseminate. New engineers want to have more sense in what they research.	Fab is a good environment for evaluating and qualifying with new sustainability approaches. Sharing of R&D results with EU and industry - dissemination.
Linkages	Using auditors to advice on what actions should be taken to reduce energy and water consumption	Partners collecting valuable recyclable materials from cleanroom tools, extraction of noble metals from waste, recycling of old deposition targets.	The industry should work more closely with RTO to develop new sustainability solutions. Engaging with national partners to understand how much material could be collected from unused processed wafers. Engaging with external recycling partners
Innovative organisation	innovative ways for how to get management to support and give funding for equipment upgrade towards more sustainable solutions	360-degree approach for how sustainability is considered in R&D projects - how to think differently, reparability concern, front architecture. Results from R&D projects are shared with partners and EU programs.	RTO has to play a major role in sustainability as also other products can use the cleanrooms to fabricate and evaluate their products. R&D organisation shares results with industry.

Data availability

The data that has been used is confidential.

References

[1] S. Hsieh, P.-Y. Lin, I.-H. Lin, D.E. Beck, C.-H. Lin, Assessing the contribution of semiconductors to the sustainable development goals (SDGs) from 2017 to 2022, Heliyon. 9 (11) (2023) e21306, https://doi.org/10.1016/j.heliyon.2023.e21306. Nov.

[2] McKinsey & Company, Keeping the semiconductor industry on the path to net zero, Accessed: Apr. 20, 2024. [Online]. Available, https://www.mckinsey.com/industries/semiconductors/our-insights/keeping-the-semiconductor-industry-on-the-path-to-net-zero, 2022.

[3] McKinsey & Company, Beyond the fab: decarbonizing scope 3 upstream emissions, Accessed: Oct. 30, 2024. [Online]. Available, https://www.mckinsey.com/industries/semiconductors/our-insights/beyond-the-fab-decarbonizing-scope-3-upstream-emissions#/, 2023.

[4] Semi, "Scope 3 category 1 GHG assessment guideline for the semiconductor sector. Semi-Semiconductor Climate Consortium (SCC)," Semiconductor Climate Consortium Report, 2023. Accessed: Apr. 20, 2024. [Online]. Available: https://www.semi.org/sites/semi.org/files/2024-01/SCC%20Prospectus%20Jan%202024.pdf.

[5] I. Cho, S. Kim, M. Yoo, Analyzing GHG emission forecasting in Korea's semiconductor and display industries using grey model, Sustain. Futures 9 (2025) 100512, https://doi.org/10.1016/j.sftr.2025.100512. Jun.

[6] M. Ruberti, Environmental performance and trends of the world's semiconductor foundry industry, J. Ind. Ecol. 28 (5) (2024) 1183–1197, https://doi.org/10.1111/jiec.13529. Oct.

[7] L. Li, H. Msaad, H. Sun, M.X. Tan, Y. Lu, A.K.W. Lau, Green innovation and business sustainability: new evidence from energy intensive industry in China, Int. J. Environ. Res. Public Health 17 (21) (2020) 7826, https://doi.org/10.3390/ijerph17217826. Oct.

[8] A. Breusova, Green economy and sustainable development: a new paradigm for traditional business models, Reliability: Theory Appl. 19 (2024) 1163–1170, https://doi.org/10.24412/1932-2321-2024-681-1163-1170. Special is.

[9] L. Li, J. Fuseini, M. Tan, and N. Sanitnuan, "Effect of green transformational leadership and organizational environmental culture on manufacturing enterprise low carbon innovation performance," 2022, doi: 10.20522/APJBR.2022.6.2.27.

[10] N. Tipanya, L. Li, and E. Salma, "Effect of environmental responsible Human resource management practice on manufacturing enterprise green technology innovation and organizational effectiveness," 2022, doi: 10.20522/APJBR.2022.6.2.1.

[11] Taruna, S. Singh, Green HRM: catalyst for sustainable development and organizational success, in: Role of Science and Technology for Sustainable Future, 2, Singapore, 2024, pp. 503–513, https://doi.org/10.1007/978-981-97-5177-8_27. Springer Nature Singapore.

[12] L. Li, Y. Wang, M. Tan, H. Sun, B. Zhu, Effect of environmental regulation on energy-intensive enterprises' Green Innovation performance, Sustainability. 15 (13) (2023) 10108, https://doi.org/10.3390/su151310108. Jun.

[13] E. Sedovs, T. Volkova, I. Ludviga, Sustainable development and strategic management - what is on the horizon in our non-ergodic world research? Sustain. Futures 9 (2025) 100414 https://doi.org/10.1016/j.sftr.2024.100414. Jun.

[14] L. Oliveira-Duarte, et al., Innovation ecosystem framework directed to Sustainable Development goal #17 partnerships implementation, Sustain. Devel. 29 (5) (2021) 1018–1036, https://doi.org/10.1002/sd.2191. Sep.

[15] J. Fauth, K. De Moortel, D. Schuurman, Living labs as orchestrators in the regional innovation ecosystem: a conceptual framework, J. Responsible Innov. 11 (1) (2024), https://doi.org/10.1080/23299460.2024.2414505. Dec.

[16] H. Etzkowitz, C. Zhou, The Triple Helix, Routledge (2017), https://doi.org/10.4324/9781315620183.

[17] M. Alam, F.-R. Lin, Internalizing sustainability into research practices of higher education institutions: case of a research university in Taiwan, Sustainability. 14 (15) (2022) 9793, https://doi.org/10.3390/su14159793. Aug.

[18] L. Mariani, B. Trivellato, M. Martini, E. Marafioti, Achieving sustainable development goals through collaborative innovation: evidence from four European initiatives, J. Business Ethics 180 (4) (2022) 1075–1095, https://doi.org/10.1007/s10551-022-05193-z. Nov.

[19] L. Kurz, L. Jost, K. Roth, P. Ohlhausen, Focusing sustainable Human resource Management—Framework for Sustainability Management in research

organizations, World Sustain. Series (2019) 57–73, https://doi.org/10.1007/978-3-030-03562-4_3.
[20] I. Kulova, V. Nikolova-Alexieva, S. Pashev, Green entrepreneurship: a review of sustainable business practices in manufacturing and high-tech industries, BIO Web Conf 130 (2024) 08001, https://doi.org/10.1051/bioconf/202413008001. Oct.
[21] Y. Song, Y. Dong, Influence of resource compensation and complete information on green sustainability of semiconductor supply chains, Int. J. Prod. Econ. 271 (2024) 109227, https://doi.org/10.1016/j.ijpe.2024.109227. May.
[22] Y.-Z. Liu, W.-M. Lu, P.P. Tran, T.A.K. Pham, Sustainable energy and semiconductors: a bibliometric investigation, Sustainability. 16 (15) (2024) 6548, https://doi.org/10.3390/su16156548. Jul.
[23] E. Qi, et al., Sustainability model for semiconductor manufacturing, in: 2024 35th Annual SEMI Advanced Semiconductor Manufacturing Conference (ASMC), IEEE, 2024, pp. 1–4, https://doi.org/10.1109/ASMC61125.2024.10545500. May.
[24] V. Narayanaswamy, K. Muthusamy, Sustainability index benchmarking in a semiconductor manufacturing environment, Adv. Mat. Res. (2011) 3377–3381, https://doi.org/10.4028/www.scientific.net/AMR.383-390.3377, 383–390Nov.
[25] C. Shen, P.P. Tran, P.T. Minh Ly, Chemical waste management in the U.S. Semiconductor industry, Sustainability. 10 (5) (2018) 1545, https://doi.org/10.3390/su10051545. May.
[26] C.-W. Hsu, A.H. Hu, C.-Y. Chiou, T.-C. Chen, Using the FDM and ANP to construct a sustainability balanced scorecard for the semiconductor industry, Expert. Syst. Appl. 38 (10) (2011) 12891–12899, https://doi.org/10.1016/j.eswa.2011.04.082. Sep.
[27] Y. Yoo, K. Cho, Key traits of leading sustainable firms in the semiconductor industry, Sustainability. 16 (11) (2024) 4563, https://doi.org/10.3390/su16114563. May.
[28] A. Ateeq, M.A. Alaghbari, A.A.-A. Al-refaei, A.Y. Ahmed, Sustainable solutions: the impact of green technologies in university operations, in: 2024 ASU International Conference in Emerging Technologies for Sustainability and Intelligent Systems (ICETSIS), IEEE, 2024, pp. 225–229, https://doi.org/10.1109/ICETSIS61505.2024.10459406. Jan.
[29] P. Konstari, K. Valkokari, Drivers and barriers for open innovation for sustainability in a shared semiconductor infrastructure, J. Open Innov.: Technol., Market, Complexity 10 (4) (2024) 100395, https://doi.org/10.1016/j.joitmc.2024.100395. Dec.
[30] P. Konstari, K. Valkokari, Value creation and capture from sustainability-oriented innovations in a shared semiconductor infrastructure, Sustain. Technol. Entrepr. 4 (2) (2025) 100104, https://doi.org/10.1016/j.stae.2025.100104. May.
[31] A. Marcon, J.L.D. Ribeiro, R.M. Dangelico, L. Fraccascia, Green Innovation Ecosystems: an exploratory study of the involved actors, Springer Proceed. Math. Statist. 367 (2021) 585–595, https://doi.org/10.1007/978-3-030-78570-3_45.
[32] McKinsey & Company, Exploring new regions: the greenfield opportunity in semiconductors, Accessed: Apr. 20, 2024. [Online]. Available, https://www.mckinsey.com/industries/semiconductors/our-insights/exploring-new-regions-the-greenfield-opportunity-in-semiconductors, 2024.
[33] R. Huggins, A. Johnston, M. Munday, C. Xu, Competition, open innovation, and growth challenges in the semiconductor industry: the case of Europe's clusters, Sci. Public Policy. 50 (3) (2023) 531–547, https://doi.org/10.1093/scipol/scad005. Jun.
[34] Y.-S. Lin, C.-F. Chien, D. Chou, UNISON decision framework for hybrid optimization of wastewater treatment and recycle for industry 3.5 and cleaner semiconductor manufacturing, Resour. Conserv. Recycl. 182 (2022) 106282, https://doi.org/10.1016/j.resconrec.2022.106282. Jul.
[35] M. Pelcat, GHG emissions of semiconductor manufacturing in 2021, Accessed: Jul. 19, 2024. [Online]. Available, https://hal.science/hal-04112708/document, 2023.
[36] N. Krishnan, S. Boyd, A. Somani, S. Raoux, D. Clark, D. Dornfeld, A hybrid life cycle inventory of nano-scale semiconductor manufacturing, Environ. Sci. Technol. 42 (8) (2008), https://doi.org/10.1021/es071174k.
[37] S.B. Boyd, Semiconductor LCA: the road ahead. Life-Cycle Assessment of Semiconductors, 2012, pp. 109–112, https://doi.org/10.1007/978-1-4419-9988-7_8. New YorkNYSpringer New York.
[38] C.-H. Kuo, A.H. Hu, L.H. Hung, K.-T. Yang, C.-H. Wu, Life cycle impact assessment of semiconductor packaging technologies with emphasis on ball grid array, J. Clean. Prod. 276 (2020) 124301, https://doi.org/10.1016/j.jclepro.2020.124301. Dec.
[39] A. Villard, A. Lelah, D. Brissaud, M. Mantelli, An eco-design tool for manufacturers of semiconductor technologies: looking for environmental opportunities in the design phase, in: 2012 IEEE International Symposium on Sustainable Systems and Technology (ISSST), IEEE, 2012, pp. 1–6, https://doi.org/10.1109/ISSST.2012.6228013. May.
[40] A. Villard, A. Lelah, D. Brissaud, Drawing a chip environmental profile: environmental indicators for the semiconductor industry, J. Clean. Prod. 86 (2015) 98–109, https://doi.org/10.1016/j.jclepro.2014.08.061. Jan.
[41] M. Ruberti, The chip manufacturing industry: environmental impacts and eco-efficiency analysis, Sci. Total. Environ. 858 (2023) 159873, https://doi.org/10.1016/j.scitotenv.2022.159873. Pt 2Feb.
[42] Y. Pan, Y. Song, C.-C. Zhang, Q. Zhu, J. Wu, Semiconductor industry's transformation path under circular economy: evidence from micro-level efficiency evaluation, Comput. Ind. Eng. 189 (2024) 109934, https://doi.org/10.1016/j.cie.2024.109934. Mar.
[43] Q. Wang, N. Huang, Z. Chen, X. Chen, H. Cai, Y. Wu, Environmental data and facts in the semiconductor manufacturing industry: an unexpected high water and energy consumption situation, Water Cycle 4 (2023) 47–54, https://doi.org/10.1016/j.watcyc.2023.01.004.
[44] M. Placet, R. Anderson, K.M. Fowler, Strategies for sustainability, Research Technology Management 48 (5) (2005) 32–41, https://doi.org/10.1080/08956308.2005.11657336.
[45] R. Varadarajan, Innovating for sustainability: a framework for sustainable innovations and a model of sustainable innovations orientation, J Acad Mark Sci 45 (1) (2017) 14–36, https://doi.org/10.1007/s11747-015-0461-6. Jan.
[46] K. Mady, M. Battour, S.S.A. Bin-Obaidellah, M.K. Al Balushi, R.E. Kennedy, Exploring environmental regulation instruments and their impact on Eco-innovation practices among SMEs: the mediating role of environmental orientation, J. Environ. Assessm. Policy Manag. (2024), https://doi.org/10.1142/S1464333224500108.
[47] R. Passaro, I. Quinto, G. Scandurra, A. Thomas, The drivers of eco-innovations in small and medium-sized enterprises: a systematic literature review and research directions, Bus. Strategy. Environ. 32 (4) (2023) 1432–1450, https://doi.org/10.1002/bse.3197.
[48] B. Harsanto, A. Mulyana, Y.A. Faisal, V.M. Shandy, M. Alam, Sustainability innovation in small Medium enterprises (SMEs): a qualitative analysis, Qualitative Report 28 (11) (2023) 3257–3271, https://doi.org/10.46743/2160-3715/2023.6193.
[49] A. Kurniawati, I. Sunaryo, I.I. Wiratmadja, D. Irianto, Sustainability-oriented open innovation: a small and medium-sized enterprises perspective, J. Open Innov.: Technol., Market, Complexity 8 (2) (2022) 69, https://doi.org/10.3390/JOITMC8020069. Jun.
[50] B. Harsanto, N. Kumar, R. Michaelides, Sustainability-oriented innovation in manufacturing firms: implementation and evaluation framework, Bus. Strategy. Environ. (2024), https://doi.org/10.1002/bse.3740.
[51] D. Baxter, M. Chipulu, Developing a new scale for measuring sustainability-oriented innovation, J. Clean. Prod. 429 (2023) 139590, https://doi.org/10.1016/j.jclepro.2023.139590. Dec.
[52] E. Milana, F. Ulrich, Do open innovation practices in firms promote sustainability? Sustain. Devel. 30 (6) (2022) 1718–1732, https://doi.org/10.1002/sd.2337. Dec.
[53] L.F. Miranda, C. Cruz-Cázares, M. Saunila, Towards a comprehensive framework to analyse the benefits of openness for sustainability-oriented innovation: a systematic literature review, Sustain. Devel. 31 (6) (2023) 4019–4038, https://doi.org/10.1002/sd.2581.
[54] E. Di Maria, V. De Marchi, K. Spraul, Who benefits from university–industry collaboration for environmental sustainability? Int. J. Sustain. Higher Edu. 20 (6) (2019) 1022–1041, https://doi.org/10.1108/IJSHE-10-2018-0172. Oct.
[55] A. Posch, G. Steiner, Integrating research and teaching on innovation for sustainable development, Int. J. Sustain. Higher Edu. 7 (3) (2006) 276–292, https://doi.org/10.1108/14676370610677847.
[56] W.L. Filho, et al., Implementing innovation on environmental sustainability at universities around theworld, Sustainability (Switzerland) 11 (14) (2019), https://doi.org/10.3390/su11143807.
[57] M.T. Amir, B. Prabawani, Sustainability-oriented innovation through shaping the ecosystem; a case of an e-bus industry in Indonesia, Cogent Business Manag. 10 (2) (2023), https://doi.org/10.1080/23311975.2023.2218681.
[58] O. Rodríguez-Espíndola, et al., The role of circular economy principles and sustainable-oriented innovation to enhance social, economic and environmental performance: evidence from Mexican SMEs, Int. J. Prod. Econ. 248 (2022) 108495, https://doi.org/10.1016/j.ijpe.2022.108495. Jun.
[59] A. Brun, F. Ciccullo, Factors affecting sustainability-oriented innovation in the leather supply chain, Strategic Change 31 (3) (2022) 305–321, https://doi.org/10.1002/jsc.2500. May.
[60] D.S. Blundo, F.E. García-Muiña, M. Pini, L. Volpi, C. Siligardi, A.M. Ferrari, Sustainability as source of competitive advantages in mature sectors, Smart Sustain. Built Environ. 8 (1) (2019) 53–79, https://doi.org/10.1108/SASBE-07-2018-0038. Apr.
[61] D. Cobben, W. Ooms, N. Roijakkers, A. Radziwon, Ecosystem types: a systematic review on boundaries and goals, J. Bus. Res. 142 (2022) 138–164, https://doi.org/10.1016/j.jbusres.2021.12.046.
[62] E. Autio, L.D.W. Thomas, Researching ecosystems in innovation contexts, Innov. Manag. Rev. 19 (1) (2022) 12–25, https://doi.org/10.1108/INMR-08-2021-0151. Mar.
[63] K. Valkokari, C.C. Amitrano, F. Bifulco, T. Valjakka, Managing actors, resources, and activities in innovation ecosystems – A design science approach, IFIP. Adv. Inf. Commun. Technol. 480 (2016) 521–530, https://doi.org/10.1007/978-3-319-45390-3_44.
[64] S. Leminen, K. De Vita, M. Westerlund, P. Ritala, Places and spaces of collaborative R&D and innovation: navigating the role of physical and virtual contexts, R&D Management 54 (2) (2024) 201–213, https://doi.org/10.1111/radm.12663. Mar.
[65] J. Han, H. Zhou, S. Lowik, P. de Weerd-Nederhof, Enhancing the understanding of ecosystems under innovation management context: aggregating conceptual boundaries of ecosystems, Ind. Market. Manag. 106 (2022) 112–138, https://doi.org/10.1016/j.indmarman.2022.08.008. Oct.
[66] G. Piantoni, M. Arena, G. Azzone, Exploring how different innovation ecosystems create shared value: insights from a multiple case study analysis, Eur. J. Innov. Manag. 26 (7) (2023) 206–232, https://doi.org/10.1108/EJIM-09-2022-0495. Dec.
[67] J.A. Gutiérrez, Á. Macken-Walsh, Ecosystems of collaboration for sustainability-oriented innovation: the importance of values in the agri-food value-chain, Sustainability. 14 (18) (2022) 11205, https://doi.org/10.3390/su141811205. Sep.
[68] S. Adomako, N.P. Nguyen, Co-innovation behavior and sustainable innovation in competitive environments, Sustain. Devel. 31 (3) (2023) 1735–1747, https://doi.org/10.1002/sd.2479.

[69] R. Watson, H.N. Wilson, E.K. Macdonald, Business-nonprofit engagement in sustainability-oriented innovation: what works for whom and why? J. Bus. Res. 119 (2020) 87–98, https://doi.org/10.1016/j.jbusres.2018.11.023. Oct.
[70] C.C. Amitrano, F. Bifulco, The co-evolution of ecosystem and university's roles: a focus on the integration of technologies and cultural heritage, J. Technol. Transf. (2024), https://doi.org/10.1007/s10961-024-10127-0. Aug.
[71] A. Williams, L.A. Blasberg, SDG platforms as strategic innovation through partnerships, J. Business Ethics 180 (4) (2022) 1041–1057, https://doi.org/10.1007/s10551-022-05194-y.
[72] T. Danko, N. Krasnokutska, N. Shyriaieva, Mapping the European innovation ecosystems for renewable energy: the role and impact of MNCs, in: 2023 IEEE International Conference on Technology and Entrepreneurship (ICTE), IEEE, 2023, pp. 20–25, https://doi.org/10.1109/ICTE58739.2023.10488535. Oct.
[73] Q. Li, Q. Gao, Y. Zhang, C. Gou, How can small and medium-sized manufacturing enterprises improve green innovation performance through innovation ecosystems? Sustainability. 16 (6) (2024) 2519, https://doi.org/10.3390/su16062519. Mar.
[74] N. Sultana, E. Turkina, Collaboration for Sustainable Innovation Ecosystem: the role of intermediaries, Sustainability. 15 (10) (2023) 7754, https://doi.org/10.3390/su15107754. May.
[75] S. Fiandrino, M. Gromis di Trana, A. Tonelli, F. Rizzato, Metagovernance forms for enhancing sustainability-oriented innovation in a knowledge ecosystem, Business Ethics, Environ. Respon. (2023), https://doi.org/10.1111/beer.12635. Dec.
[76] A. Ruiz, J. Vinke-De Kruijf, J. Santos, E. Keijzer, L. Volker, A. Dorée, The slow implementation of sustainable innovations in the asphalt paving sector: the role of actors and their interactions, Construction Manag. Econ. 42 (10) (2024) 902–925, https://doi.org/10.1080/01446193.2024.2360992. Oct.
[77] P. Artin, Critical sustainability factors of regional SMEs; A case study of regional Australia, Curr. Res. Environ. Sustain. 4 (2022) 100138, https://doi.org/10.1016/j.crsust.2022.100138. Jan.
[78] "VTT Micronova.". https://www.vttresearch.com/en/ourservices/micronova-sustainable-multi-user-semiconductor-rd-piloting-environment, 2024.
[79] T.A. Strom, G. Haugstad, J. Shu, R. Seshadri, Shared instrumentation facilities: benefiting researchers and universities, and sustaining research excellence, MRS Bull 45 (5) (2020) 331–335, https://doi.org/10.1557/mrs.2020.130. May.
[80] E. Heinemann, The value of network sustainability: why we join research infrastructures, in: 22nd International Conference on Electronic Publishing - Connecting the Knowledge Commons: From Projects to Sustainable Infrastructure, ELPUB, 2018, p. 2020.
[81] J. Helman, M. Rosienkiewicz, M. Molasy, M. Cholewa, Infrastructure sharing model as a support for sustainable manufacturing, Smart Innov., Systems Technol. 200 (2021) 71–80, https://doi.org/10.1007/978-981-15-8131-1_7.
[82] E. Brea, A framework for mapping actor roles and their innovation potential in digital ecosystems, Technovation 125 (2023) 102783, https://doi.org/10.1016/j.technovation.2023.102783. Jul.
[83] R.K. Yin, *Case Study Research and Applications*, Sixth Edition, SAGE Publications, Inc., 2018.
[84] R. Adams, S. Jeanrenaud, J. Bessant, D. Denyer, P. Overy, Sustainability-oriented innovation: a systematic review, Int. J. Manag. Rev. 18 (2) (2016) 180–205, https://doi.org/10.1111/ijmr.12068. Apr.

Publication II

Konstari, P., and Valkokari, K.

Drivers and barriers for open innovation for sustainability in a shared semiconductor infrastructure

Reprinted with permission from
Journal of Open Innovation: Technology, Market, and Complexity
10, 100395

Journal of Open Innovation: Technology, Market, and Complexity 10 (2024) 100395

Contents lists available at ScienceDirect

Journal of Open Innovation: Technology, Market, and Complexity

journal homepage: www.sciencedirect.com/journal/journal-of-open-innovation-technology-market-and-complexity

Drivers and barriers for open innovation for sustainability in a shared semiconductor infrastructure

Piia Konstari [a,*], Katri Valkokari [b]

[a] Microelectronics and quantum technology, VTT Technical Research Centre of Finland, PO Box 1000, FI-02044 VTT, Finland
[b] Foresight and data economy, VTT Technical Research Centre of Finland, PO Box 1300, Tampere FI-33101, Finland

ARTICLE INFO

Keywords:
Sustainability
Open innovation
Sustainability-oriented innovation
Semiconductor cleanroom
Drivers and barriers
Research infrastructure

ABSTRACT

A shared-use semiconductor research infrastructure can be studied as a local innovation ecosystem consisting of the infrastructure operating company and the user companies. The level of open innovation for sustainability activities possible to initiate in the infrastructure is affected by the operating company and the user companies. This study focuses on developing a conceptual framework for analysing the drivers and barriers for open innovation for sustainability in the research infrastructure. The research is done as a qualitative multiple case-study in the local semiconductor ecosystem in Otaniemi, Finland. We find out that the level of understanding and ambitions related to sustainability are diverse in the different user companies. Many factors can be considered both as drivers and barriers for open innovation for sustainability depending on the context and the companies' ambition levels. The sustainability of a shared-use infrastructure is a complex topic that requires further research to better understand how open innovation for sustainability related activities can be brought forward in such an ecosystem. The study contributes to the current understanding of open innovation for sustainability by recognising the role of shared-used research infrastructure in innovation processes within the local ecosystem.

1. Introduction

In the semiconductor industry, state-of-the-art technological requirements meet environmental and societal challenges (Lin et al., 2022). Semiconductor manufacturing infrastructure (semiconductor cleanrooms) and manufacturing are both costly and environmentally burdening. The fabrication processes burden the environment as they use large amounts of water, energy and various poisonous materials. The fabrication produces large amounts of wastewater (Lin et al., 2022) and green-house gases (GHG) (Pelcat 2023; Nagapurkar et al., 2023).

According to Hsieh et al. (2023), semiconductors contribute positively to several sustainable development goals (SDG). However, they continue, semiconductor also have a negative impact on the environment. To tackle upstream topics, Yang et al. (2024) discusses in a recent publication if digitalization and intellectual capital could advance sustainable open innovation in the natural resources sector. In a recent publication, Lamsal et al. (2023) give a general overview of the semiconductor industry. Huggins et al. (2023) discuss the current European semiconductor industry and related challenges to also open innovation. The different business models (integrated device manufacturer (IDM), fabless, foundry) of the semiconductor industry are explained briefly by for example Hung et al. (2017). Wang et al. (2023) discuss the environmental issues of the semiconductor industry and highlight that the development of the semiconductor industry is expected to be done based on local environmental and ecological situation, and that it is probable that the semiconductor industry will see more sustainability related actions. Ruberti (2023), on the other hand, analysed key environmental performance of the semiconductor manufacturing value chain.

As semiconductor infrastructure is cost intensive, especially small- and medium sized companies (SMEs) use shared infrastructure like university laboratories or national laboratories to fabricate prototypes and validate their designs. Scaling up from research and development (R&D) volumes to production requires then access to manufacturing infrastructure like foundries that can handle larger volumes (Congressional Research Service Report R47508, 2023). Some of the shared semiconductor infrastructures let the personnel of the external companies access the fabrication facilities themselves, whereas the majority does not allow that but offer the fabrication and prototyping as a service (VTT Micronova webpage, 2024).

A shared fabrication facility affects sustainability related topics of

* Corresponding author.
E-mail address: piia.konstari@vtt.fi (P. Konstari).

https://doi.org/10.1016/j.joitmc.2024.100395
Received 20 May 2024; Received in revised form 23 September 2024; Accepted 1 October 2024
Available online 5 October 2024

the different user companies including SMEs, large companies, universities, and research organizations. Benefits of infrastructure sharing model for sustainability has been discussed by e.g. Helman et al. (2021), who also underlined that infrastructure sharing is one element of open innovation. In the case when personnel of the user companies of the shared infrastructure access themselves the fabrication facilities, an interesting open innovation ecosystem is formed (Chesbrough, 2003).

In shared semiconductor infrastructure, people from competing organizations work side by side and assumably share knowledge and information. The importance of knowledge sharing for employees' individual creativity and innovation capability was studied by Arsawan et al. (2022) at Indonesian small- and medium sized companies (SME). Aisjah et al. (2023), on the other hand, emphasized the link between business performance of SMEs, collaborative knowledge creation and innovation in their study among Indonesian SMEs.

Sustainability-oriented innovation (SOI) was presented by Adams et al. (2016). In our study, we follow the definition by Chistov et al. (2021) for eco-innovations and explore in our study open innovation for sustainability in the context of shared infrastructure. Earlier studies of sustainability-oriented open innovations has been done for example by Kurniawati et al. (2022) in the context of SMEs.

The shared semiconductor infrastructure forms an interesting ecosystem for our study, as the user companies both share the infrastructure as well as the fabrication equipment. They are forced to collaborate at some level. Some companies are very secret about the technology they develop, whereas others consider openness and knowledge sharing beneficial for their innovation activities. In addition, their view on sustainability varies, and hence their interest in engaging into open innovation activities for sustainability.

There are hardly any studies published about drivers and barriers for open innovations for sustainability in shared research infrastructures with multiple user organisation, some of them competitors. Consequently, the previous studies have different categorisations of drivers and barriers. Law and Gunasekaran (2012) named the key factors that influences sustainability development in Hong Kong high tech companies as management, internal factors, and external factors. Hueske and Guenther (2021) named the drivers and barriers for implementing sustainability strategies in institutions of higher education as external stakeholders, organization, group and individual. And Neri et al. (2021) analysed drivers and barriers for adoption of industrial sustainability measures in SMEs. Escobar et al. (2023) researched the barriers for sustainable green innovations and defined the main barriers as regulations, knowledge, financial and market.

This paper builds on these previously presented theoretical models for drivers and barriers for sustainability in different contexts, but taking into consideration the open innovation aspect and the underlying factors at the user companies. The aim of the paper is to provide with new insights of the role of a shared semiconductor research infrastructure for open innovation for sustainability activities by adopting previously presented factors into the local semiconductor ecosystem that the shared infrastructure constitutes. This research gap is quite important to tackle, as importance of sustainability have recently emerged at the semiconductor industry. Therefore, research also looks for answers to the underlying standpoints that what sustainability means for the different infrastructure user companies and how the sustainability reporting requirements affect their sustainability views.

Next, we present the most relevant literature for this research and the methodology used for it. The research is conducted as a multiple case study with a qualitative research approach among the group of companies currently active in the Otaniemi semiconductor ecosystem. Data is gathered via semi-structured interviews. Then, we present key findings, a conceptual framework and discuss whether the identified factors are drivers or barriers for open innovation for sustainability. Finally, we present the conclusions and suggestions for further research.

We provide evidence of the variation of the level of sustainability knowledge within a company, insight in that the user companies' origin affect the approach the companies have for sustainability, evidence of that the operational focus of the company affects their sustainability related efforts, understanding of how the user companies' customer's look at sustainability, evidence for what kinds of innovation activities companies look for in a shared infrastructure, as well as the effect of laws, regulations, and funding on companies' sustainability targets. We analyse the main findings of the research through a conceptual framework for company's internal and external factors that can be either drivers or barriers for open innovations for sustainability. We argue that all these forms the basis for the company's eagerness to engage into open innovations for sustainability related activities, and this in turn affects the sustainability of the local ecosystem.

2. Literature review

Although there are active discussions on sustainability-oriented innovations (SOI) in general, there is scarce, if any, research focusing on neither sustainability in shared infrastructures in the context of semiconductor industry, nor on the drivers and barriers for such. Chistov et al. (2021) studied open eco-innovations. Some ecosystem related SOI research has so far been done by e.g. Rodríguez-Espíndola et al. (2022), Brun and Ciccullo (2022), and Settembre Blundo et al. (2019), but the authors have not identified any prior research for SOI in the semiconductor ecosystem

2.1. Sustainability in the semiconductor industry

The state-of-the-art consulting company reports of sustainability in the semiconductor industry focus on the supply chain and reduction of greenhouse gas (GHG) emissions in scope 1, 2, and 3 type of emissions (Semi, 2023; McKinsey and Company, 2022; McKinsey and Company, 2024).

The academic discussion related to sustainability in the semiconductor industry is rather scattered. One focus seems to be the operational and technical side related to reducing the environmental burden of the manufacturing. Another major topic is related to sustainability reporting. However, the authors have not managed to identify any prior research in the academic discussion related to neither SOI in the semiconductor industry, nor SOI related to shared semiconductor infrastructure

Qi et al. (2024) suggested recently a method for how the commercial and sustainability related efficiency of a semiconductor process step should be measured. Lin et al. (2022) researched the optimization of wastewater treatment of semiconductor cleanrooms. Pelcat (2023), on the other hand, researched the scope 1 (direct emissions) and scope 2 (emissions caused by energy consumption) carbon footprint of the GHG emissions of the semiconductor industry.

Hsieh et al. (2023) studied recently how semiconductors in general contribute to the sustainability development goals. To understand the effect of semiconductors on the environment, life cycle assessments of semiconductors have been scattered, by for example Krishnan et al. (2008), Boyd (2012) and Kuo et al. (2022). In addition, Villard et al. (2012) suggested a model for the microelectronics environmental indicators to describe the biggest effects of microelectronics on the environment.

In a recent study, Ruberti (2023) studied the environmental effect and eco-efficiency of the semiconductor industry. Pan et al. (2024) evaluated the efficiency of semiconductor manufacturing. And Wang et al. (2023) discussed the environmental issues of the semiconductor industry. And Kurrahman et al. (2024) recently discussed sustainable development and sustainable balanced scorecards in the semiconductor industry.

2.2. Open innovation and sustainability-oriented innovation

Chesbrough (2003) defined open innovation as the practice of

leveraging incoming and outgoing knowledge to speed up internal innovation and broaden the market for external application of innovative solutions. Some years later Dahlander and Gann (2010) discussed the level of openness in open innovation. Also Bigliardi and Filippelli (2022) presented a wide review on the sustainability and open innovation topic lately.

Chistov et al. (2021) studied open eco-innovations and define it as "*Open Eco-innovation is the use of purposive inflows and outflows of knowledge, resources and commercialization paths to develop and/or adopt innovations improving the environmental performance of firms*". Following this definition, in this study we explore open innovation for sustainability in the context of shared infrastructure.

Huggins et al. (2023) discusses the potential of the European semiconductor industry. They underline that innovation within high tech industries, like the semiconductor industry, is open, as innovations occurs most often in collaboration between different organizations. This is according to them important as the industry is rather dynamic and constantly changing as the companies are looking for constantly improving their output. Open innovation in this industry often is "roadmapping", "path extension" rather than "new path creation". They mention that outdated regulations and geopolitics are barriers for open innovation in this field. Other limiting factors mentioned include lack of venture capital, IP protection and unsuccessful scaling up of business.

Sustainability-oriented open innovations in SMEs were studied by Kurniawati et al. (2022), who presented the relationship between goal, output, process, stakeholders, and supporting factors in that context. Osorno-Hinojosa et al. (2023) on the other hand studied the meaning of open innovation for SMEs in emerging economies. And Milana and Ulrich (2022) studied whether open innovation promotes sustainable value creation in companies. Furthermore, Oliveira et al. (2019) studied how Brazilian design houses use open innovation in joint development projects of microelectronics circuits.

The concept of open sustainability-oriented innovation is presented by Ghassim and Foss (2020) as the intersection of open innovation, corporate sustainability and external stakeholders. Urbinati et al. (2023) on their side discusses the intersection between open sustainable innovation and sustainable open innovation. Also Kimpimäki et al. (2022) concentrated on the theoretical connections between open innovation and sustainability. Bogers et al. (2020) reported on a case study of how sustainable open innovation was implemented as a grand challenge in the Danish beer industry. Cholez et al. (2023) studied the inter-organizational collaboration in the agrifood sector for SOI. Also Krasnokutska et al. (2024) studied open innovation for sustainability in the agri-food sector. Miranda et al. (2023) also conducted literature research on the benefits of open innovation for sustainability-oriented innovations. And Cano and Londoño-Pineda (2020) discussed the relationship between sustainability and open innovation.

Helman et al. (2021) underlined that sharing economy is one element of open innovation, and that sharing of advanced manufacturing infrastructure is highly sustainable as it allows for a higher utilization rate. And Onoda and Ito (2022) stated that research infrastructure plays a central role in driving open innovation. Their study included shared use measurement infrastructure in Japan. Robaeyst et al. (2021) studied stakeholder identification and selection processes for open innovation in the regional open innovation ecosystem that a city constitutes.

Grimaldi et al. (2021) presented a framework for intellectual property (IP) protection strategies and open innovation. They divided them into defensive, collaborative and impromptu strategies. They concluded in their study that collaborative IP strategies are more effective than defensive ones.

A thorough analysis of sustainability-oriented innovation (SOI) has been presented by Adams et al. (2016) and Varadarajan (2017). A comprehensive review of sustainability-oriented innovation is also presented in the doctoral dissertation of Tura (2018).

In addition, there are several publications about qualitative case studies of sustainability-oriented innovation. Harsanto et al. (2023) studied SOI in Indonesian SMEs. SMEs in Mexico and in Spain were studied by Rodríguez-Espíndola et al. (2022), a large company in France by Orellano et al. (2021), the overall leather industry by Brun and Ciccullo (2022) or the ceramic district of Sassuolo by Settembre Blundo et al. (2019). Watson et al. (2020) studied how nonprofits and business should engage to generate SOI and presented a framework for such collaboration.

In the semiconductor field, Shin et al. (2017) concluded in their publication that fabless semiconductor companies have an advantage in product innovation when they can focus all their efforts on that and leave the process innovation to their manufacturing/foundry partner. Although the previous research offers valuable perspectives on sustainability-oriented innovations in context with open innovations, they do not directly address studies of such in shared research infrastructures.

2.3. Sharing infrastructures and sustainability

Sustainability of research infrastructures is discussed in Heinemann (2020). They highlight that there are three areas of sustainability development goals in research infrastructures: economic sustainability, technical sustainability, and network sustainability.

Helman et al. (2021), on the other hand, brings forward the benefit of sharing infrastructure with respect to sustainability. They define the sharing infrastructure as: "*sharing infrastructure is sharing free capacity of machines and equipment in order to increase their use and strengthen the economy towards sustainable development of industry*". Helman et al. (2021) found out that sharing of infrastructure allows for cost savings with regards to infrastructure, competence and skills. They mention lack of business models as one barrier for sharing infrastructures.

The challenges and opportunities of implementing core infrastructures and research infrastructures at six European universities were studied by Jürgens et al. (2024). They concluded that such infrastructure provides cutting edge technology, and the institutions running that infrastructure is committed to scientific innovation and long-term sustainability. Hockberger et al. (2013) analyse the best practices for intensified collaboration between core facilities at US universities and the private sector both for non-profit and commercial organizations.

Strom et al. (2020) underlined the benefits of shared facilities, in their case shared instrumentation facilities. They highlighted the benefit of the investments into shared facilities through recruitment of talents to the community, long term economic growth through maintaining and sustaining the start-up culture, training and education of future workforce, and outreach. They also underlined the need of supporting policy, funding, contacts and initiatives. Similarly, Cartwright et al. (2024) discusses the challenges and opportunities for an open-access core facility – a microscopy facility. They highlight that generally access to the very latest technology is heavily restricted, which is naturally affecting the success of the investment, to minimize the likelihood of equipment damage and misuse. Furthermore, Bowen et al. (2022) reminded that shared infrastructure is cost efficient and sustainable solution and that the subsidies for keeping such running should be considered as investments that include education and innovation.

On the testbed side, J. Y. Lee et al. (2015) discussed a testbed for companies for sustainable manufacturing. On the living lab research side, Berberi et al. (2023) and Bouwma et al. (2022) recently researched the role of living labs in sustainability transition. Liedtke et al. (2012) earlier addressed living labs and the adoption of sustainability in a home environment. These are, however, a little off topic related to this research as they do not comprise deep tech and complex technology infrastructure but rather evolving ones.

2.4. Drivers and barriers for sustainability in different contexts

The previous literature has identified a variety of drivers and barriers

for sustainability and several categorisations have been presented. The closest prior studies for our research include Neri et al. (2021), Schöggl et al. (2024), and Tura et al. (2019). Beyer (2022) studied barriers to innovation activities and developed a framework divided into internal and external factors for that. This one can partly be built upon for our research.

Neri et al. (2021) categorized the drivers and barriers for industrial sustainability adoption in SMEs to external (regulatory, support, market, external pressure) and internal (organization, management behaviour, workers behaviour, information, technology/service, economic, staff, innovation). They also studied the differences between European countries. The SMEs were also touched by Moursellas et al. (2024), who recently studied the drivers and barriers for sustainability in European SMEs on economic, social, and environmental levels. They stayed, however, at the level of naming performances and practices of these.

Tura et al. (2019) studied the drivers and barriers for circular economy and developed a framework for that with seven factors: environmental, economic, social, political, and institutional, technological, and informational, supply chain, and organizational. And Schöggl et al. (2024) studied barriers to sustainable and circular product design in the European automotive industry. They categorised the barriers into five levels: (1) external, (2) strategic, (3) operational, (4) personal and (5) tool related. For example, as external barrier they mentioned lack of customer demand, and as personnel reluctance to adopt sustainability-specific practices.

Other related research in the electronics industry include Law and Gunasekaran (2012) who studied sustainability development in electronics related manufacturing firms in Hong Kong. As critical factors for sustainable development, they presented management, internal factors, and external factors. Also, Ahmadi-Gh and Bello-Pintado (2022) researched sustainability in manufacturing plants from electronics, mechanical and transportation equipment companies. They concluded that greater control does not always advance sustainability and underlined the importance of training.

On telecommunications side, Y.-C. Lee et al. (2023) studied drivers and constraints influencing the adoption of sustainable development practices within the telecommunications industry. They proposed a theoretical framework including regulatory pressure, stakeholder expectations, resource scarcity, competitive advantage, innovation and efficiency, long-term viability and risk mitigation, investor and financial community pressure, cost and ROI concerns, technological limitations, global supply chain complexity, competitive pressure and lack of awareness and commitment.

Escobar et al. (2023) studied barriers for sustainable green innovations and named financial and government regulations as the main barriers.

The role of non-profit organizations (NPO) as facilitators for sustainable social innovation is discussed by Vigoroso et al. (2023). They conclude that NPOs can facilitate the open innovation activities that are crucial for the survival, competitiveness and social sustainability of businesses. They also highlight that open innovation is heavily based on trust.

2.5. Sustainability reporting

Due to the increased public awareness of the environmental issues of semiconductor manufacturing, the semiconductor industry has been forced to react. Sustainability Reporting (SR) has become important for the companies in the field (Yoo and Cho, 2024; Van der Ploeg and Vanclay, 2013). Corporate Social Responsibility (CSR) reports provide information about the companies' economic, environmental and social performance and enable hence stakeholders to evaluate the companies' contribution to sustainable development (Olanipekun et al., 2021; Mitra et al., 2014). The Global Reporting Initiative (GRI) outlines a framework for such reports (Van der Ploeg and Vanclay, 2013).

The sustainability reporting practices have been studied extensively by for example Benvenuto et al. (2023). They present different business and institutional drivers for sustainability reporting. Fifka (2014) brings forward benefits and difficulties with sustainability reporting and argues both ways. Businesses can improve their brand, attract employees, and become more cost efficient, but also, reporting is an administrative burden, requirements vary based on industry, and there are several dilemmas with the information to be disclosed.

Yoo and Cho (2024) studied the semiconductor companies that were either high- and low-performers in Sustainalytics' environmental, social and governmental (ESG) ratings to understand current gaps in sustainability management in the semiconductor industry. Thijssens et al. (2016) studied the company internal factors for generating sustainability reports and the outcomes in some Dutch companies. Pizzi et al. (2024) discussed the trustfulness of the current sustainability reporting – the reporting quantity has dramatically increased but the quality has not. Many sustainability reports ignore to report negative topics.

3. Methodology

This research focuses on investigating the drivers and barriers for open innovation for sustainability in a shared semiconductor research infrastructure.

As prior research in the same field has not been identified, a qualitative research approach was chosen as this study aims at creating new understanding of a particular case and not at proving already existing theories. To study an emerging phenomenon in a new context, such as open innovation for sustainability in a shared infrastructure, a qualitative case study is an appropriate methodology (Yin, 2018). A qualitative multiple-case study was selected as the appropriate research design (Eisenhardt, 1989) as the aim is to understand the view of several user companies on the topic in a new context and to synthesize the answers. Semi-structured interviews were selected as the information gathering method, with questions spanning widely over background information of the companies, activities in the shared research infrastructure, and the companies' views on what sustainability is and what should be done in the shared research infrastructure to advance sustainability-oriented innovations.

The main research questions for the multiple-case study were defined as

RQ1: What does sustainability mean and include for the case companies at the shared research infrastructure?

RQ2: What are the drivers and barriers at the case companies for engaging in open innovation for sustainability related activities in the shared research infrastructure?

The Otaniemi shared semiconductor infrastructure and the company ecosystem around it was selected for this study because of its long traditions and because it offers open access for external companies, which is not common in the industry (VTT Micronova webpage, 2024), and forms hence an open innovation ecosystem. This ecosystem has developed around the semiconductor infrastructure in Otaniemi, Finland, since the construction of "Micronova" in the 1990s and has enabled the birth of a magnitude of innovations and new businesses. The now planned infrastructure expansion is called "Kvanttinova", and it continues to strengthen the capabilities to further develop specialised microelectronics innovations in Finland. The Otaniemi semiconductor ecosystem forms an interesting and unique research object for understanding how open innovations for sustainability can be advanced in a shared research infrastructure. In addition to the available infrastructure, this depends on the sustainability goals and motivations of the user companies, as well as on their innovation and IP strategies.

We selected the participating companies to the research from the Kvanttinova interest group. The companies include current research infrastructure (Micronova) user companies and some potential new users to the research infrastructure expansion (Kvanttinova). We selected in total 14 companies for the study and contacted them to present the study, inquire for their interest to participate and get the

right contact persons for the semi-structured interviews. The appointed interviewees had all sustainability related responsibilities at their companies and were hence considered by the companies to be the correct persons to participate.

The research information sheet and the interview questions were shared with the companies in advance. The interview was titled "Company expectation on sustainability measures in Micronova and Kvanttinova". The questions were categorised into three categories: (a) General questions, (b) Micronova related questions, and (c) Kvanttinova related questions. In (a) the questions included information about the company in general and their or their mother company's view on sustainability in general and about their connection to Micronova and/or Kvanttinova. (b) Included questions about their view on sustainability related topics in the existing Micronova infrastructure, and (c) included questions about what they expect related to sustainability in the yet to be constructed Kvanttinova.

All 14 semi-structured interviews were done in December 2023 over Teams and recorded, transcribed, and sent for verification to the interviewed people as text documents. In total 23 persons participated in the 14 interviews and after that three additional people contributed to the answers by filling in missing information to the transcribed interview documents. Some of the interviewees completed or modified their answers during the verification process. The companies and their verified answers were pseudonymised (Company A-N) and brought into NVivo software tool for qualitative research. The responses were then coded with terms including Micronova, Kvanttinova, sustainability reporting requirement, funding comments, corporate sustainability view, governmental and regulations, Kvanttinova-Micronova ecosystem, general comments on semiconductor sustainability, general sustainability requirements, why to move from Micronova to Kvanttinova, company view on handprint, company view on footprint etc. The coded text was then reviewed, analysed by the authors, and summarised. The framework that we present later in Chapter 5 was developed based on this raw data.

The case companies and interviewed persons are presented in Table 1. We categorized the interviewed companies into two categories: small- and medium sized companies (SMEs) and large companies. Categorizations was done with help of additional company information found from Orbis company information portal. To ensure anonymity of companies, the category small-and medium sized companies was chosen to include companies that have a yearly turnover of below 50M€ and include start-ups, and the headcount ranges from 7 to 300 persons. The large companies have a yearly turnover over 50M€ and headcount over 300 persons.

The interviewed persons included employees from different functions in the companies as shown in Table 1: CTOs, senior technology managers, processing leads, general managers of the Finnish sites, quality managers, corporate sustainability managers. The interviewees had different experiences and backgrounds: some had been at the companies for a long time, whereas others were rather new hires. They were all appointed by the company contact persons to be the right persons for this research. It is, however, notable, that especially in SMEs people have several responsibilities, which can be seen from the titles of the people.

The reliability of this research can be considered good in its specific context: the interviewed people had relevant titles for the research and the answers received from the different interviews started to repeat themselves. The interviewees were also requested to verify the answers they had given during the semi-structured interviews to ensure high quality answers.

4. Key findings

In this chapter we present the key findings from the semi-structured interviews divided into company internal and external factors. Table 2 summarises the characteristics of the SMEs and large companies in this research and presents their different motivations for utilising the shared

Table 2
Characteristics of case companies – differences between SMEs and large companies.

Characteristics of small and medium sized companies	Characteristics of large companies
Often spin-offs or start-ups based on technologies researched and developed first at research organization or university, results of outbound open innovation activities.	Mainly own large cleanrooms in Finland for volume manufacturing and R&D.
Need the research infrastructure for daily operations to development and fabrication.	Interested in inbound open innovation activities, in evaluating new state-of-the-art technical capabilities and acquiring new know-how.
When growing, will invest into a certain amount of own infrastructure for back-end processes but leave the investment-heavy semiconductor processing to the shared research infrastructure. Hence dependent on inbound open innovation activities in the shared research infrastructure.	Mother companies of acquired SMEs fit into this category. Those are looking for expansion possibilities, for inbound open innovation activities.
Ready for smaller investments into dedicated critical equipment into shared infrastructure.	Might use some shared equipment as back-up.
Dependent on the sustainability of the shared research infrastructure.	Interested in learning about sustainability and to move the knowledge in-house – in inbound open innovation activities.

Table 1
Interviewed companies and persons.

Company	Industry field	Established	Finnish category	Owner location	Interviewees	Duration of Teams interview
A	Machinery	1990–1999	SME	Americas	CTO, Quality manager	44 min
B	Devices	2000–2009	SME	Americas	CEO for Finland	52 min
C	Machinery	−1989	SME	Europe	Managing director	42 min
D	Devices	2010–2019	Large		Senior process engineer, ESG manager	35 min
E	Equipment	2010–2019	Large		Head of chip production, Sustainability director	28 min
F	Devices	2010–2019	SME	Asia	Operations manager, Head of finance	35 min
G	Devices	2000–2009	Large	Asia	R&D technology manager, Process development manager, Facility manager, Environmental manager	43 min
H	Machinery	−1989	Large	Asia	Senior technology manager, Quality engineer	30 min
I	Machinery	1990–1999	SME	Europe	Managing director for Finland, Research team leader	52 min
J	Machinery	2010–2019	Large		CTO, Senior process development manager, Quality engineer	43 min
K	Devices	2020-	SME		Fabrication lead	23 min
L	Devices	2020-	SME	Americas	Senior technology director	47 min
M	Machinery	−1989	Large		Senior R&D scientist, Sustainability manager	41 min
N	Machinery	2000–2009	SME	Americas	Managing director for Finland	23 min

research infrastructure.

4.1. Shared infrastructure users

There are two types of companies active in the shared research infrastructure: SMEs and large companies. SMEs are often the result of outbound open innovation activities of the local RTO or university. Large companies look for inbound open innovation possibilities in the shared infrastructure innovation ecosystem. The mother companies of the local SMEs have most often similar interests than the local large companies.

The interviewed SMEs need the semiconductor research infrastructure and equipment for their daily operations – R&D and manufacturing. They are often spin-offs from local research organisation or university, and hence results of outbound open innovation. Most have been established thanks to the available technical capabilities and take hence advantage of inbound open innovation in the shared infrastructure. Some of these SMEs have been acquired by foreign companies. The available infrastructure is vital for these companies to exist and grow. The research infrastructure far dictates the sustainability of their operations and supply chain, and their carbon footprint is affected by the shared research infrastructure and its technical implementation and operations. The Operations manager from company F explained it like this: "*We are a spin-off from VTT, so the cleanroom is essential for us, without the cleanroom in Micronova there would be no company. Our business had developed from zero to what it is today thanks to Micronova cleanroom.*"

The other group of companies can be considered to consist of larger companies with own semiconductor manufacturing infrastructure. They do not need the research infrastructure for their own daily activities, but they are interested in being part of the open innovation activities in the shared infrastructure innovation ecosystem. They want access to know-how, new technologies and capabilities through participating in the open innovation ecosystem. They participate in jointly funded R&D projects to get access to information and know-how. These companies want to learn of new technical and operational sustainability-oriented innovation practices in the research infrastructure and transfer that to their in-house infrastructure as inbound open innovation. They consider the new research infrastructure expansion as the new determiner for the sustainability level of the local semiconductor industry. Company G technology manager said: *"Micronova provides both facilities and know-how for joint research and development with VTT and Aalto which helps us to develop our future technology and products."*

The mother companies of the first group of SMEs, have many analogies with the large companies. These look for possibilities to expand to Finland thanks to existing research infrastructure and capabilities. Two companies highlighted that sustainability would be a central requirement for additional investment decision. As the mother companies must deliver on their net zero promises, they will soon be looking for ways to decrease the CO_2 emissions. Company B CEO said "[*Company] is internally looking for possibilities to bring in new products for doing more for other BUs at [Company in Finland] - how to utilize contacts to Finnish semiconductor cluster to make different kind of products than now. If that goes successfully, a bit more R&D to Kvanttinova*."

4.2. Internal factors

Depending on the interviewee's position in the organisation, their level of knowledge and understanding of the sustainability topic was varying. For many of the technical and quality persons, sustainability seemed to be only linked to environmental topics. Some technical managers said that their technology or product is the company's sustainability goal. Sustainability managers also highlighted the other sustainability pillars like social wellbeing and sustainable business. The regulatory side was highlighted especially by general managers and sustainability managers that are people who must deal with the corporate sustainability reporting tasks. Some of the interviewed persons showed clear own interest in the topic and highlighted personal interest areas in sustainability.

Some companies highlighted the difference in sustainability interest between younger and older generations. Some underlined the importance of management support.

On the question "*What does sustainability mean for your company*?" company L Senior Director answered, "*That we should aim at sustainable products, good quality, small size - more environmentally friendly*" and company K fabrication lead answered that "*Expectation and goal that our technology enables a solution with less energy consumption than the current technology*". Company D ESG manager, on the other hand, stated that "*It means responsibility of environmental and social topics.*" Whereas company N Country manager said, "*Sustainability plays a significant role in our business strategy.*"

There was a clear difference related to expectations on collaborative action and sustainability related actions on the cleanroom operations and technical solutions for companies that had operational focus on manufacturing, versus those that were focusing only on R&D activities and were hence not part of the supply chain. The research team leader from Company I said: "In general, *if we could reduce footprint/wafer in Micronova and/or Kvanttinova we would be very happy to support it by helping Micronova and/or Kvanttinova – we are willing to do that if there is some step that should or could be implemented to achieve that.*" expressing hence the interest for collaboration and open innovation for sustainability in the infrastructure itself.

Companies that were doing manufacturing in the research infrastructure were requested to calculate their carbon emissions on at least a quarterly basis for at least scope 1 and 2 type of emissions as these are required for their sustainability reports. They also had pressure on reducing the emissions on a yearly basis. Company B CEO said: "*Sustainability is an important topic for us, comes from shareholders requirements on environmental sustainability. We have started publishing Company specific sustainability report, every business unit needs to collect environmental data related to operations and file those to corporate system on a quarterly basis*."

All other companies that mentioned tight reporting requirements included estimates of the impact of the semiconductor processing in the research infrastructure to their numbers. Company B Country manager explained their approach as following: "*Right now we calculate use of water in cleanroom by calculating all cleanroom working hours spent there and divide total water consumption of Micronova by number of working hours Micronova's cleanroom has been used ant take that time the working number we have been using cleanroom – we get a rough estimate / average for that."* As the data was not easily available, these companies were interested in open innovations for obtaining such data.

A company in the large companies' category with in-house semiconductor manufacturing infrastructure was performing detailed analysis, estimations, and reporting on scope 1, 2, and 3 emissions as well as life cycle assessments (LCA) on the company's operations and products. They said that the effect of their own semiconductor manufacturing on the full picture was neglectable and hence not considered for the moment. "*We will do no breakdown to level of microfabricated products as we are not delivering outside of company*." – Company M Sustainability manager.

Some of the companies that were only doing R&D activities in the research infrastructure mentioned that their impact on the company level net zero targets were considered negligible and hence they were not put under tight reporting requirements. They had, however, also requirements on looking into the topic and doing something about the topic. Company F Operations manager said "*We do not get too much input on sustainability requirements from our headquarters… The requests are so far modest from the headquarters.*" However, they were interested in learning about the topic from the shared infrastructure.

Several companies commented how sustainability topics are linked to the technical performance of their products. One of the interviewed

companies stated that semiconductor processing is technology driven and that the technical performance requirements limit the sustainability related actions that can be taken. They said that focus should be on the technology development that is happening inside the cleanroom. Company G Technology manager said: "*From manufacturing point of view, we try to do the manufacturing as sustainable as possible; we focus of course on the quality and performance of our products but within these constraints we try to select good methods and materials and also improve.*" And company M sustainability manager stated: "*I am not sure when it [sustainability] would be a strict criterion. It is different to ask questions but then actually not to buy a superior product because of lack of specific carbon footprint information, I do not know if that will ever happen.*"

Some equipment manufacturing companies underlined that they themselves need to be proactive and consider how customers will use their equipment as those will affect several customers emissions – these companies underlined their responsibility to care for sustainability. Company A CTO formulated it like this: "*There are three ways to increase sustainability: (1) You fill your responsibility yourself. (2) Your customer says that you must do something in a more sustainable manner - public pressure. (3) Government asking by law, regulations."*

One company also brought forward the importance of the shared research infrastructure as an inbound open innovation channel. The senior process engineer from Company D said: "*Partly new employees are attracted by [Company D] as we meet them in the cleanroom – we get to know the people in the cleanroom, and it is a good channel for recruiting from university*."

4.3. External factors

In all companies the focus of sustainability reporting was on the supply chain and environmental aspects, such as greenhouse gas emission, to which the shared semiconductor infrastructure is a large contributor. Thus, there was a clear difference among the companies for sustainability reporting requirements based on the origin of the headquarters.

The companies that were headquartered in Europe (including Finland) or USA and doing manufacturing had most very strict requirements on sustainability reporting. Most of these companies were requested to calculate their carbon emissions on a quarterly basis for at least scope 1 and 2 emissions. They also had pressure on reducing the emissions on a yearly basis, and hence were heavily interested in how this could be achieved in the shared semiconductor infrastructure. They were interested in engaging into open innovation for sustainability activities.

Those companies who focused on R&D and were either Finnish or headquartered in Europe or USA, did not have any strict requirements on carbon emission reporting. Some mentioned that their impact on the company level net zero targets were considered negligible and hence they were not put under tight reporting requirements. They had, however, also requirements on looking into the topic and doing something about the topic – especially through open innovation for sustainability activities. Company C country manager said "*Even in Finland we just started [looking into sustainability] last month and we assigned a few people to be more active and keep the connection with global company on that one, and to build more awareness and to basically feed these customer requirements also back into very early-stage R&D*."

The interviewed companies that were headquartered in Asia stated that sustainability was very important for their company and that they were encouraged to do as much as possible for the topic. The Asian headquarters seemed to look at them as the role model for how sustainability related topics should be handled. However, they were not facing as strict reporting requirements from their headquarters as the American ones. Company G environmental manager said "*All our factories worldwide are expected to have local sustainability programs and activities to improve sustainability locally and affect the local environment… It is much better possibilities to achieve sustainability targets here than in Asia, so we are the voice of Europe of sustainability to headquarters*."

All the interviewed persons were not in touch with customers, but most were aware of their companies' customer's requirements related to sustainability.

Customers are not only evaluating companies based on products but also on basis of the overall company and on how they tackle environmental topics. Many customers were asking companies to sign their sustainability corporate agreements or signing on to larger sustainability frameworks. Customers do this as part of due diligence and when mapping their own emissions. Customers were also requesting information on used materials and substance. Some customers had Restriction of Hazardous Substances Directive (RoHS) related requirements and requirements on decreasing or stopping use of persisting organic pollutants in products. Some companies underlined that customers expect them to comply to standards. If the exceed the targets, it can be considered as a competitive advantage. Company D ESG manager formulated it as "*New customers are doing due diligence. Customers expect that we fulfil certain standards. It is a competitive advantage if we do well in the sustainability area.*"

Case companies' customers were in general also interested in how companies plan to reduce their emissions and waste because that is directly affecting the customer's numbers. Company H Senior technology manager put it like this: "*Our customers require us to follow their sustainability targets, like net zero. That means for us that we have to require same from our suppliers. Net zero means in practice that our suppliers have to reduce their GHG emissions remarkably (like 50 %)*." Customers have started to ask also for the companies' science-based targets and asked for more aggressive targets for e.g. footprint/wafer. But companies also got practical requests on for example not to include plastics in package materials. Hence, most of the companies felt encouraged to look for sustainability-oriented innovations through open innovation activities.

Many of the companies stated that the laws and regulations related to sustainability are rather tight in Europe and Finland. Semiconductor infrastructure is then in the forefront of worldwide sustainability only by fulfilling these. Some companies see sustainability only as a cost factor, whereas others wish to advance it in every possible way in-house or through open innovation.

In addition to these regulatory requirements, especially the large company group expects new research infrastructure to be implemented beyond regulations so that it becomes a sustainability role model for the semiconductor industry in Finland. After that, the large companies wished to adopt the new measures to their own facilities through inbound open innovation. However, companies also stated that it should be carefully considered what measures are taken in the name of sustainability as the funding is limited and hence the impact of the taken measures and return of investment should be carefully evaluated. Especially some of the large companies underlined the responsibility of the shared infrastructure operator in this case the RTO of sharing know-how and educating others about sustainability and about setting the barrier of the sustainability of the entire local ecosystem.

4.4. Summary of findings

Sustainability signifies different things to different companies. For some, it is the guiding lighthouse and in the core of the strategy, for others still an undiscovered dimension. Some companies viewed sustainability as a competitive advantage, while others saw it as a cost factor and regulations to be fulfilled.

The operational focus of the case company affects the companies' interest in advancing sustainability related topics. Those with manufacturing in the research infrastructure are due to many reasons more pressed to focus on sustainability than those with R&D.

Both SMEs and large companies were interested in engaging into open innovation for sustainability related activities in the shared research infrastructure. The SMEs were interested in that as they use the infrastructure daily and could easily take advantage of the result,

whereas the large companies were interested in transferring the results to their own infrastructure – into practicing inbound open innovation.

The origin of the company and the local culture affect the pressure from the headquarters on sustainability. American corporations seem to rely on tight reporting on carbon emissions, even on cost of accuracy, to confirm shareholders that they are committed to advance sustainability. Asian corporations, on the other hand, seem to consider European sites as role models compared to the sustainability situation in Asia. They encourage the local companies to engage into sustainability advancing activities based on their interest.

Many companies stated that their customers require sustainability related actions from them – more exactly from the supply chain. Nobody, however, said that they would request sustainability related topics from their collaboration partners. Some of the companies also questioned whether sustainability would ever be the key factor for decision making and believed that product's superior performance would always be the guiding factor.

5. Discussion

All the identified prior studies presented in chapter 2 are specific to certain cases and cannot be generalized neither directly applied to our study. All the previous identified studies have different categorisations of drivers and barriers for sustainability. None of them have earlier linked open innovation, sustainability-oriented innovations and shared infrastructure in the semiconductor industry.

Hence, we present our conceptual framework, shown in Table 3, for underlying drivers and barriers at companies affecting their interest for engaging into open innovation for sustainability related activities in a shared research infrastructure. This categorization is based on the results of our multiple case study and the companies' answers in the semi-structured interviews. In the previous chapter, we presented the findings as internal and external factors. Next, we map these internal and external factors into the categories of Table 3 as those can include both internal and external perspectives and discuss whether they are drivers of barriers for open innovation for sustainability engagements.

5.1. Company strategy

When the case company has included sustainability into its strategy, this factor is a clear driver for the company to engage into SOI activities. In case the management complies with the strategy and effectively communicates it to the organization, the management will also be SOI drivers. However, if the management fails to communicate the strategy and sustainability focus, this will become a barrier as employees do not understand the company's sustainability related targets and fail to understand their own role in advancing sustainability and SOI. If the company's value proposition is linked to the strategy and includes sustainability aspects, it becomes a driver and vice versa.

If the company's strategy includes inbound open innovation activities, it is more likely to engage into open innovation for sustainability activities in a shared infrastructure. In this case it is obvious that the use of a shared infrastructure is strategically important for the company, as it sees the power of collaborative approach for looking for sustainability-oriented innovations. An important factor that will then still affect the company's interest in engaging into true open innovation for sustainability is its IP strategy. This will become either a driver or a barrier for the company's engagement into open innovation for sustainability activities, as also presented by Grimaldi et al. (2021). The interest for what kind of SOI activities the company engages into is also linked to what kind of IP the company has decided to keep in house – design or also processing know-how (Hung et al., 2017). It is interesting that none of the interviewees mentioned IP but focused mainly on environmental topics. This might also imply that sustainability is not seen as a competitive factor but a true collaborative topic. This, on the other hand, would imply that companies are on a strategic level even more eager to engage into open innovation activities for sustainability than for other topics.

Our findings are well aligned with the previous studies as factors like corporate strategy, management and awareness were also identified by Neri et al. (2021), Tura et al. (2019) and Schöggl et al. (2024) as important drivers i.e. the lack of those caused the factor to become a barrier for sustainability.

The company branding is also definitely a driver for SOI and can be used also to increase the company value in the eyes of the company owners or shareholders. This was also noted by Neri et al. (2021). Nowadays the shareholders are mainly a driver for SOI activities, as it is not acceptable anymore to ignore sustainability related topics and omit one's responsibilities.

The effect of the company origin can be seen in two different ways. First, cultural aspects and second, point of comparison. Whether the sustainability situation in the country of origin is better or worse than in the ecosystem under study, seems to affect the level of required actions from the case company. How these are requested and in what extent seems to depend on the culture and business practices. It is questionable whether these are drivers or barriers for SOI actions, depending on the situation they can be both. These were not classified as drivers or barriers by Neri et al. (2021), Tura et al. (2019) and Schöggl et al. (2024). Asian headquarters gave the local companies more choice on how they address sustainability. In such cases when the local company is a spin-off, it is presumable that they have close ties to the organisation they originate from and the threshold to collaborate with the originating organisation is presumable rather low, in case IP topics can be agreed upon. This, on the other hand, should favour open innovation for sustainability. It is questionable whether the tight reporting requested by American mother companies motivates SOI activities. If scope 1,2, and 3 carbon emission reporting is most important, the focus will probably not be on true open innovation for sustainability in the shared infrastructure but on monitoring. This on the other hand, can be seen as a barrier for open innovation for sustainability activities.

5.2. Operations management

Whether current sustainability reporting is a driver or barrier for engaging into SOI activities is debatable. Too tight and exact company internal reporting requirements when no accurate data is available puts the emphasize on quantity and not on quality of the reported data. Numbers are roughly estimated, and decisions are made on guestimates. We would tend to argue that this is at least not favouring SOI actions but

Table 3
Our conceptual framework for case company internal and external factors affecting the possibilities for initiating open innovation for sustainability related activities in the shared semiconductor cleanroom environment.

Category	Case company internal factors	Network related, Case company external factors
Company strategy	Strategic goals, Innovation strategy, IP strategy Management Communication Value proposal Branding	Shareholders, Company owners Effect of company origin
Operations management	Sustainability reporting	Stakeholders - Suppliers, Customers, Partners
Social behaviour		Individual interest
Knowledge management	Learning	Education
Technological aspects	Technology	Shared infrastructure and available equipment
Finance	Own financing	External funding
Policy and regulatory	Corporate responsibility	Laws and regulations
	Company operational profile (manufacturing/R&D)	

mainly underlining a need for a balanced sustainability scorecard.

Companies focus on understanding and tracking sustainability in the supply chain on the most visible topics for their reporting. In this way, other partners like R&D partners are neglected. One of the interviewed companies said that they do not consider the carbon emissions of their own semiconductor cleanroom as they consider it such a small part of the scope 1,2, and 3 emissions.

From a research infrastructure and local ecosystem perspective, this is alarming. The current habit of putting focus on the supply chain encourages the companies to ignore R&D partners and local research infrastructure partners. This makes it difficult for local actors to advance sustainability. Hence, reporting can be seen as a barrier for SOI actions in the shared infrastructure. We see a clear need for sustainability evaluations of partners also outside of the supply chain.

If a method would be available for tracking the quality of the sustainability reporting data, that would certainly become a driver for open innovation for sustainability activities in a shared infrastructure.

According to our findings, customers most often seem to be drivers for SOI actions. They become more and more demanding related to performance, environmental actions, and lower cost. It is to be seen if customers are ready to accept lower product performance in favour for sustainability. The previous literature has conflicting views on the role of customers in sustainability. Neri et al. (2021) recognized customer pressure as a sustainability driver, whereas Schöggl et al. (2024) a noted lack of customer demand as a barrier for sustainability in their cases.

Our findings show that for the customers there is no difference in whether it is open innovation for sustainability or company internal SOI. However, we can assume that if the customers ask the companies to engage into SOI related activities, the companies would be more eager to engage into open innovations for sustainability related activities in the shared research infrastructure as that would allow them to take advantage of the sustainability-oriented innovations of the community.

5.3. Social behaviour

As companies already fulfil regulations by law, the individual employees and their areas of interest affects the actions beyond that. People's own accountability for sustainability is a SOI driver. And vice versa, lack of interest is a barrier. Here, our findings coincide with Neri et al. (2021) and Schöggl et al. (2024). If the individuals feel accountable for advancing sustainability, they will make extra efforts in the name of sustainability. They can also motivate others in the network to advance sustainability related actions in the common ecosystem.

5.4. Knowledge management

It is crucial to teach people about sustainability and let them know how they can contribute. When done thoroughly, learning becomes a driver for SOI actions. But, if employees do not understand what sustainability means, neither how they can contribute to advancing sustainability, the lack of learning becomes a barrier for further actions. On the other hand, the network might in this case become a driver for SOI actions within the ecosystem through offering education and training to companies that do not have sustainability related know-how in house. This was also recognized by Neri et al. (2021), Schöggl et al. (2024) and Tura et al. (2019).

Many of the interviewees mentioned that they were looking for sustainability related know-how from the infrastructure operator and from other users of the shared infrastructure. Hence, the shared research infrastructure can be considered a central place for learning and teaching about sustainability in the semiconductor industry, making it an important open innovation ecosystem just like defined by Helman et al. (2021). The community and the spirit within the shared infrastructure users will at the end affect the level of related know-how in the local ecosystem, especially among such companies that do not have specific sustainability related roles in-house. This category includes especially SMEs, to which inbound open innovation form a central path for acquiring new know-how on topics that are not part of their core functions, like mentioned by Osorno-Hinojosa et al. (2023).

5.5. Technological aspects

Neri et al. (2021), Tura et al. (2019) and Schöggl et al. (2024) all listed technology or tools as barriers for sustainability. The research infrastructure, in this case a semiconductor cleanroom, is a high-tech infrastructure equipped with manufacturing equipment. Modern infrastructure and equipment most often are more sustainable than older ones. Old research infrastructure and equipment most often are more environmentally burdening.

Many of the case companies underlined the importance of their products i.e. the semiconductor technology that is developed within the research infrastructure and produced with the manufacturing equipment. Until now, the semiconductor technology development has been mainly done with priority to performance and low cost. However, emphasize is now also on lower energy consumption and more sustainable materials. We classify the semiconductor technology itself as a driver for SOI – to develop next-generation technology and enable the development of our digital society, innovative approaches are needed with sustainability focus.

In the case of initiating open sustainability-oriented innovations in shared research infrastructure, the presence of the latest equipment might not motivate the users to enter collaborative sustainability-oriented innovation activities related to the equipment. In those cases, the focus is often on new device and process development. However, the presence of old environmentally burdening equipment can motivate the users to investigate alternative solutions, for example alternative processing methods. As this issue is common for all users of the shared infrastructure, this is an obvious target for open innovation for sustainability related activities.

Technology can hence be seen both as a driver and a barrier for open innovations for sustainability related activities in a shared semiconductor research infrastructure.

5.6. Finance

Semiconductor infrastructure is costly to build and operate and sufficient funding is crucial. In general, funding is made available to fulfil the minimum regulatory requirements for the infrastructure itself. However, funding will most often be restricting how much beyond the requirements sustainability related actions can be taken in the infrastructure. Careful return on investment calculations might be needed to justify additional investments.

Funding is also limiting the amount of new equipment that can be procured to the semiconductor infrastructure, forcing some old equipment to be used even though it is not that environmentally friendly. Additional R&D funding for green topics will on the other hand help to engage into further open joint R&D activities in the shared infrastructure.

The authors tend towards classifying funding as a barrier for open innovation for sustainability related activities in shared infrastructure. Funding was classified as a barrier by Neri et al. (2021), Tura et al. (2019) and Schöggl et al. (2024). However, in case of readily available company own financial means, financials can also be classified as a SOI driver, if the company contributes to SOI investments in the shared infrastructure.

5.7. Policy and regulatory

Laws and regulations force companies to act related to sustainability. All companies must fulfil the regulatory requirements. In that sense, these can be seen as external sustainability drivers, as also categorized by Neri et al. (2021) and Tura et al. (2019). These can also be seen as

barriers for further SOI actions if the company considers all actions above the regulatory requirements as additional cost factors. Huggins et al. (2023) classified outdated regulations as barriers for open innovation in the semiconductor field.

The regulations are always driving the companies to prioritize the sustainability topic in a certain way. In this study, several companies' clear priority was reporting on scope 1, 2, and 3 carbon emissions in their supply chain and complying with different regulatory frameworks. Hence, the companies put focus on manufacturing sites. This, on the other hand, puts the focus away from small R&D sites. Hence, in some respects the current laws and regulations can be seen as external barriers for advancing sustainability in local research infrastructures which are used for R&D. This company behaviour had not been discussed by Neri et al. (2021), Tura et al. (2019) and Schöggl et al. (2024).

On the other hand, if regulations drive companies to find new methods to reduce their emissions, they might be eager to engage in SOI activities to scout for possible inbound open innovations in the field of sustainability. Depending on the company's strategy, this might then positively affect the level of engagement in open SOI activities in the shared infrastructure.

6. Conclusions

This research has focused on understanding the drivers and barriers at the case companies of a shared research infrastructure that affects their motivation to engage into open innovation for sustainability related activities in the local innovation ecosystem that the shared research infrastructure forms. We can conclude that there are two types of companies active in the infrastructure: SMEs and large companies, who have different kinds of targets related to open innovation for sustainability. The SMEs are often the result of outbound open innovation activities and dependent on the research infrastructure for their operations. Hence, the IP strategy of the SMEs can be considered more open than the IP strategy of the large companies, as it relies in many ways on open innovations in the shared research infrastructure, whereas the IP strategy of the large companies is more closed as they own their own infrastructure and have their proper manufacturing processes in-house.

Our first research question addressed the meaning of sustainability for the different case companies. We conclude that the meaning of sustainability differs for the companies depending on at least their strategy, size, focus, industry, technology, available resources, funding, and origin. Sustainability reporting requirements make some of the case companies to focus on actions in their supply chain with less focus on R&D partners. In other words, their focus is currently more on monitoring and taking operative actions than on sustainability-oriented innovations. Our results also imply that the companies do not always consider sustainability a competitive factor but a collaborative one. However, considering sustainability and cleverly branding it can give the companies competitive advantage.

Our second research questions addressed the drivers and barriers at the case companies for engaging into open innovations for sustainability related activities in the shared research infrastructure. We approached this question through the conceptual framework presented in Table 3, where we divided the factors into company internal and external, i.e. network, related factors.

Our framework built on and expanded the different sustainability frameworks developed by Neri et al. (2021), Tura et al. (2019) and Schöggl et al. (2024). Neri et al. (2021) had the case of drivers and barriers for industrial sustainability adoption in SMEs. Tura et al. (2019) studied drivers and barriers for circular business. And Schöggl et al. (2024) studied barriers for implementing sustainable design into the automotive sector. Many of the factors they identified are like the ones we decided to include in our framework. However, none of the previous studies addressed open innovations for sustainability related activities in shared infrastructure and hence cannot be directly compared to our research. Our framework complements the comparison points identified in the previous literature by adding factors like innovation and IP strategy, company origin and stakeholders, sustainability reporting requirements, and corporate responsibility.

For the second research question, we conclude that depending on the context, many of the factors can be seen both as drivers and barriers for open innovation for sustainability. Several of the presented factors have been discussed already earlier in the literature, but we also introduce complementing factors like the effect of case company origin and the effect of owner and shareholder sustainability reporting requirements. Company internal drivers include company value proposition, innovation and IP strategy, branding, good management and communication, brand, corporate responsibility, and state-of-the-art technology. Network related drivers are at least company owners, different stakeholders, and individual interest. Clear company internal barriers, on the other hand, were weak management and communication, and lack of know how. External barriers included at least funding and outdated infrastructure.

Our research results serve as discussion openers for discussion about possibilities to initiate and advance open innovation for sustainability related activities on different levels in shared research infrastructure that forms a local ecosystem. The results highlight the importance of considering sustainability locally also outside of the supply chains, and sheds light on the responsibility of the shared infrastructure operator in educating the ecosystem, setting the barrier and generating open innovation activities with sustainability focus. Our research highlights the complexity of accelerating open innovation activities for sustainability in shared research infrastructure as the user companies' interests and goals vary heavily based on a magnitude of underlying drivers and barriers. Our research also continues the discussion on the importance of knowledge sharing for innovations and the link between collaborative knowledge creation and business performance studied by Arsawan et al. (2022) respectively Aisjah et al. (2023) in different geographical contexts.

In the semiconductor industry, the focus on sustainability is a rather new thing. This was visible in our research through the varied knowledge of the topic and lack of engagement at some companies. Neri et al. (2021) concluded that the combined effect of SMEs has a significant effect on the sustainability from an environmental and social perspective. According to Osorno-Hinojosa et al. (2023), the SMEs are also those that benefit most out of open innovation. One form of open innovation is according to Helman et al. (2021) a shared infrastructure and Onoda and Ito (2022) argued that research infrastructure plays a central role in driving open innovation. Hence, we can conclude that the combined effect of the attitudes of the user companies of a shared research infrastructure is major on the level of SOI actions that can be initiated in that local ecosystem, and that the shared research infrastructure is the focal point for open innovation activities in the local ecosystem.

Our conceptual framework is the main theoretical contribution of this study. In our framework we combine two disciplines - open innovation and sustainability-oriented innovation – and name the central drivers and barriers for advancing those two disciplines simultaneously. In addition, we also combine semiconductor industry with innovation management. The research contributes to the academic discussion by bringing up the topic of open innovation with sustainability focus in shared research infrastructures and in local ecosystems.

The managerial implication of our study includes perspective and ideas for open innovation for sustainability related activities in local ecosystems like the shared semiconductor infrastructure. Our results highlight the complexity of the topic in the semiconductor industry and serves as an intermediator between organisational units. Our results also highlight the importance of considering sustainability proactively in the local ecosystem, for example through open innovation. Managers can use our findings to initiate various SOI actions as well as possible drivers and barriers related to these actions in their organizations.

Regarding its limitations, this empirical research is based on case study of one innovation ecosystem undergoing a co-evolution state

within the shared research infrastructure. Thus, the empirical findings are tentative and not generalizable. Instead, they open avenues for further studies. Therefore, further research is needed to continue by conducting a complementary investigation into other (international) open innovation or SOI ecosystems in the context of semiconductor industry. Doing so can help support the implementation of the ecosystemic changes that are needed in the semiconductor industry to gain the increasing pressures towards sustainability. Interesting topics for further research include how to extract value from open innovation for sustainability and SOI in general in shared research infrastructures and how to motivate the user companies to commonly engage into SOI activities in the local ecosystem, and what kind of open innovation activities with sustainability focus the user companies actually engage into.

Ethical statement

The research plan and dataprotection plan for the research was reviewed together with the Dataprotection Officer of the authors' organization prior to starting the research. Consent to the research was received from all participants. This research did not require institutional review board approval because it does not deal with patient information neither with animal testing. The authors do not have conflict of interests related to this study, neither have they received funding or the study.

CRediT authorship contribution statement

Piia Konstari: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Katri Valkokari:** Supervision, Methodology, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Adams, R., Jeanrenaud, S., Bessant, J., Denyer, D., Overy, P., 2016. Sustainability-oriented innovation: a systematic review. Int. J. Manag. Rev. *18* (2), 180–205. https://doi.org/10.1111/ijmr.12068.

Ahmadi-Gh, Z., Bello-Pintado, A., 2022. Why is manufacturing not more sustainable? The effects of different sustainability practices on sustainability outcomes and competitive advantage. J. Clean. Prod. *337*, 130392. https://doi.org/10.1016/j.jclepro.2022.130392.

Aisjah, S., Arsawan, I.W.E., Suhartanto, D., 2023. Predicting SME's business performance: Integrating stakeholder theory and performance based innovation model. J. Open Innov.: Technol., Mark., Complex. *9* (3), 100122. https://doi.org/10.1016/j.joitmc.2023.100122.

Arsawan, I.W.E., Koval, V., Suhartanto, D., Harbar, Z., Maslennikov, Y., 2022. EMPLOYEE-DRIVEN INNOVATION CAPABILITY: THE ROLE OF KNOWLEDGE, CREATIVITY, AND TIME SUFFICIENCY. Intellect. Econ. *16* (2), 138–165. https://doi.org/10.13165/IE-22-16-2-08.

Benvenuto, M., Aufiero, C., Viola, C., 2023. A systematic literature review on the determinants of sustainability reporting systems. Heliyon *9* (4). https://doi.org/10.1016/j.heliyon.2023.e14893.

Berberi, A., Beaudoin, C., McPhee, C., Guay, J., Bronson, K., Nguyen, V.M., 2023. Enablers, barriers, and future considerations for living lab effectiveness in environmental and agricultural sustainability transitions: a review of studies evaluating living labs. Local Environ. https://doi.org/10.1080/13549839.2023.2238750.

Beyer, K., 2022. Barriers to innovative activity of enterprises in the sustain development in times of crisis. Procedia Comput. Sci. *207*, 3140–3148. https://doi.org/10.1016/j.procs.2022.09.372.

Bigliardi, B., Filippelli, S., 2022. Sustainability and open innovation: main themes and research trajectories. Sustainability *14* (11), 6763. https://doi.org/10.3390/su14116763.

Bogers, M., Chesbrough, H., Strand, R., 2020. Sustainable open innovation to address a grand challenge. Br. Food J. *122* (5), 1505–1517. https://doi.org/10.1108/BFJ-07-2019-0534.

Bouwma, I., Wigboldus, S., Potters, J., Selnes, T., van Rooij, S., Westerink, J., 2022. Sustainability transitions and the contribution of living labs: a framework to assess collective capabilities and contextual performance. Sustain. (Switz.) *14* (23). https://doi.org/10.3390/su142315628.

Bowen, S.K., Kigyeni, J., Constable, S., Mundoma, C., 2022. A Shift in Our Thinking: Reframing Shared Research Resources as Investments in Education and Innovation, Not Subsidized Science, 3fc1f5fe.f1e46498 J. Biomol. Tech.: JBT *33* (4). https://doi.org/10.7171/3fc1f5fe.f1e46498.

Boyd, S.B., 2012. Semiconductor LCA: The Road Ahead. *Life-Cycle Assessment of Semiconductors*. Springer New York, pp. 109–112. https://doi.org/10.1007/978-1-4419-9988-7_8.

Brun, A., Ciccullo, F., 2022. Factors affecting sustainability-oriented innovation in the leather supply chain. Strateg. Change *31* (3), 305–321. https://doi.org/10.1002/jsc.2500.

Cano, J.A., Londoño-Pineda, A., 2020. Scientific Literature Analysis on Sustainability with the Implication of Open Innovation. J. Open Innov.: Technol., Mark., Complex. *6* (4), 162. https://doi.org/10.3390/joitmc6040162.

Cartwright, H.N., Hobson, C.M., Chew, T.-L., Reiche, M.A., Aaron, J.S., 2024. The challenges and opportunities of open-access microscopy facilities. J. Microsc. *294* (3), 386–396. https://doi.org/10.1111/jmi.13176.

Chesbrough, H.W., 2003. The era of open innovation. MIT Sloan Manag. Rev. *44* (3), 35–41.

Chistov, V., Aramburu, N., Carrillo-Hermosilla, J., 2021. Open eco-innovation: A bibliometric review of emerging research. J. Clean. Prod. *311*, 127627. https://doi.org/10.1016/j.jclepro.2021.127627.

Cholez, C., Pauly, O., Mahdad, M., Mehrabi, S., Giagnocavo, C., Bijman, J., 2023. Heterogeneity of inter-organizational collaborations in agrifood chain sustainability-oriented innovations. Agric. Syst. *212*, 103774. https://doi.org/10.1016/j.agsy.2023.103774.

Congressional Research Service Report R47508. (2023). *Semiconductors and the Semiconductor Industry*. https://crsreports.congress.gov (accessed 26 July 2024).

Dahlander, L., Gann, D.M., 2010. How open is innovation? Res. Policy *39* (6), 699–709. https://doi.org/10.1016/j.respol.2010.01.013.

Eisenhardt, K.M., 1989. Building Theories from Case Study Research. *Source.: Acad. Manag. Rev.* Vol. 14 (Issue 4). ⟨https://www.jstor.org/stable/258557⟩.

Escobar, A., Luna, J., Caraballo, A., 2023. Barriers to sustainable green innovation in meeting the challenges of the global economy of firms. Glob. J. Environ. Sci. Manag. *9* (SI), 219–232. https://doi.org/10.22034/GJESM.2023.09.SI.13.

Fifka, M.S., 2014. Sustainability Reporting: A Challenge Worthwhile. *CSR, Sustain., Ethics Gov.* https://doi.org/10.1007/978-3-642-38753-1_16.

Ghassim, B., Foss, L., 2020. How Do Leaders Embrace Stakeholder Engagement for Sustainability-Oriented Innovation? *New Leadership in Strategy and Communication*. Springer International Publishing, pp. 63–80. https://doi.org/10.1007/978-3-030-19681-3_6.

Grimaldi, M., Greco, M., Cricelli, L., 2021. A framework of intellectual property protection strategies and open innovation. J. Bus. Res. *123*, 156–164. https://doi.org/10.1016/j.jbusres.2020.09.043.

Harsanto, B., Mulyana, A., Faisal, Y.A., Shandy, V.M., Alam, M., 2023. Sustainability Innovation in Small Medium Enterprises (SMEs): A Qualitative Analysis. Qual. Rep. *28* (11), 3257–3271. https://doi.org/10.46743/2160-3715/2023.6193.

Heinemann, E. (2020). The value of network sustainability: Why we join research infrastructures. *22nd International Conference on Electronic Publishing - Connecting the Knowledge Commons: From Projects to Sustainable Infrastructure*, ELPUB 2018.

Helman, J., Rosienkiewicz, M., Molasy, M., Cholewa, M., 2021. Infrastructure Sharing Model as a Support for Sustainable Manufacturing. *Smart Innov., Syst. Technol.* Vol. 200, 71–80. https://doi.org/10.1007/978-981-15-8131-1_7.

Hockberger, P., Meyn, S., Nicklin, C., Tabarini, D., Turpen, P., Auger, J., 2013. Best Practices for Core Facilities: Handling External Customers. jbt.13-2402-001 J. Biomol. Tech.: JBT *24* (2). https://doi.org/10.7171/jbt.13-2402-001.

Hsieh, S., Lin, P.-Y., Lin, I.-H., Beck, D.E., Lin, C.-H., 2023. Assessing the contribution of semiconductors to the sustainable development goals (SDGs) from 2017 to 2022. Heliyon *9* (11), e21306. https://doi.org/10.1016/j.heliyon.2023.e21306.

Hueske, A.-K., Guenther, E., 2021. Multilevel barrier and driver analysis to improve sustainability implementation strategies: Towards sustainable operations in institutions of higher education. J. Clean. Prod. *291*, 125899. https://doi.org/10.1016/j.jclepro.2021.125899.

Huggins, R., Johnston, A., Munday, M., Xu, C., 2023. Competition, open innovation, and growth challenges in the semiconductor industry: the case of Europe's clusters. Sci. Public Policy *50* (3), 531–547. https://doi.org/10.1093/scipol/scad005.

Hung, H.-C., Chiu, Y.-C., Wu, M.-C., 2017. Analysis of Competition between IDM and Fabless-Foundry Business Models in the Semiconductor Industry. IEEE Trans. Semicond. Manuf. *30* (3), 254–260. https://doi.org/10.1109/TSM.2017.2699739.

Jürgens, A., Tedeschi, G., D'Errico, G., Kilian, K., Zawadzki, K., Daniel, O., Leibfried, A., Poschet, G., Lau, L., Helm-Petersen, N., 2024. Navigating the frontier: research infrastructures, core facilities and a new paradigm at European Universities. Cogent Educ. *11* (1). https://doi.org/10.1080/2331186X.2024.2365613.

Kimpimäki, J.-P., Malacina, I., Lähdeaho, O., 2022. Open and sustainable: An emerging frontier in innovation management? Technol. Forecast. Soc. Change *174*. https://doi.org/10.1016/j.techfore.2021.121229.

Krasnokutska, N., Merino, A., Escudero Guirado, C., Díaz-Carmona, E.M., 2024. Open innovation for sustainability in the agri-food sector: why, who and how? Eur. J. Innov. Manag. https://doi.org/10.1108/EJIM-09-2023-0766.

Krishnan, N., Boyd, S., Somani, A., Raoux, S., Clark, D., Dornfeld, D., 2008. A hybrid life cycle inventory of nano-scale semiconductor manufacturing. Environ. Sci. Technol. *42* (8). https://doi.org/10.1021/es071174k.

Kuo, T.-C., Kuo, C.-Y., Chen, L.-W., 2022. Assessing environmental impacts of nanoscale semi-conductor manufacturing from the life cycle assessment perspective. Resour., Conserv. Recycl. *182*, 106289. https://doi.org/10.1016/j.resconrec.2022.106289.

Kurniawati, A., Sunaryo, I., Wiratmadja, I.I., Irianto, D., 2022. Sustainability-Oriented Open Innovation: A Small and Medium-Sized Enterprises Perspective. J. Open

Innov.: Technol., Mark., Complex. *8* (2), 69. https://doi.org/10.3390/JOITMC8020069.
Kurrahman, T., Tsai, F.M., Jeng, S.Y., Chiu, A.S., Wu, K.J., Tseng, M.L., 2024. Sustainable development performance in the semiconductor industry: A data-driven practical guide to strategic roadmapping. J. Clean. Prod. *445*, 141207. https://doi.org/10.1016/J.JCLEPRO.2024.141207.
Lamsal, R.R., Devkota, A., Bhusal, M.S., 2023. Navigating Global Challenges: The Crucial Role of Semiconductors in Advancing Globalization. J. Inst. Eng. (India): Ser. B *104* (6), 1389–1399. https://doi.org/10.1007/s40031-023-00938-4.
Law, K.M.Y., Gunasekaran, A., 2012. Sustainability development in high-tech manufacturing firms in Hong Kong: Motivators and readiness. Int. J. Prod. Econ. *137* (1), 116–125. https://doi.org/10.1016/j.ijpe.2012.01.022.
Lee, J.Y., Shin, S.-J., Lee, Y.T., Libes, D., 2015. Toward development of a testbed for sustainable manufacturing. Concurr. Eng. Res. Appl. *23* (1), 64–73. https://doi.org/10.1177/1063293X14559527.
Lee, Y.-C., Dervishi, I., Mousa, S., Safiullin, K.I., Ruban-Lazareva, N.V., Kosov, M.E., Ponkratov, V.V., Pozdnyaev, A.S., Mikhina, E.V., Elyakova, I.D., 2023. Sustainable Development Adoption in the High-Tech Sector: A Focus on Ecosystem Players and Their Influence. Sustainability *15* (18), 13674. https://doi.org/10.3390/su151813674.
Liedtke, C., Jolanta Welfens, M., Rohn, H., Nordmann, J., 2012. LIVING LAB: User-driven innovation for sustainability. Int. J. Sustain. High. Educ. *13* (2), 106–118. https://doi.org/10.1108/14676371211211809.
Lin, Y.-S., Chien, C.-F., Chou, D., 2022. UNISON decision framework for hybrid optimization of wastewater treatment and recycle for Industry 3.5 and cleaner semiconductor manufacturing. Resour., Conserv. Recycl. *182*, 106282. https://doi.org/10.1016/j.resconrec.2022.106282.
McKinsey & Company. (2022). *Keeping the semiconductor industry on the path to net zero*. https://www.mckinsey.com/industries/semiconductors/our-insights/keeping-the-semiconductor-industry-on-the-path-to-net-zero (accessed 20 April 2024).
McKinsey & Company. (2024). *Exploring new regions: The greenfield opportunity in semiconductors*. https://www.mckinsey.com/industries/semiconductors/our-insights/exploring-new-regions-the-greenfield-opportunity-in-semiconductors (accessed 20 April 2024).
Milana, E., Ulrich, F., 2022. Do open innovation practices in firms promote sustainability? Sustain. Dev. *30* (6), 1718–1732. https://doi.org/10.1002/sd.2337.
Miranda, L.F., Cruz-Cázares, C., Saunila, M., 2023. Towards a comprehensive framework to analyse the benefits of openness for sustainability-oriented innovation: A systematic literature review. Sustain. Dev. *31* (6), 4019–4038. https://doi.org/10.1002/sd.2581.
Mitra, P.K., Agrawal, V., Ghosh, A., 2014. Exploring the Factors for Effective Sustainability Reporting: A Survey of Indian Chemical Industry. Asian Soc. Sci. *11* (3), 197–211. https://doi.org/10.5539/ass.v11n3p197.
Moursellas, A., Malesios, C., Skouloudis, A., Evangelinos, K., Dey, P.K., 2024. Perceived enablers and barriers impacting sustainability of small-and-medium sized enterprises: A quantitative analysis in four European countries. Environ. Qual. Manag. *33* (3), 433–448. https://doi.org/10.1002/tqem.22128.
Nagapurkar, P., Nandy, P., Nimbalkar, S., 2023. Cleaner chips: decarbonization in semiconductor manufacturing. Sustainability *16* (1), 218. https://doi.org/10.3390/su16010218.
Neri, A., Cagno, E., Trianni, A., 2021. Barriers and drivers for the adoption of industrial sustainability measures in European SMEs: Empirical evidence from chemical and metalworking sectors. Sustain. Prod. Consum. *28*, 1433–1464. https://doi.org/10.1016/j.spc.2021.08.018.
Olanipekun, A.O., Omotayo, T., Saka, N., 2021. Review of the Use of Corporate Social Responsibility (CSR) Tools. Sustain. Prod. Consum. *27*, 425–435. https://doi.org/10.1016/j.spc.2020.11.012.
Oliveira, X.L.C., Olave, M.E.L., Moreno, E.D., Silva, G., 2019. Open innovation in the semiconductor industry: analysis of Brazilian design houses. Innov. Manag. Rev. *17* (2), 133–156. https://doi.org/10.1108/INMR-02-2019-0014.
Onoda, T., Ito, Y., 2022. On the boundary of services and research collaborations in Japanese state-of-the-art academic research infrastructures. Sci. Public Policy *49* (3), 488–498. https://doi.org/10.1093/scipol/scac002.
Orellano, M., Lambey-Checchin, C., Medini, K., Neubert, G., 2021. A methodological framework to support the sustainable innovation development process: a collaborative approach. Sustainability *13* (16), 9054. https://doi.org/10.3390/su13169054.
Osorno-Hinojosa, R., Koria, M., Ramírez-Vázquez, D. del C., Calvario, G., 2023. Designing Platforms for Micro and Small Enterprises in Emerging Economies: Sharing Value through Open Innovation. Sustainability *15* (14), 11460. https://doi.org/10.3390/su151411460.
Pan, Y., Song, Y., Zhang, C.-C., Zhu, Q., Wu, J., 2024. Semiconductor industry's transformation path under circular economy: Evidence from micro-level efficiency evaluation. Comput. Ind. Eng. *189*, 109934. https://doi.org/10.1016/j.cie.2024.109934.
Pelcat, M. (2023). *GHG emissions of semiconductor manufacturing in 2021*. https://hal.science/hal-04112708/document (accessed 19 July 2024).
Pizzi, S., Venturelli, A., Caputo, F., 2024. Restoring trust in sustainability reporting: the enabling role of the external assurance. Curr. Opin. Environ. Sustain. *68*, 101437. https://doi.org/10.1016/j.cosust.2024.101437.
Qi, E., Luo, T., Wick, M., Armer, H., Raiford, M., Marteniz, T., Mittal, S., 2024. Sustainability Model for Semiconductor Manufacturing. 35th Annu. SEMI Adv. Semicond. Manuf. Conf. (ASMC) *2024*, 1–4. https://doi.org/10.1109/ASMC61125.2024.10545500.
Robaeyst, B., Baccarne, B., Duthoo, W., Schuurman, D., 2021. The City as an Experimental Environment: The Identification, Selection, and Activation of Distributed Knowledge in Regional Open Innovation Ecosystems. Sustainability *13* (12), 6954. https://doi.org/10.3390/su13126954.
Rodríguez-Espíndola, O., Cuevas-Romo, A., Chowdhury, S., Díaz-Acevedo, N., Albores, P., Despoudi, S., Malesios, C., Dey, P., 2022. The role of circular economy principles and sustainable-oriented innovation to enhance social, economic and environmental performance: Evidence from Mexican SMEs. Int. J. Prod. Econ. *248*, 108495. https://doi.org/10.1016/j.ijpe.2022.108495.
Ruberti, M., 2023. The chip manufacturing industry: Environmental impacts and eco-efficiency analysis. Sci. Total Environ. *858* (Pt 2)), 159873. https://doi.org/10.1016/j.scitotenv.2022.159873.
Schöggl, J.-P., Baumgartner, R.J., O'Reilly, C.J., Bouchouireb, H., Göransson, P., 2024. Barriers to sustainable and circular product design – A theoretical and empirical prioritisation in the European automotive industry. J. Clean. Prod. *434*, 140250. https://doi.org/10.1016/j.jclepro.2023.140250.
Semi. (2023). *SCOPE 3 CATEGORY 1 GHG ASSESSMENT GUIDELINE FOR THE SEMICONDUCTOR SECTOR SEMI-Semiconductor Climate Consortium (SCC)*. https://www.semi.org/sites/semi.org/files/2024-01/SCC%20Prospectus%20Jan%202024.pdf (Accessed 20 April 2024).
Settembre Blundo, D., García-Muiña, F.E., Pini, M., Volpi, L., Siligardi, C., Ferrari, A.M., 2019. Sustainability as source of competitive advantages in mature sectors. Smart Sustain. Built Environ. *8* (1), 53–79. https://doi.org/10.1108/SASBE-07-2018-0038.
Shin, N., Kraemer, K.L., Dedrick, J., 2017. R&D and firm performance in the semiconductor industry. Ind. Innov. *24* (3), 280–297. https://doi.org/10.1080/13662716.2016.1224708.
Strom, T.A., Haugstad, G., Shu, J., Seshadri, R., 2020. Shared instrumentation facilities: Benefiting researchers and universities, and sustaining research excellence. MRS Bull. *45* (5), 331–335. https://doi.org/10.1557/mrs.2020.130.
Thijssens, T., Bollen, L., Hassink, H., 2016. Managing sustainability reporting: many ways to publish exemplary reports. J. Clean. Prod. *136*, 86–101. https://doi.org/10.1016/j.jclepro.2016.01.098.
Tura, N., 2018. Value creation for sustainability-oriented innovations: challenges and supporting methods. Acta Univ. Lappeenrantaensis 799. LUT Yliop. 2018.
Tura, N., Hanski, J., Ahola, T., Ståhle, M., Piiparinen, S., Valkokari, P., 2019. Unlocking circular business: A framework of barriers and drivers. J. Clean. Prod. *212*, 90–98. https://doi.org/10.1016/j.jclepro.2018.11.202.
Urbinati, A., Shams Esfandabadi, Z., Messeni Petruzzelli, A., 2023. Assessing the interplay between Open Innovation and Sustainability-Oriented Innovation: A systematic literature review and a research agenda. Bus. Ethics, Environ. Responsib. *32* (3), 1078–1095. https://doi.org/10.1111/beer.12540.
Van der Ploeg, l, Vanclay, f, 2013. Credible claim or corporate spin?: a checklist to evaluate corporate sustainability reports. J. Environ. Assess. Policy Manag. *15* (03), 1350012. https://doi.org/10.1142/S1464333213500129.
Varadarajan, R., 2017. Innovating for sustainability: a framework for sustainable innovations and a model of sustainable innovations orientation. J. Acad. Mark. Sci. *45* (1), 14–36. https://doi.org/10.1007/s11747-015-0461-6.
Vigoroso, L., Sorrenti, R., Cavallo, E., Caffaro, F., 2023. Non-Profit Organizations as Facilitators of the Sustainable Social Innovation of Firms: An Italian Case Study. Sustain. (Switz.) *15* (10). https://doi.org/10.3390/su15108058.
Villard, A., Lelah, A., Brissaud, D., Mantelli, M., 2012. An eco-design tool for manufacturers of semiconductor technologies: Looking for environmental opportunities in the design phase. IEEE Int. Symp. . Sustain. Syst. Technol. (ISSST) *2012*, 1–6. https://doi.org/10.1109/ISSST.2012.6228013.
VTT Micronova webpage (2024). https://www.vttresearch.com/en/ourservices/micronova-sustainable-multi-user-semiconductor-rd-piloting-environment (accessed 26 July 2024).
Wang, Q., Huang, N., Chen, Z., Chen, X., Cai, H., Wu, Y., 2023. Environmental data and facts in the semiconductor manufacturing industry: An unexpected high water and energy consumption situation. Water Cycle *4*, 47–54. https://doi.org/10.1016/j.watcyc.2023.01.004.
Watson, R., Wilson, H.N., Macdonald, E.K., 2020. Business-nonprofit engagement in sustainability-oriented innovation: What works for whom and why? J. Bus. Res. *119*, 87–98. https://doi.org/10.1016/j.jbusres.2018.11.023.
Yang, F., Luo, C., Pan, L., 2024. Do digitalization and intellectual capital drive sustainable open innovation of natural resources sector? Evidence from China. Resour. Policy *88*, 104345. https://doi.org/10.1016/j.resourpol.2023.104345.
Yin, R.K., 2018. *Case study Research and Applications* (Sixth Edition). SAGE Publications, Inc.
Yoo, Y., Cho, K., 2024. Key traits of leading sustainable firms in the semiconductor industry. Sustain. (Switz.) *16* (11). https://doi.org/10.3390/su16114563.

Publication III

Konstari, P., and Valkokari, K.
Value creation and capture from sustainability-oriented innovations in a shared semiconductor infrastructure

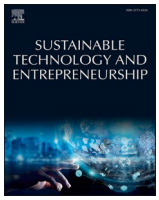
Reprinted with permission from
Sustainable Technology and Entrepreneurship
4, 100104

Sustainable Technology and Entrepreneurship 4 (2025) 100104

Contents lists available at ScienceDirect

Sustainable Technology and Entrepreneurship

journal homepage: www.journals.elsevier.com/sustainable-technology-and-entrepreneurship



Full Length Article

Value creation and capture from sustainability-oriented innovations in a shared semiconductor infrastructure

Piia Konstari [a,*], Katri Valkokari [b]

[a] Microelectronics and quantum technology, VTT Technical Research Centre of Finland, PO Box 1000 FI-02044, VTT, Finland
[b] Foresight and data economy, VTT Technical Research Centre of Finland, PO Box 1300 FI-33101, Tampere, Finland

ARTICLE INFO

Keywords:
Sustainability
Sustainability-oriented innovation
Value creation
Value capture
Shared infrastructure
Entrepreneurship

ABSTRACT

A shared semiconductor research infrastructure can be studied as a local innovation ecosystem consisting of an infrastructure-operating company and user companies. This study focuses on investigating the forms of sustainable value that such infrastructure provides for its users, as well as value creation and capture from sustainability-oriented innovation activities in a shared infrastructure. The research was conducted as a qualitative multiple-case study in a Finnish semiconductor innovation ecosystem at the end of 2023. It shows that the shared infrastructure provided users with environmental, social, and economic forms of sustainable value. The study also provides evidence that value creation from sustainability-oriented innovations takes place at three levels—operational, organizational, and system—in a shared infrastructure. The value is then captured through an increase in company value, user company business growth, and business expansion through open innovation, consumption data availability, best practice dissemination, and knowledge development, as well as new entrepreneurial opportunities by the infrastructure-operating company. This study contributes to the discussion and understanding of value creation and capture from sustainability-oriented innovations in the semiconductor industry. The results can be used by entrepreneurs, decision-makers, and management to understand how they can capture value from sustainability-oriented actions.

Introduction

Sustainability is a growing topic of discussion in the semiconductor industry. Several companies in this ecosystem have made net zero promises and are now looking for ways to deliver them. According to leading consulting companies, their efforts center on a sustainable supply chain and on reducing greenhouse gas (GHG) emissions (McKinsey & Company, 2022, 2023, 2024; Semi, 2023). At the same time, there is an ongoing discussion in Europe on possible new legislation to ban perfluoroalkyl and polyfluoroalkyl substances—materials that are crucial for the fabrication of today's semiconductor devices (European Chemical Agency, 2024; European Semiconductor Industry Association, 2023). Due to these trends, sustainability-oriented innovation (SOI) is a topic gaining in urgency for the semiconductor industry.

Semiconductor infrastructure is cost intensive, and only large companies can afford proper fabrication facilities. Small and medium-sized companies (SMEs) typically use shared infrastructure for product development and piloting or small-volume fabrication. The resources available to SMEs and large companies for sustainability-related actions vary, with SMEs typically having limited resources, expertise, and financial means (Álvarez Jaramillo et al., 2019). Konstari and Valkokari (2024) studied a Finnish shared semiconductor infrastructure and presented the drivers of and barriers to companies that used the infrastructure to engage in open innovation for sustainability-related activities. The environmental sustainability of the semiconductor industry was discussed by Ruberti (2023) and Wang et al. (2023).

It has been proven that SOIs can result in value creation (Hermundsdottir & Aspelund, 2021), and questions of how and why companies should include sustainability in their business models have been addressed (Ademi et al., 2024). Green innovations and products can give companies a competitive advantage (Al-Abdallah & Al-Salim, 2021), and environmental sustainability–related initiatives positively affect company value (García-Sánchez et al., 2020; Geiszler et al., 2018). SOIs in large companies and SMEs have been studied widely (Klewitz & Hansen, 2014). Drivers for engagement in sustainability practices in organizations have been identified as personal, organizational, and contextual (Lazarte-Aguirre, 2024).

* Corresponding author.
E-mail address: piia.konstari@vtt.fi (P. Konstari).

https://doi.org/10.1016/j.stae.2025.100104
Received 18 November 2024; Accepted 25 February 2025
Available online 25 February 2025

It has been indicated that living labs play a central role in driving innovation, sustainability, and the process of value cocreation (Compagnucci et al., 2021). Thus, it is important to consider sustainability both at the company and ecosystem levels so that the internal goals of all stakeholders as well as the larger system can be achieved with business models for sustainability (Dormeier et al., 2024). However, it is a challenge to create and capture value in open eco-innovation networks due to the low return on investment (Garcia et al., 2019). It is possible for competitors to collectively drive for sustainability through coopetition-based and value-based networks, solve problems collectively, and create new value (Rodríguez et al., 2024). The business case of living labs depends on two things: the value of being part of a living lab and the development and maintenance of the infrastructure itself (Burbridge et al., 2017).

There has been a topical discussion on the impact of businesses on sustainable development goals (SDGs) (Suárez Giri & Sánchez Chaparro, 2023) as well as on sustainable supply chain management (Mugoni et al., 2024). The discussion on the sustainability of the semiconductor industry follows the same trends, with much of it currently surrounding green energy (Liu et al., 2024), green supply chains (Song & Dong, 2024), efficient manufacturing (Narayanaswamy & Muthusamy, 2011; Qi et al., 2024), waste management (Shen et al., 2018), sustainability balanced scorecards (Hsu et al., 2011), and the fact that semiconductors contribute significantly to the SDGs (Hsieh et al., 2023; Liu et al., 2024). High-performing semiconductor companies emphasize sustainable development across the entire industry ecosystem rather than focusing solely on internal sustainability aspects (Yoo & Cho, 2024).

In summary, the approaches taken so far have concentrated more on elements of sustainability than on trying to combine several disciplines to analyze execution, practices, and behaviors. Because there seems to be no prior research on the topic of value creation and capture from SOIs in the context of the semiconductor industry, there is a clear research gap to be filled. Likewise, there has been no research exploring issues regarding shared infrastructure in technology-intensive industries with several entrepreneurs working side by side, nor have the entrepreneurial opportunities that SOIs offer been studied. The lack of case studies and practical examples is obvious.

Nordic countries and companies are recognized for their sustainability practices and are considered forerunners not only for advancing sustainability but also for being living lab pioneers (Leminen et al., 2021; Strand, 2024). Hence, it is of interest to dig deeper into the sustainability-oriented views and actions of Finnish semiconductor companies in a shared infrastructure.

This study focuses on value creation and capture from SOIs in a Finnish semiconductor innovation ecosystem at the end of 2023 and explores entrepreneurial opportunities from practical SOI activities. This shared semiconductor infrastructure forms an interesting open innovation environment (Chesbrough, 2003) in which personnel work side by side—something that is unique at this scale in the technology-intensive semiconductor industry—and is an embodiment of a living lab in the semiconductor context. Users share both the facility and fabrication equipment and sporadically encounter other users during their work, which allows for information exchange.

The objective of this study is to cover part of the research gap regarding case studies and gain new understanding of what shared infrastructure means for entrepreneurs from a sustainability perspective in addition to the practical value creation and capture methods of SOIs in shared infrastructure with multiple user companies in the semiconductor industry. The two research questions are as follows:

RQ1. *What sustainable values does shared semiconductor infrastructure represent for user companies?*

RQ2. *How can value from SOI actions be created and captured by the actors in the innovation ecosystem under study?*

A qualitative multiple-case study was chosen as the research method for this study. Data were collected through semi-structured interviews conducted at the end of 2023 with the companies described by Konstari and Valkokari (2024) in the Finnish shared semiconductor infrastructure.

The research topic is highly relevant for stakeholders such as entrepreneurs, funding organizations, research and technology infrastructure operators, research organizations, and academia to understand the dynamics of the field and to be able to act accordingly.

The main findings include evidence of what forms of sustainable value shared infrastructure represents for user companies, as well as how such infrastructure enables value creation and capture from SOIs for individual actors. The results represent the views of one Finnish semiconductor innovation ecosystem users and cannot be generalized. Further research is required to compare the results of this study to those of other semiconductor ecosystems in Europe and worldwide and to dig deeper into shared infrastructure models for SOI.

The structure of this article is as follows. Section 2 presents the research framework and a review of the most relevant findings from the literature. Section 3 includes the methodology, describing the procedures and the sample used in this study. Section 4 presents the key findings of the research and discusses them. Section 5 concludes the study.

Literature review

This section presents prior research that is most relevant to this study. The term “sustainable value” refers to the forms of economic, social, and environmental value that shared infrastructure provides its users (Evans et al., 2017). The term “value from SOIs” refers to the business creation of SOI activities within this infrastructure.

Sustainability-oriented innovations and sustainable value

The most common divisions of SOI are operational optimization, organizational transformation, and system building (Adams et al., 2016). SOIs are crucial for long-term environmental, social, and economic objectives because they integrate ecological and social factors into products, processes, and organizational structures to minimize environmental impact and benefit communities while keeping companies profitable (Dőry, 2023).

The sustainability transition has been identified as place specific, and inter-organizational relations are of great importance (Hansen & Coenen, 2015). In addition, collaboration among stakeholders such as governments, private sectors, and research institutions is important for advancing SOI (Sarkis et al., 2010). In contrast to large enterprises, achieving sustainability can be challenging for SMEs, which deal with limited product ranges, capital assets, and human resources. A solution could be to engage with external actors, such as government institutions, larger areas of the private sector, and other SMEs (Mukaromah et al., 2023).

The theoretical perspectives of business model innovations for sustainability that lead to companies’ better economic, environmental, and social performance have been discussed in the literature, and sustainable value has been defined to include economic, environmental, and social values (Evans et al., 2017). It has been suggested that the most important function of business models between innovation and value outcomes includes iterative intermediation and alignment between different areas of firms and their businesses as well as different social actors (Lüdeke-Freund, 2020).

Value creation and capture from sustainability

The creation of sustainable value for all stakeholders is challenging because it requires companies to deliver value to shareholders without taking it away from other stakeholders. Traditionally, economic added value has been used to evaluate supply chain performance. However, to

generate sustainable value, companies must also address environmental and societal impacts, since these are crucial areas in which value can be gained or lost for other stakeholders (Badurdeen et al., 2013; Cabral & Gohr, 2023; Khorram Niaki & Nonino, 2018).

Companies engage in green innovation to increase efficiency or to change how they operate. The main driver for engaging in green innovation is not the aim to reduce environmental footprints but to address existing issues in the industry to ensure a profitable future through new market opportunities and an increased level of servitization (Abadzhiev et al., 2022). For example, sustainable procurement generates value for several stakeholders, including firms, suppliers, clients, investors, municipalities, schools, NGOs, and associations. This value encompasses economic, social, environmental, and ethical sustainability aspects (Boruchowitch & Fritz, 2022).

Corporate sustainability reporting, combined with green innovation and green supply chain management, has been shown to drive sustainable corporate performance, especially in SMEs (Le et al., 2022). However, the value capture method must be carefully considered since licensing product innovations can cause a loss of competitive edge for eco-innovators (Chen & Dimitrov, 2017). In general, practitioners and researchers often find it challenging to achieve a return on sustainability investment, but this is possible by taking a systematic approach (Atz et al., 2021).

Business model innovations have been identified as essential for developing sustainable business practices at both the company and system levels. These innovations generate, create, deliver, and capture economic, social, and environmental value for various stakeholders (Koistinen et al., 2018). Although the benefits of infrastructure-sharing models for sustainability have been identified, there is a lack of business models for sustainable sharing infrastructures (Helman et al., 2021). For the benefit of different stakeholders, business models for sustainability should be considered at a level higher than the company level—that is, at the system level or in networks. For success, it is important that the internal goals of all stakeholders as well as the wider system are achieved (Dormeier et al., 2024). An emerging approach to advancing sustainability and engaging various actors is for business incubators to foster networking and open innovation collaborations among entrepreneurs and external stakeholders. Sustainability-oriented business incubation is an emerging topic for both scholars and practitioners that emphasizes sustainable value creation through open innovation (Cirule & Uvarova, 2022).

Value is cocreated in ecosystems (Mbanefo & Grobbelaar, 2024), and system-level sustainable innovations often arise from networks (Breuer & Lüdeke-Freund, 2017). It is important to consider the needs of different stakeholders (Dormeier et al., 2024); likewise, innovation ecosystems should focus on evaluating value that satisfies all actors in two ways: collective orchestration and continuous search Oskam et al. (2021). It is important that innovation ecosystems create and capture value from complex value propositions (Dattée et al., 2018). Hence, companies facing complex environments tend to turn to ecosystem partners, such as research organizations or solution providers, to gain knowledge and technologies. These partners offer various types of business model innovation based on factors such as the role of companies in the innovation ecosystem and their maturity. However, the contribution of different innovation ecosystem actors to business model innovation is not always evident (Mesquita et al., 2023).

Although prior research related to value creation and capture from sustainability is significant, no previous study has addressed the forms of sustainable value that a shared infrastructure represents for its users or value creation and capture from sustainability in an innovation ecosystem consisting of a shared semiconductor infrastructure.

Methods and analysis

This section introduces the research methodology and the frameworks used for the data analysis.

Methodology

A qualitative research approach was selected as the research method since the aim was to develop new insights rather than validate existing theories or develop new ones. To investigate emerging phenomena, such as value creation and value capture from SOIs in an innovation ecosystem with multiple actors, a qualitative case study is an appropriate research methodology (Yin, 2018). A qualitative multiple-case study design was chosen as the research approach (Eisenhardt, 1989) to map the insights of user companies and synthesize their responses. Semi-structured interviews were selected as the data collection method.

Organizational research guidelines were followed, and consent for the research was received from the ethics officer following a review of the research information sheet, which covered data processing and included a plan for protecting the data.

The study was conducted in a Finnish semiconductor innovation ecosystem, which is one of the few semiconductor research infrastructures in the world that offers open access to external companies, thereby providing a unique research object. This innovation ecosystem served as an interesting research object for value creation and capture from SOIs arising from the activities and interactions of the innovation ecosystem actors.

In total, 14 out of 18 companies active in the local ecosystem were selected for this study. Four companies were excluded because they did not find the topic relevant. The selected companies were either active in the current shared infrastructure or interested in engaging in expansion. The characteristics of the selected companies and the interviewees are shown in Table 1. The establishment years of the companies have been grouped into larger time periods to guarantee anonymity. The companies were categorized as SMEs or large companies with the help of

Table 1
Interviewed companies and people.

Company	Establishment period of time	Category	Interviewees	Interview duration (minutes)
A	1990–1999	SME	CTO, quality manager	44
B	2000–2009	SME	CEO for Finland	52
C	–1989	SME	Managing director	42
D	2010–2019	Large	Senior process engineer, HR	35
E	2010–2019	Large	Head of chip production, sustainability director	28
F	2010–2019	SME	Operations manager, head of finance	35
G	2000–2009	Large	R&D technology manager, process development manager, facility manager, environmental manager	43
H	–1989	Large	Senior technology manager, quality engineer	30
I	1990–1999	SME	Managing director for Finland, research team leader	52
J	2010–2019	Large	CTO, senior process development manager, Quality engineer	43
K	2020–	SME	Fabrication lead	23
L	2020–	SME	Senior technology director	47
M	–1989	Large	Senior R&D scientist, sustainability manager	41
N	2000–2009	SME	Managing director for Finland	23

additional information from the Orbis company information portal. The SMEs were companies with an annual turnover of below €50 million and included start-ups, with headcounts ranging from 7 to 300 people. The large companies, on the other hand, had a yearly turnover of over €50 million and a headcount of over 300 people.

The interviewees nominated by the companies included employees with a variety of job functions and different levels of knowledge of the research topic, as shown in Table 1. The representatives of large companies often had direct responsibility for sustainability, while the SME representatives had a much broader range of responsibilities, with sustainability among the areas they covered. However, they were all considered by their respective companies to be the best persons to participate in the research—something that mirrors the fragmented understanding of the sustainability topic in the industry.

The research information sheet, which included details about privacy, was shared with the nominated representatives. Prior to the interviews, the interviewees provided consent to participate in the research, have their personal data processed, and be quoted in publications.

The interviews included questions about the companies' background information, involvement in the shared research infrastructure, expectations of and wishes for infrastructure and technology development, and recommendations for enhancing sustainability efforts within the research infrastructure. The semi-structured interviews were conducted via Teams in December 2023; they were recorded and transcribed into text files, which were shared with the interviewees for verification. Table 1 shows the duration of the interviews.

Afterwards, the interviewees verified their answers and, in some cases, consulted with additional internal resources to obtain more information. The returned text files were then pseudonymized and downloaded to NVivo 14 software for qualitative research. Relevant raw data were coded into the categories "sustainable value," "value creation," and "value capture" to obtain a clear overview of what the interviewees had said related to these topics and the research questions. NVivo 14 was not used for additional analysis, but the summaries of the coded parts were reviewed and analyzed by the multidisciplinary research team to bring in different perspectives and enhance theoretical triangulation.

The reliability of this research can be considered good in terms of its specific context: the interviewees had relevant positions in their companies, and the interview discussion answers started to repeat themselves. In addition, 14 out of 18 companies active in the ecosystem participated in the study, corresponding to a 78 % representation of the number of companies active in the ecosystem. The four that did not find the topic relevant were all SMEs—a fact that supports the fragmented level of sustainability understanding of SMEs (Konstari & Valkokari, 2024).

Data analysis

For the analysis of the first research question, the framework presented by Evans et al. (2017) (see Fig. 1) was adapted and complemented.

For the analysis of the second research question, SOI was categorized into operational optimization, organizational transformation, and system building, as suggested by Adams et al. (2016).

Results and discussion

In this section, the results of the multiple-case study are presented and discussed, beginning with the forms of value for sustainability mentioned by infrastructure users, followed by value creation and capture from SOIs.

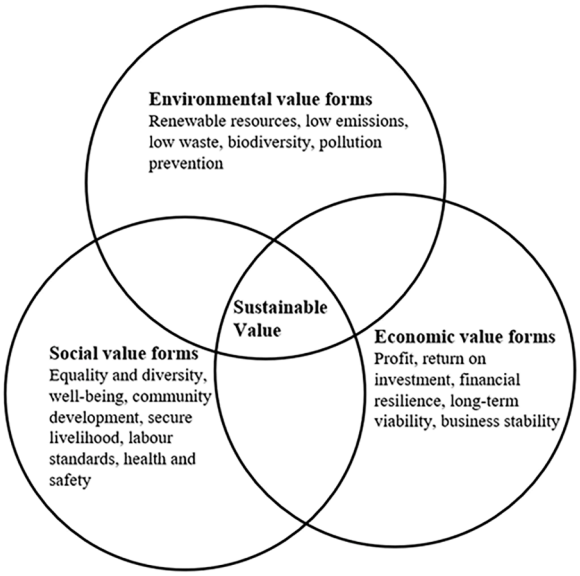


Fig. 1. Sustainable value (Evans et al., 2017).

Forms of sustainable value provided by the shared infrastructure

The framework proposed by Evans et al. (2017), shown in Fig. 1, was used to analyze the findings related to the first research question.

Forms of sustainable value were mentioned in all the interviews in the context of what shared infrastructure provided to the user companies. The findings were summarized and categorized from the semi-structured interviews by analyzing and generalizing the category coded as "sustainable value." These are shown in Table 2, where the numbers in parentheses indicate the number of companies that mentioned the form of value in question.

Table 2
Forms of sustainable value.

Economic value	Environmental value	Social value
Access to other users' tools (1)	Adequate cleanroom size with high usage rate (4)	Access to European community (1)
Business expansion (10)	Alternative and renewable energy sources (3)	Collaborative efforts and synergies (8)
Business growth (10)	Alternative materials (3)	Collective responsibility for the future (1)
Business stability and continuity (8)	Carbon emissions reduction (7)	Diversity, equality, inclusion (1)
Infrastructure for own use, either as a primary or secondary line (11)	Collective waste and wastewater handling (5)	Health and wellbeing of employees (3)
Local infrastructure (13)	New process and material development (8)	Information sharing, teaching, and learning (6)
New business through collaboration (9)	Recycling and circularity (4)	Local community and innovation ecosystem (10)
New technological solutions (12)	Reduced pollution (4)	Local sustainability benchmark (3)
Open access to equipment either as a primary or secondary line (14)	Reduction in energy, electricity, water, chemical, and raw material consumption (9)	Reliable long-term infrastructure availability (11)
Operational efficiency of infrastructure and tools (architecture, tool operation) (8)	Responsible sourcing (2)	Secure and safe place (1)
Up-to-date situational understanding (accurate measurement data enables cost savings) (7)	Reuse and recovery of, e.g., heat and cold (4)	Workplaces/ employment (3)

Forms of economic value

The most commonly mentioned forms of economic value involved access to infrastructure and equipment, enabling business stability, continuity, and growth. This was emphasized by Company E's head of chip production and Company F's operations manager, as well as Company D's senior process engineer, who said, "*We target to have our own space and also to use the [common equipment]. We want to increase capacity of R&D and of technology development.*" The shared infrastructure and open access to equipment were therefore considered to enable their entrepreneurship.

In addition, access to new technologies for business expansion to new areas was mentioned. This was emphasized especially by large companies looking to test new technologies. Company G's R&D technology manager said, "*It will be a possibility for us to evaluate new technologies before investing own tools*."

Business opportunities from the ecosystem were mentioned in two ways: in the shared semiconductor infrastructure itself and through the infrastructure operator's connections with the wider European semiconductor ecosystem. Company N's managing director said, "*Also we need to be open minded of what can be the capabilities that others can offer in the context of the ecosystem…. If they provide technologies and services that can benefit us.*" Company D's senior process engineer wished for "*increased collaboration within Europe and in Finland.*"

Forms of environmental value

The environmental value of reducing energy, electricity, water, chemical, and/or raw material consumption was raised in a number of interviews, as was the link between reporting and the reduction of such consumption.

The effective use of materials in the infrastructure was mentioned by several companies. For example, Company E's head of chip production said that the company expected "*comprehensive and advanced waste management with an emphasis on circularity. Use of carbon neutral/green energy, energy saving actions; if possible, generate part of the energy from your own renewable sources (solar, etc.).*"

Most companies had targets for carbon emission reduction and expected the infrastructure provider to help them meet the GHG emission reduction targets set forth by the supply chain, as well as provide the required data for sustainability reporting. In particular, this was pointed out by Company H's senior technology manager. Also, Company D's HR said, "*We expect that all numbers and reports should be publicly available so that we would know where we are in [infrastructure expansion] operations. Reporting should include at least electricity consumption, water handling, chemical usage, waste production—everything, in quantity. … We need to report these in* CO_2 *equivalents.*"

Forms of social value

Different forms of social value were mentioned, many of which were linked to teaching and learning about environmental topics. The ecosystem's societal responsibility as a role model for the Finnish semiconductor industry was mentioned by Company H's senior technology manager: "*We hope [infrastructure expansion] would be world leading in [terms of sustainability] and serve as an example for companies. But you need to make compromises based on cost; it cannot be world leader in all areas.*" Also, Company D called for the infrastructure operator to take societal responsibility and requested that consumption benchmark data be made openly available.

The learning side of the shared infrastructure was mentioned by Companies B and I. Company B's CEO said, "*Add more environmental awareness to training of new operators – that would have fastest impact on environmental things… Provide guidelines for tools for more environmentally friendly operation of tools - People are probably interested.*"

Collaborative and networking factors were mentioned by several companies, from both technology development and socializing perspectives. Company A's CTO said that the company wanted to use "*[equipment] for collaboration actions*." Company D's HR said, "*Then the social aspect is important; we would like to have there a break room for the people that work in the cleanroom, for example*."

Summary of discussions related to the first research question

Synthesizing the results, the shared infrastructure under study was an open-access infrastructure that enabled the existence and growth of businesses with a focus on reducing their environmental burdens, acting as focal points, knowledge sources, and innovation centers for the local industry, and connecting users to the wider semiconductor community. This aligns with the findings for living labs by Compagnucci et al. (2021). For the users, the shared infrastructure was something more than just a fabrication place; it was an open innovation ecosystem. The user companies saw a magnitude of possibilities and opportunities to collaborate and cocreate in the infrastructure.

Hence, we can complement the definition of the living lab in this specific case by including sustainable value: an open-access infrastructure that enables the existence and growth of businesses with a focus on reducing their environmental burdens, acting as focal point, knowledge source, and innovation center for the local industry, and connecting users to the wider semiconductor ecosystem.

Value creation and capture from sustainability-oriented innovations

In general, there were many remarks about value creation and capture from sustainability in the semi-structured interviews related to the second research question. The interviewees who commented most on value creation from SOIs were technical staff or environmental/quality managers, while those who commented most on value capture from SOIs were senior managers.

Value creation from sustainability-oriented innovations

The results for value creation from SOI activities are presented in Table 3 and are divided into operational optimization (infrastructure- and tool-related topics and consumption measurement–related topics), organizational transformation (new technology and process development), and system building (joint R&D projects and learning-related topics) (Adams et al., 2016). The answers are divided into two actor groups in the innovation ecosystem: the user companies and the infrastructure-operating company. The numbers in parentheses indicate the number of companies that mentioned the topic.

Operational optimization. The optimization of tools and the collective optimization of infrastructure functions were mentioned by some companies as value-creation methods through the shared infrastructure. Company C's CEO mentioned, "*It is always better to have some systems*

Table 3
Value creation from SOI actions.

	Value creation from sustainability-oriented innovation actions
By user companies	Operational optimization: optimization of the operational model (4) Organizational transformation: New process and technology evaluation and development using shared infrastructure or own tools, either alone or in collaboration with others (12) System building: Jointly funded R&D projects, collaboration, networking, learning (10)
By shared infrastructure operator	Operational optimization: Infrastructure implementation, solutions and equipment selections; joint solutions for infrastructure, building automation, waste handling (10) Organizational transformation: Evaluation of new ways to minimize the environmental burden in operations; Hosting a measurement system for consumption data tracking (8) System building: Collaboration, networking, teaching (9)

which are not tailored for individual tools but which consider larger parts of the facility. … If you can plan it for a number of tools, you can automatically plan it for systems taking care of excess heat, cleaning exhaust gases … plan for it more economically on a bigger scale." Company D's senior process engineer had a similar opinion but also mentioned collective waste handling.

The optimization of operational models was mentioned by Company G's facility manager, who said, "*Activities to minimize chemical consumption in clean room are of interest—minimization of water consumption and considering different [types of] water.*" Company K's fabrication lead was of the same opinion but highlighted the need to maximize tool usage. Company N's managing director also highlighted the importance of value creation through accurate measurement of energy and water consumption to identify hotspots and improve them. The importance of sustainability in new equipment procurement was highlighted by Company I's research team leader and Company A's CTO.

There was therefore clear interest in immediately acting to improve sustainability on the operational side through infrastructure optimization, waste handling (Shen et al., 2018), fabrication optimization (Narayanaswamy & Muthusamy, 2011; Qi et al., 2024), and considering sustainability in tool procurement (i.e., in the supply chain) (Boruchowitch & Fritz, 2022; Mugoni et al., 2024; Song & Dong, 2024). These results are therefore well aligned with both the general and semiconductor industry–specific discussions.

Organizational transformation. The user companies considered that value was created for them through the availability of tools and technologies. Company F's operations manager addressed tool availability, saying, "*We also wish that there will be new tools available in the [infrastructure] that can make availability and reliability better and will speed up our R&D.*" Company A's CTO was of the same opinion but mentioned new technology development: "*[Infrastructure expansion] will be essential for developing new state-of-the-art tools and processes and co-optimizing our own processes with other process steps*." In addition, Company G's R&D technology manager mentioned the importance of evaluating new technologies in the shared infrastructure.

Joint R&D projects with the infrastructure provider were mentioned by many companies. For example, Company M's senior R&D scientist raised this and its meaning for the company: "[C*ompany] will continue the fruitful project-based research and development co-operation. … A growing proportion of [company's] product offering is based on earlier co-development in [infrastructure], and we expect similar success stories in the future.*"

These results clearly show that companies that use a shared infrastructure create value thanks to the infrastructure and toolset offered by the shared infrastructure operator. The infrastructure also enables collaborative R&D projects in public–private partnerships or as contract research. The results are aligned with those for living labs identified by Compagnucci et al. (2021), who found that shared infrastructure creates value by enabling innovation. The results are also aligned with Mukaromah et al. (2023), who found that SMEs' sustainability benefits from engaging with external stakeholders.

System building. Joint R&D and learning through innovation networks were the two most commonly mentioned topics in the system building category. The infrastructure operator was considered to have know-how about sustainability and technology in general that the other companies were interested in receiving. These companies wanted the infrastructure operator to share knowledge about how sustainability should be considered in a semiconductor clean room with the rest of the semiconductor industry in Finland.

Company H's senior technology manager put it well: "*The biggest sustainability effect of [infrastructure expansion] on Finnish society is solutions and ideas of what can be implemented in [infrastructure expansion]; then, the info will be spread to the Finnish industry — spill-off effect.*" Hence, value would be created by knowledge diffusion from the infrastructure to the wider ecosystem. The senior technology manager continued, "*In bigger picture, [the infrastructure operator] is testing new stuff. If they are successful, then industry can implement it. You have well knowledged personnel there who concentrate on sustainability.*" Company G's R&D technology manager was of the same opinion but called for collaboration and knowledge sharing to advance sustainability in semiconductor processing.

Collaboration and open innovation were mentioned by Company D's senior process engineer: "*We can improve technology development; we are looking forward to collaboration with other companies present in [infrastructure expansion]*." Company I's research team leader went further and suggested open innovation and collaboration for the sustainability of the shared infrastructure: "*If we could reduce footprint/wafer in [the infrastructure], we would be very happy to support it by helping… We are willing to do that if there is some steps that should or could be implemented to achieve that.*"

The innovation network was also emphasized from a talent pool perspective. Company B's CEO said, "*In general, it is beneficial if more operations in semiconductor field is in same region in Finland. [There would be a] generally positive effect on new talent, more contacts to R&D and companies.*"

These results are partly in contrast with those of Abadzhiev et al. (2022), who found that companies engaged in green innovation only to increase efficiency or to change how they operated. Several companies were interested in engaging in collaborative activities to reduce the environmental footprint of the shared infrastructure, and several interviewees highlighted a personal interest in reducing environmental burdens. This is aligned with previous research that found that one of the key drivers for engagement in sustainability actions was personal motivation (Lazarte-Aguirre, 2024).

At the ecosystem level, the results are well aligned with previous findings (Compagnucci et al., 2021; Mbanefo & Grobbelaar, 2024). In addition, it was evident that the user companies trusted the infrastructure operator in delivering the required and trusted information to them when faced with the complex challenge of becoming more sustainable. This finding is in line with previous findings (Mesquita et al., 2023).

The user companies did not seem to consider that sustainability was competitive, and all indicated that collaboration for sustainability would be possible in the shared infrastructure—a result that aligns with earlier findings (Rodríguez et al., 2024). The companies did not see sustainability as part of their core business but as a complementary, noncompetitive area. This implies that the shared infrastructure was more than just an infrastructure; it was a true innovation ecosystem able to deliver results that individual user companies could not deliver separately.

Value capture from sustainability-oriented innovations

The value captured from SOI actions mentioned in the interviews can be divided into company value, user company business growth, business expansion through open innovation, consumption data availability, best practice dissemination, and knowledge development. A summary of the findings is presented in Table 4, where the number in parentheses indicates the number of companies mentioning the topic.

Company value. The value of companies today seems tightly linked to their sustainability-related actions. Company B's CEO said, "*Nowadays, it is a bad thing if a company doesn't care about environment and employees — make sure that [company] does not waste resources, protects environment, takes care of employees and also their well-being, exercises responsible use of chemicals, cares about the health of employees. A corporation cannot be attractive for shareholders if operations are not based on sustainable operations and ways of working. We must care of the company's value.*" Company D's HR was of the same opinion.

Many of the interviewees mentioned the need to comply with

Table 4
Value capture from sustainability-oriented actions.

	Value capture from sustainability-oriented innovations
By user companies	Increase in company value (shareholders) (4) Business growth (customers) (8) Business expansion through open innovation (7) Knowledge development of personnel (6) Operational efficiency (7)
By the shared infrastructure operator	Providing open-access shared infrastructure services that act as an open innovation ecosystem for sustainability-oriented innovations (14) Measuring consumption and providing user company–specific consumption data as a service (5) Best practice dissemination (3) Knowledge development and teaching (5) Innovations and IP (1)

different regulations and reporting requirements to grow company value in the eyes of shareholders, with value capture coming from the public image of the company. These results are aligned with previous findings (Ademi et al., 2024; Al-Abdallah & Al-Salim, 2021; García-Sánchez et al., 2020; Konstari & Valkokari, 2024); that is, engagement in SOIs helps in creating value for companies and gives them a competitive advantage.

Business growth. Business growth was mentioned by many companies as a value-capturing method of the shared infrastructure. Company F's operations manager said, "*Our business has developed from zero to what it is today thanks to [infrastructure].*" Company D's senior process engineer said that infrastructure expansion enabled the "*scaling up of manufacturing.*" Company J's CTO said, "*[Infrastructure] has helped us in efforts to take materials to global semiconductor industry.*" Hence, the shared infrastructure was seen as enabling profitable entrepreneurship.

Company H's senior technology manager said that if the infrastructure was not expanded, "*the biggest harm would be in the R&D department. It would decrease the number of new technologies that we develop; we would not get really any new fields. In the long run, it would decrease amount of sales in new technologies if we would not have new technologies.*" This implies that a large part of the value capture is the business generated for the user companies and the wider ecosystem. Therefore, it can be assumed that the same thing is valid for SOIs.

Company C's managing director highlighted business capture through customers' businesses: "[Having] *our tools later in the semiconductor factories will contribute a lot to their footprint. We can positively impact on that one and reduce the footprint the more and then the more we add value to our customers… [It is] important to look how our customers will use [the tools] as [the customers] are driving the bigger volume and how much impact in the final applications all these considerations these will have."* Company A's CTO said, "*We developed, together with our customers,* e.g. *more efficient … components which are essential* e.g. *for renewable energy production.*" Both interviewees implied that the main value capture from the SOIs in the shared infrastructure came through their customers' businesses.

The SOI activities in the shared infrastructure enabled the growth of existing businesses as well as the establishment of completely new entrepreneurships. The value of SOI was captured either through the companies' own businesses or through their customer's businesses.

Business expansion through open innovation. Company C's managing director mentioned value capture within the shared infrastructure from new business through open innovation activities within the shared infrastructure: "*Then we go for new developed [solutions] to really find solutions which are much more sustainable than what we have today. … Whatever is developed [in the infrastructure expansion], … we could actually spin off or transfer to other [infrastructure expansion or user] projects, start-ups, or other companies. We could be very open and interested in doing so, as long as we are from an IP perspective protected.*"

Thus, the value capture method might not always be obvious—a result that aligns with Dattée et al. (2018)—because the impacts of SOI are widespread in the supply chain and ecosystem. The IP side is an interesting topic in the open innovation context and requires a thorough balancing of the chosen approach. On the one hand, open innovation could, in this case, advance the sustainability of the local ecosystem and, even wider, result in value capture; on the other hand, the IP owner would be at risk of losing business. This risk was previously identified by Chen and Dimitrov (2017).

Consumption data. The possibility of value capture through accurate consumption measurement data was mentioned by a number of interviewees. Company B's CEO said, "*Getting environmental report and processing data from clean room has the biggest environmental footprint to [the company]. Optimizing [the infrastructure's] footprint would have biggest effect on [our company's] Finland footprint. … [We] need solid reasoning for numbers, as these numbers are published and may have impact on company value.*" Company D's HR and Company G's manager also said that they needed accurate consumption measurement data. This was clearly a value-capture opportunity for the infrastructure operator.

This finding shows that there are real business opportunities linked to sustainability for players with an entrepreneurial mindset. Many user companies requested data and said that it was crucial for them. This is linked to operational improvement, the most obvious and straightforward way of value creation and capture from SOI. However, none of the interviewees suggested that they would be ready to pay for such data, but they assumed that it would be shared with them free of charge. However, to meet the requirements of the different actors in the ecosystem (Burbridge et al., 2017; Dormeier et al., 2024; Mesquita et al., 2023; Oskam et al., 2021), a new business model for sustainability must be invented to satisfy the needs of the different actors in the ecosystem.

Best practice dissemination. The diffusion of knowledge to companies from the infrastructure operator can be considered value capture through best-practice dissemination. In this case, best practices are taken into use in the wider ecosystem. However, this approach does not capture monetary value for the infrastructure provider but for the user companies.

Company H's senior technology manager mentioned open innovation for best sustainability practices: "*We are, in general, more interested in knowledge about sustainability than in the actions of what is happening because then we can utilize that [knowledge] in our company.*" Company G's facility manager was of the same opinion, saying, "*Information should be shared with the users of [the infrastructure expansion] on, for example, efficient ways to use the energy, how to handle chemicals, new ways to reduce emissions of semiconductor factories. … To know and share information on facility level, where there are no technology-related restrictions, we need co-operation on that area.*"

These quotes bring forward the aforementioned dilemma of the user companies wanting to capture value without investments because they do not consider the sustainability of the semiconductor industry to be a competitive topic. To capture value from sustainability-oriented actions for all actors, this dilemma must be tackled and solved for wider SOI engagement and adaptation. Our findings are hence in line with earlier research (Compagnucci et al., 2021; Dormeier et al., 2024; Mesquita et al., 2023) and demonstrate a practical example of how this topic is encountered in practice.

Knowledge development. In general, knowledge development related to sustainability was mentioned by several companies as a value-capture method. Company M's senior R&D scientist said, "[C*ompany] constantly recruits personnel with microfabrication expertise. Many of them have gained support to develop their personal skills and expertise as well as, in some cases, a formal academic degree, through work years done in*

[infrastructure] facility." Hence, the knowledge that people gain about sustainability in the shared infrastructure is of advantage to them at later phases of their careers and provides the basis for long-term value capture from SOI activities in the shared infrastructure.

Another angle related to knowledge development could be deduced from the fact that the level of understanding of the interviewees varied greatly. The shared infrastructure is an innovation ecosystem enabling its participants' knowledge development thanks to encounters and knowledge sharing during daily work in the infrastructure. Hence, the innovation ecosystem takes care to decrease the risk of value uncaptured (or missed) from SOI due to a limited understanding of the sustainability topic in the companies. The innovation ecosystem thus contributes significantly to the knowledge development and innovation activities of its participants. This result aligns with previous research (Compagnucci et al., 2021; Mbanefo & Grobbelaar, 2024).

Summary of discussions related to the second research question

This section summarizes and discusses the main findings on value creation and capture from SOIs by actors in the innovation ecosystem. As shown in Table 3, the infrastructure enables value creation from SOIs at different levels: operational, organizational, and system. The value capture from these takes place through increases in company value, user company business growth, business expansion through open innovation, consumption data availability, best practice dissemination, and knowledge development, as presented in Table 4.

For sustainability to be thoroughly implemented in the semiconductor industry, the findings indicate that a change of mindset is required in similar innovation ecosystems related to value creation and capture from SOI. If sustainability is not considered a competitive advantage, it encourages actors to share information more freely but also slows down larger investments because the need for business continuity by all actors is not satisfied.

Our results are aligned with the previous understanding that it may be difficult to get companies to invest in eco-innovations because the value capture is at the societal level and not at the organizational or inter-organizational levels in which they operate (Garcia et al., 2019). Hence, a relevant question is whether tight regulation is the only way to drive companies to pay more attention to sustainability, since they must all follow the laws. In any case, new business models must be created urgently to drive further sustainability, and a mindset change is required among innovation ecosystem actors such that business must be sustainable for all parties involved, as highlighted by recent research (Dormeier et al., 2024). In this way, the biggest impact on SDGs can be achieved (Suárez Giri & Sánchez Chaparro, 2023).

Conclusions

The main theoretical contributions of the study are the combination of different perspectives of several previous studies and theories, the presentation of the forms of sustainable value of a shared semiconductor infrastructure in Table 2, and the mapping of the value created and captured from SOIs in a shared semiconductor infrastructure in Tables 3 and 4, respectively.

The results show that a shared infrastructure provides environmental, social, and economic value for sustainability to its users and enables entrepreneurship. Consequently, by addressing the needs of individual ecosystem actors, it is possible to create and capture value from SOIs for all innovation ecosystem actors and find entrepreneurial opportunities.

This article is among the first qualitative studies on SOI in semiconductor innovation ecosystems. The managerial implications of our study include perspectives on value creation and value capture from SOIs in a shared semiconductor infrastructure. Managers can use our findings to initiate various activities related to SOIs in their organizations and to understand how value can be captured from those activities. New entrepreneurs can also use the results to innovate new business models for sustainability.

As for its limitations, this qualitative research includes a multiple-case study of an innovation ecosystem constituting a shared research infrastructure. Consequently, the findings are preliminary and cannot be generalized. However, they pave the way for further studies. First, future research should focus on performing complementary investigations into other (international) innovation ecosystems within the semiconductor industry. This can help facilitate the implementation of the necessary ecosystemic changes for industry to meet the rising demands for sustainability and enable the generation of business models that favor value capture from SOIs. Another relevant future research approach would be longitudinal case studies of joint SOI activities in shared infrastructures, which would allow for a deeper analysis of shared infrastructure models for SOI.

Ethical statement

Review or approval by an ethics committee was not needed for this study because the study does neither cover patient information nor animal testing.

CRediT authorship contribution statement

Piia Konstari: Writing – original draft, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Katri Valkokari:** Supervision, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.stae.2025.100104.

References

Abadzhiev, A., Sukhov, A., Sihvonen, A., & Johnson, M. (2022). Managing the complexity of green innovation. *European Journal of Innovation Management, 25*(6), 850–866. https://doi.org/10.1108/EJIM-02-2022-0098

Adams, R., Jeanrenaud, S., Bessant, J., Denyer, D., & Overy, P. (2016). Sustainability-oriented innovation: A systematic review. *International Journal of Management Reviews, 18*(2), 180–205. https://doi.org/10.1111/ijmr.12068

Ademi, B., Sætre, A. S., & Klungseth, N. J. (2024). What do established companies do to factor in sustainability into their business models? *Business Strategy and the Environment*. https://doi.org/10.1002/bse.3980

Al-Abdallah, G. M., & Al-Salim, M. I. (2021). Green product innovation and competitive advantage: An empirical study of chemical industrial plants in Jordanian qualified industrial zones. *Benchmarking: An International Journal, 28*(8), 2542–2560. https://doi.org/10.1108/BIJ-03-2020-0095

Álvarez Jaramillo, J., Zartha Sossa, J. W., & Orozco Mendoza, G. L. (2019). Barriers to sustainability for small and medium enterprises in the framework of sustainable development— <scp>L</scp>iterature review. *Business Strategy and the Environment, 28*(4), 512–524. https://doi.org/10.1002/bse.2261

Atz, U., Van Holt, T., Douglas, E., & Whelan, T. (2021). The return on sustainability investment (ROSI): Monetizing financial benefits of sustainability actions in companies. In *Sustainable consumption and production, II* pp. 303–354). Springer International Publishing. https://doi.org/10.1007/978-3-030-55285-5_14

Badurdeen, F., Goldsby, T. J., Iyengar, D., & Jawahir, I. S. (2013). Transforming supply chains to create sustainable value for all stakeholders. In *Treatise on sustainability science and engineering, 9789400762* pp. 311–338). Springer Netherlands. https://doi.org/10.1007/978-94-007-6229-9_18

Boruchowitch, F., & Fritz, M. M. C. (2022). Who in the firm can create sustainable value and for whom? A single case-study on sustainable procurement and supply chain stakeholders. *Journal of Cleaner Production, 363*, Article 132619. https://doi.org/10.1016/j.jclepro.2022.132619

Breuer, H., & Lüdeke-Freund, F. (2017). Values-based network and business model innovation. *International Journal of Innovation Management, 21*(3). https://doi.org/10.1142/S1363919617500281

Burbridge, M., Morrison, G. M., van Rijn, M., Silvester, S., Keyson, D. V., Virdee, L., et al. (2017). Business models for sustainability in living labs. *Living labs* (pp. 391–403). Springer International Publishing. https://doi.org/10.1007/978-3-319-33527-8_30

Cabral, N. G. C., & Gohr, C. F. (2023). Sustainable value creation in sharing economy: Conceptual framework proposition and application in Brazilian offline communities. *Technological Forecasting and Social Change, 186*, Article 122124. https://doi.org/10.1016/j.techfore.2022.122124

Chen, J. Y., & Dimitrov, S. (2017). Eco-innovation with opportunity of licensing and threat of imitation. *Journal of Cleaner Production, 147*, 306–318. https://doi.org/10.1016/j.jclepro.2017.01.052

Chesbrough, H. W. (2003). The era of open innovation. *MIT Sloan Management Review, 44*(3), 35–41.

Cirule, I., & Uvarova, I. (2022). Open innovation and determinants of technology-driven sustainable value creation in incubated start-ups. *Journal of Open Innovation: Technology, Market, and Complexity, 8*(3), 162. https://doi.org/10.3390/joitmc8030162

Compagnucci, L., Spigarelli, F., Coelho, J., & Duarte, C. (2021). Living labs and user engagement for innovation and sustainability. *Journal of Cleaner Production, 289*, Article 125721. https://doi.org/10.1016/j.jclepro.2020.125721

Dattée, B., Alexy, O., & Autio, E. (2018). Maneuvering in poor visibility: How firms play the ecosystem game when uncertainty is high. *Academy of Management Journal, 61*(2), 466–498. https://doi.org/10.5465/amj.2015.0869

Dormeier, C., Mindt, N., Niemeyer, J. F., Asghari, R., & Mennenga, M. (2024). Review and framework for the engineering of business models for sustainability: A system of systems perspective. *Sustainable Production and Consumption, 51*, 1–22. https://doi.org/10.1016/j.spc.2024.08.030

Dőry, T. (2023). Key factors of sustainability-oriented innovation on competitiveness of SMEs: A review. *Chemical Engineering Transactions, 107*, 31–36. https://doi.org/10.3303/CET23107006

Eisenhardt, K. M. (1989). Building theories from case study research. In *Source: The academy of management review, 14*. https://www.jstor.org/stable/258557.

European Chemical Agency. (2024). *Per- and polyfluoroalkyl substances (PFAS)*. https://echa.europa.eu/hot-topics/perfluoroalkyl-chemicals-pfas.

European Semiconductor Industry Association. (2023). *The European semiconductor industry and pfas*. https://www.eusemiconductors.eu/sites/default/files/20230713_ESIASummaryPaper-PFAS.pdf.

Evans, S., Vladimirova, D., Holgado, M., Van Fossen, K., Yang, M., Silva, E. A., et al. (2017). Business model innovation for sustainability: Towards a unified perspective for creation of sustainable Business models. *Business Strategy and the Environment, 26*(5), 597–608. https://doi.org/10.1002/bse.1939

Garcia, R., Wigger, K., & Hermann, R. R. (2019). Challenges of creating and capturing value in open eco-innovation: Evidence from the maritime industry in Denmark. *Journal of Cleaner Production, 220*, 642–654. https://doi.org/10.1016/j.jclepro.2019.02.027

García-Sánchez, I., Gallego-Álvarez, I., & Zafra-Gómez, J. (2020). Do the ecoinnovation and ecodesign strategies generate value added in munificent environments? *Business Strategy and the Environment, 29*(3), 1021–1033. https://doi.org/10.1002/bse.2414

Geiszler, M., Muenzen, J., & Lippitt, J. (2018). The effect of environmental sustainability initiatives on firm value. *The International Journal of Sustainability in Economic, Social, and Cultural Context, 14*(3), 21–31. https://doi.org/10.18848/2325-1115/CGP/v14i03/21-31

Hansen, T., & Coenen, L. (2015). The geography of sustainability transitions: Review, synthesis and reflections on an emergent research field. *Environmental Innovation and Societal Transitions, 17*, 92–109. https://doi.org/10.1016/j.eist.2014.11.001

Helman, J., Rosienkiewicz, M., Molasy, M., & Cholewa, M. (2021). Infrastructure sharing model as a support for sustainable manufacturing. *Smart Innovation, Systems and Technologies, 200*, 71–80. https://doi.org/10.1007/978-981-15-8131-1_7

Hermundsdottir, F., & Aspelund, A. (2021). Sustainability innovations and firm competitiveness: A review. *Journal of Cleaner Production, 280*, Article 124715. https://doi.org/10.1016/j.jclepro.2020.124715

Hsieh, S., Lin, P. Y., Lin, I. H., Beck, D. E., & Lin, C. H. (2023). Assessing the contribution of semiconductors to the sustainable development goals (SDGs) from 2017 to 2022. *Heliyon, 9*(11), e21306. https://doi.org/10.1016/j.heliyon.2023.e21306

Hsu, C. W., Hu, A. H., Chiou, C. Y., & Chen, T. C. (2011). Using the FDM and ANP to construct a sustainability balanced scorecard for the semiconductor industry. *Expert Systems with Applications, 38*(10), 12891–12899. https://doi.org/10.1016/j.eswa.2011.04.082

Khorram Niaki, M., & Nonino, F. (2018). The value for sustainability. In D. T. Pham (Ed.), *The management of additive manufacturing. enhancing business value* (1st ed, pp. 67–90). Springer Nature. https://doi.org/10.1007/978-3-319-56309-1_3.

Klewitz, J., & Hansen, E. G. (2014). Sustainability-oriented innovation of SMEs: A systematic review. *Journal of Cleaner Production, 65*, 57–75. https://doi.org/10.1016/j.jclepro.2013.07.017

Koistinen, K., Laukkanen, M., Mikkilä, M., Huiskonen, J., & Linnanen, L. (2018). Sustainable system value creation: Development of preliminary frameworks for a business model change within a systemic transition process. *CSR, sustainability, ethics and governance* (pp. 105–127). https://doi.org/10.1007/978-3-319-73503-0_6

Konstari, P., & Valkokari, K. (2024). Drivers and barriers for open innovation for sustainability in a shared semiconductor infrastructure. *Journal of Open Innovation: Technology, Market, and Complexity, 10*(4), Article 100395. https://doi.org/10.1016/j.joitmc.2024.100395

Lazarte-Aguirre, A. (2024). Pathways to sustainable entrepreneurship: Analysing drivers of sustainable entrepreneurial orientation. *Sustainable Technology and Entrepreneurship, 3*(3), Article 100081. https://doi.org/10.1016/j.stae.2024.100081

Le, T. T., Vo, X. V., & Venkatesh, V. G. (2022). Role of green innovation and supply chain management in driving sustainable corporate performance. *Journal of Cleaner Production, 374*, Article 133875. https://doi.org/10.1016/j.jclepro.2022.133875

Leminen, S., Rajahonka, M., Westerlund, M., & Hossain, M. (2021). Collaborative innovation for sustainability in Nordic cities. *Journal of Cleaner Production, 328*, Article 129549. https://doi.org/10.1016/j.jclepro.2021.129549

Liu, Y. Z., Lu, W. M., Tran, P. P., & Pham, T. A. K. (2024). Sustainable energy and semiconductors: A bibliometric investigation. *Sustainability, 16*(15), 6548. https://doi.org/10.3390/su16156548

Lüdeke-Freund, F. (2020). Sustainable entrepreneurship, innovation, and business models: Integrative framework and propositions for future research. *Business Strategy and the Environment, 29*(2), 665–681. https://doi.org/10.1002/bse.2396

Mbanefo, C. C., & Grobbelaar, S. S. (2024). Unveiling the core elements of platform ecosystem development: A systemic lens for value co-creation in small and medium enterprises and orchestrators. *Management Review Quarterly*. https://doi.org/10.1007/s11301-024-00416-1

McKinsey & Company. (2022). *Keeping the semiconductor industry on the path to net zero*. https://www.mckinsey.com/industries/semiconductors/our-insights/keeping-the-semiconductor-industry-on-the-path-to-net-zero.

McKinsey & Company. (2023). *Beyond the fab: Decarbonizing scope 3 upstream emissions*. https://www.mckinsey.com/industries/semiconductors/our-insights/beyond-the-fab-decarbonizing-scope-3-upstream-emissions#/.

McKinsey & Company. (2024). *Exploring new regions: The greenfield opportunity in semiconductors*. https://www.mckinsey.com/industries/semiconductors/our-insights/exploring-new-regions-the-greenfield-opportunity-in-semiconductors.

Mesquita, M., Simões, A. C., Teles, V., et al. (2023). The role of digitalization, servitization and innovation ecosystem actors in boosting business model innovation – A literature review. In J. Machado, F. Soares, J. Trojanowska, V. Ivanov, K. Antosz, Y. Ren, et al. (Eds.), *Lecture notes in mechanical engineering* (pp. 114–127). Springer Nature Switzerland AG. https://doi.org/10.1007/978-3-031-09360-9_10.

Mugoni, E., Kanyepe, J., & Tukuta, M. (2024). Sustainable supply chain management practices (SSCMPS) and environmental performance: A systematic review. *Sustainable Technology and Entrepreneurship, 3*(1), Article 100050. https://doi.org/10.1016/j.stae.2023.100050

Mukaromah, H., Permana, C. T., & Astuti, W. (2023). Aiming towards creative city: How surakarta city government applied the sustainability-oriented innovation (SOI) as a strategy to empower local small and medium creative industries. *IOP Conference Series: Earth and Environmental Science, 1186*(1), Article 012018. https://doi.org/10.1088/1755-1315/1186/1/012018

Narayanaswamy, V., & Muthusamy, K. (2011). Sustainability index benchmarking in a semiconductor manufacturing environment. *Advanced Materials Research, 383–390*, 3377–3381. https://doi.org/10.4028/www.scientific.net/AMR.383-390.3377

Oskam, I., Bossink, B., & de Man, A. P. (2021). Valuing value in innovation ecosystems: How cross-sector actors overcome tensions in collaborative sustainable business model development. *Business & Society, 60*(5), 1059–1091. https://doi.org/10.1177/0007650320907145

Qi, E., Luo, T., Wick, M., Armer, H., Raiford, M., Marteniz, T., et al. (2024). Sustainability model for semiconductor manufacturing. In *2024 35th Annual SEMi advanced semiconductor manufacturing conference (ASMC)* (pp. 1–4). https://doi.org/10.1109/ASMC61125.2024.10545500

Rodríguez, A., Alcalde-Heras, H., & Iñigo, E. A. (2024). Exploring coopetition and value-based networks in business models for sustainability—A case study of the specialty coffee industry in Colombia. *Business Strategy and the Environment*. https://doi.org/10.1002/bse.3878

Ruberti, M. (2023). The chip manufacturing industry: Environmental impacts and eco-efficiency analysis. *The Science of the Total Environment, 858*(Pt 2), Article 159873. https://doi.org/10.1016/j.scitotenv.2022.159873

Sarkis, J., Cordeiro, J. J., & Vazquez Brust, D. A. (2010). Facilitating sustainable innovation through collaboration. In J. Sarkis, D. Vazquez Brust, & J. J. Cordeiro (Eds.), *Facilitating sustainable innovation through collaboration* (pp. 1–16). Springer. https://doi.org/10.1007/978-90-481-3159-4_1.

Semi. (2023). Scope 3 category 1 GHG assessment guideline for the semiconductor sector. *Semi-semiconductor climate consortium (SCC)*. https://www.semi.org/sites/semi.org/files/2024-01/SCC%20Prospectus%20Jan%202024.pdf.

Shen, C., Tran, P. P., & Minh Ly, P. T. (2018). Chemical waste management in the U.S. Semiconductor industry. *Sustainability, 10*(5), 1545. https://doi.org/10.3390/su10051545

Song, Y., & Dong, Y. (2024). Influence of resource compensation and complete information on green sustainability of semiconductor supply chains. *International Journal of Production Economics, 271*, Article 109227. https://doi.org/10.1016/j.ijpe.2024.109227

Strand, R. (2024). Global sustainability frontrunners: Lessons from the Nordics. *California Management Review, 66*(3), 5–26. https://doi.org/10.1177/00081256241234709

Suárez Giri, F., & Sánchez Chaparro, T. (2023). Measuring business impacts on the SDGs: A systematic literature review. *Sustainable Technology And Entrepreneurship, 2*(3), Article 100044. https://doi.org/10.1016/j.stae.2023.100044

Wang, Q., Huang, N., Chen, Z., Chen, X., Cai, H., & Wu, Y. (2023). Environmental data and facts in the semiconductor manufacturing industry: An unexpected high water and energy consumption situation. *Water Cycle, 4*, 47–54. https://doi.org/10.1016/j.watcyc.2023.01.004

Yin, R.K. (2018). *Case study research and applications* (L. Fargotstein, Ed.; Sixth Edition). SAGE Publications, Inc.

Yoo, Y., & Cho, K. (2024). Key traits of leading sustainable firms in the semiconductor industry. *Sustainability, 16*(11), 4563. https://doi.org/10.3390/su16114563

Publication IV

Konstari, P., and Valkokari, K.
Roles for and impact creation of sustainability-oriented innovations in a shared semiconductor infrastructure

Reprinted with permission from
International Journal of Innovation Management
29, 2025

OPEN ACCESS
International Journal of Innovation Management
2540020 (31 pages)

DOI: 10.1142/S1363919625400201

World Scientific
www.worldscientific.com

ROLES FOR AND IMPACT CREATION OF SUSTAINABILITY-ORIENTED INNOVATIONS IN A SHARED SEMICONDUCTOR INFRASTRUCTURE

PIIA KONSTARI [*,‡] and KATRI VALKOKARI [†]

[*]*Microelectronics and Quantum Technology*
VTT Technical Research Centre of Finland
P.O. Box 1000, FI-02044 VTT, Espoo, Finland
[†]*Foresight and Data Economy, VTT Technical Research Centre of Finland*
P.O. Box 1300, FI-33101 Tampere, Finland
[‡]*piia.konstari@vtt.fi*

Received 13 June 2025
Accepted 23 July 2025
Published 30 September 2025

A shared semiconductor infrastructure can be studied as a provider-driven living lab. The infrastructure hosts several actors, who undertake different activities in the infrastructure and play different roles. The shared infrastructure provider plays several active roles for sustainability-oriented innovation (SOI) in the living lab. The user companies take either an active or a passive role for SOI. In addition, based on their personal interests, the user-company employees take their own roles for advancing SOI in the shared infrastructure. In any case, a strong orchestrator is needed for true co-innovation activities among the actors of the living lab. Based on the actors, resources and roles, and activities, we analyse the impact of SOI activities on a regional, national and global scale. We analyse the impact of SOI activities in the semiconductor living lab and conclude that the impact can be categorised on different geographical levels, both related to the development of the digital society, research activities, industry development as well as society in general. SOI activities have the biggest impact when integrated into research activities, industrial offering and diffused to the global semiconductor industry while sustainably advancing the development of our digital society. Next-generation semiconductor devices themselves are SOIs and affect eight of the United Nations (UN) sustainable development goals (SDGs).

[‡]Corresponding author.

Keywords: Sustainability-oriented innovation; living lab; semiconductor industry; semiconductor infrastructure; sustainable development goals; ecosystem roles; actors, resources and roles, activities; impact.

Introduction

Semiconductor technology contributes to eight of the sustainable development goals (SDGs) (Hsieh *et al.*, 2023). Sustainability is also a rising topic in the semiconductor industry as semiconductor companies worldwide have made their net zero promises and now look for practical ways to tackle the sustainability topic to meet their sustainability goals and targets. The semiconductor market has grown dramatically over the past decade and will continue to grow, driven by increased demand for integrated circuits (ICs) for e.g., artificial intelligence (AI), internet-of-things (IoT) and electric vehicles (EV) (Morsy *et al.*, 2025). However, semiconductor manufacturing consumes large amounts of energy and water and generates notable amounts of hazardous waste and greenhouse gas (GHG) emissions (Ruberti, 2024).

The fabrication of semiconductor devices requires sophisticated and costly infrastructure that needs continuous care and upgrading to stay on par with state-of-the-art capabilities and infrastructure. Due to this, semiconductor start-ups and small- and medium-sized enterprises (SMEs) are most often dependent on fabrication infrastructure provided by external parties for kicking off their business.

Such infrastructure can be provided by universities, commercial foundries or research and technology organisations (RTOs) and is most often shared by several users i.e., the employees of several companies work side by side in the infrastructure provided by an operator, forming a local innovation ecosystem (Konstari and Valkokari, 2024).

The drivers and barriers for the engagement of the user companies in sustainability-oriented innovation (SOI) activities in such shared semiconductor infrastructure have been earlier studied by Konstari and Valkokari (2024). Konstari and Valkokari (2025) also studied the value creation and capture of SOI activities in such an infrastructure. Based on these earlier findings, it can be concluded that such and ecosystem formed by the user companies, the infrastructure and the infrastructure operator can be considered a living lab (LL) including different actors, resources and activities — a provider-driven LL (Leminen *et al.*, 2012), where the users can be studied in a real-world context instead of in a laboratory scene (Ballon and Schuurman, 2015; Lakatos *et al.*, 2024), and where the LL has the role of innovation orchestrator in the regional innovation ecosystem (RIE) (Fauth *et al.*, 2024). In this case, the real-world context is the shared infrastructure which constitutes the focal point for the local innovation ecosystem.

The participants of LLs and open innovation networks take different kinds of roles based on their interest and purpose (Leminen *et al.*, 2014; Nyström

et al., 2014). Hence, the user companies of the shared infrastructure, as well as their employees, also have different kinds of roles for SOI-related activities. Therefore, the complexity of evaluating the impact of LLs has been widely recognised. An impact evaluation framework of LLs has been suggested by, for example, Ballon *et al.* (2018), and the recent framework was suggested by Valkokari *et al.* (2024). The authors have not identified any existing research on the impact of specific SOI actions in LLs or shared infrastructures.

Understanding the impact of SOI activities in the LL can be considered crucial for setting the activities into perspective on different horizons and guiding choices and everyday actions towards those with the most impact. Hence, there is a clear research gap to tackle. To build up the understanding of the impact levels, the main research questions for this study are as follows.

RO1: What roles are there in the living lab for advancing sustainability-oriented innovation activities?

RO2: What is the impact of the sustainability-oriented innovation activities in the shared semiconductor infrastructure?

This research is a qualitative multiple case study at the end of 2023 of the impact of SOI activities in a Finnish shared semiconductor infrastructure — a provider-driven LL, where the local RTO provides access to semiconductor equipment. The analytical framework used is the actors, resources, activities model (ARA model) (Håkansson and Snehota, 1997; Valkokari *et al.*, 2016). The impact study builds further on the impact framework presented by Valkokari *et al.* (2024) and adapts it for SOI activities in a regional semiconductor innovation ecosystem. The Nordic countries are considered forerunners in collaborative innovation for sustainability, hence making the Finnish LL an interesting research object (Leminen *et al.*, 2021).

The research topic is relevant for several stakeholders, who can use the results to understand the roles for and impact of SOI activities: infrastructure user companies, infrastructure providers, academia, funding organisations and policy makers.

The main theoretical contribution of this study includes the ARA model analysis of roles for SOI impact creation, as well as the framework for the impact of SOI activities in the semiconductor LL. The LL operator plays an active role in SOI creation, whereas the user companies and their employees adopt different roles based on their goals and personal interests. The impact framework of SOI includes regional, national and global impact dimensions for industry, research and society in general. SOI activities have the biggest impact when advancing the sustainable development of next-generation digital technologies that advance United Nations (UN) SDGs and when integrated into research activities, industrial offerings and diffused to the global semiconductor industry.

The structure of the paper is as follows. The second section introduces the most central literature for this study. The third section presents the research approach. The fourth section describes the findings and discusses them. The fifth section concludes the research and suggests further research directions.

Literature Review

Impact of sustainability-oriented innovations

The concept of SOI was presented by Adams *et al.* (2016), who categorised them into operational optimisation, organisational transformation and systems building.

The effectiveness of commercialisation of SOI is characterised by the sustainability-oriented criteria — enhancement of the company's image, and the efficiency is affected by various regulatory topics (Kalmakova *et al.*, 2021). Also, environmental regulations can encourage commercialisation of eco-innovations (Lu *et al.*, 2025).

The inclusion of external stakeholders and openness to external opinions have been identified as factors positively affecting the impact of SOI on a system level (Goodman *et al.*, 2023). SOI has been proven to positively affect the performance of SMEs (Fatoki, 2019), and eco innovations positively affect the sustainability performance of companies (Eusebio, 2024).

There are, however, also criticisms related to SOI — does SOI really affect the sustainability on a system level or is the discussion too innovation-centric to drive for transition (Hansen *et al.*, 2022). To address this criticism, more research on the impact of specific SOI activities is needed. Currently, such research is limited, leaving many potential impacts of SOI unexplored.

Characteristics of living labs

In LLs, the users are studied in a real-world context instead of in a laboratory scene (Ballon and Schuurman, 2015; Lakatos *et al.*, 2024). LL activities include a variety of stakeholders and result in outcomes (Hossain *et al.*, 2019).

LLs can be divided into utiliser-driven (by companies developing their products), enabler-driven (by public or non-governmental actors for projects), provider-driven (by e.g., research institutes and universities for promoting research and development and knowledge creation) and user-driven (by users to solve topical problems) (Leminen *et al.*, 2012). Users are involved in LLs through recruitment, motivation, co-creation and relation (Huang *et al.*, 2024).

Urban living labs (ULLs) are public spaces where local authorities try to solve societal challenges by engaging citizens to collaborate and innovate and attract a lot of research attention. ULLs are often led by research institutions, mainly due to

the type of public research funding available, causing a lack of private sector engagement. The Nordic countries have been pioneers in the ULL development (Voytenko *et al.*, 2016). Often, it is, however, challenging for ULLs to generate systematic change beyond their own boundaries (von Wirth *et al.*, 2019).

Innovation infrastructures can also be LLs, where companies and research organisations collaborate with a purpose (Guzmán *et al.*, 2013). An LL can just be an experimental, co-creation space where open innovation is used to solve specific challenges (Leminen *et al.*, 2020). The role of LLs in taking scientific discoveries to industrialisation has been recognised, but the way LLs are organised to achieve this varies a lot depending on their value proposition and LL design elements. The LL can be the technology sponsor, the opportunity spotter, the network orchestrator, or the community anchor (Abi Saad and Agogué, 2024).

LLs can drive innovation and experimentation in sustainability that results in solutions for economic, environmental and social challenges (Lakatos *et al.*, 2024). LLs are real-life open innovation ecosystems that use iterative feedback for innovation to create sustainable impact.

Collaborative innovation drives for sustainability in co-working spaces, fab labs, green public procurement, hackathons, hubs, makerspaces, participatory budgeting and LLs, with both stakeholder relationships and the innovation context playing important roles (Leminen *et al.*, 2021).

LLs have different ways to engage users, including firms and business systems, in activities for promoting co-creation of value that may benefit the different aspects of sustainability: economy, society and the environment. Such ways include keeping focus on entrepreneurship and innovation and actively disseminating with digital tools. Funding is highly essential for the operations and success of the LL, likewise, the need to have sustainability as a strategic factor as otherwise the sustainability outcomes are side products of the main activities (Compagnucci *et al.*, 2021). SMEs that participate in an LL improve their sustainability innovation performance (Alexandrakis *et al.*, 2022).

The effectiveness of LLs can be influenced by various factors. The key enablers for successful LLs include strong collaborative and iterative processes with networks and partnerships, whereas key barriers include issues related to supporting technologies, time and cost of collaboration and LL lifetime uncertainties (Berberi *et al.*, 2023). One major reason for users to engage in innovation communities is learning (Ståhlbröst and Kareborn, 2011).

LLs take the role of innovation orchestrators in the RIE in the middle of government, academia, industry and society in general. They act as connectors, integrate actors and have central knowledge, tools and experience to connect different initiatives in the RIE. They guide the ecosystem towards results satisfying all stakeholders' needs through governance, structure and decision-making processes in the ecosystem. The

key success factors are government policies, strategic integration, formal collaborations and the provision of proof of the LLs' success (Fauth *et al.*, 2024).

Whether LLs at the end promote innovation or not, is, however, yet unproven — it is just an expectation from the definition of the LL but exact proof thereof is missing (Paskaleva and Cooper, 2021).

Actor roles in living labs

Roles of actors in LLs or innovation ecosystems have lately gained loads of interest. Those are not tied to each other but co-evolve over time. In addition, actor roles in innovation ecosystems are context-specific and difficult to generalise (Carrara and Freisinger, 2024). The roles of the actors are always case-specific and tied to a certain activity. The roles that can be identified for e.g., ecosystem emergence (Dedehayir *et al.*, 2022) are not the same as those for agricultural LLs (Toffolini *et al.*, 2021).

Leminen *et al.* (2014) identified four user roles in LLs: informant, tester, contributor, co-creator. Nyström *et al.* (2014) identified 17 open innovation network roles: coordinator, builder, messenger, facilitator, orchestrator, integrator, informant, tester, contributor, co-creator, webber, instigator, gatekeeper, advocate, producer, planner, and accessory provider.

Another categorisation of roles has been identified for gaming innovation ecosystems: leadership, direct value creation, value support, and encouraging entrepreneurship (Klimas and Czakon, 2022).

For collaboration in humanitarian innovation ecosystems, the role definition has been identified to be simpler: facilitator, provider, researcher, user, utiliser, enabler, champion, communicator, leader, implementer (Darkwa, 2025).

Table 1 summarises the roles and their characteristics from three papers that the authors consider most relevant as references for this study: (a) Nyström *et al.* (2014), (b) Dedehayir *et al.* (2022) and (c) Darkwa (2025). However, the authors have not managed to locate any specific role analysis related to SOI in LLs or innovation ecosystems. Hence, further research is needed to this field.

Impact of living labs

The impact of LLs is a less studied subject due to its complexity. Ståhlbröst (2012) suggested that the key principles of LLs are value, sustainability, influence, realism and openness. It has proven challenging to evaluate isolated outcomes and indirect outcomes of LLs. A logical model for analysing the impact of LLs was created by Ballon *et al.* (2018), who defined the first dimension of the model to three layers (input, activity and output) and then categorised the effects to short

Table 1. Roles and their characteristics: (a) Nyström *et al.* (2014), (b) Dedehayir *et al.* (2022), (c) Darkwa (2025).

Role	Source	Characteristics
Accessory provider	a	Proactively promotes its offerings and expertise
Activist	b	Objects to others' actions
Advocate	a	Provides information externally
Assembler	b	Produces goods and services by combining components, materials and services, and processes information provided by others
Builder	a	Fosters close relationships among participants in the LL
Champion	b	Engages actively with the overall objectives of the project, plays a key role in numerous research-engineering interaction events, successfully navigates technical and organisational challenges, and drives the project to completion through determination and energy
	c	Champions lab programs
Co-creator	a	The user collaborates with the research and development (R&D) team and other LL actors to co-design a service, product, or process
Communicator	b	Presents research findings and communicates debates to the public
	c	They oversee lab program communications
Complementor	b	Offers specialised functions or expertise in a specific area, contributing to overall product development goals
Consultant	b	Offers supplementary technical details and guidance
Contributor	a	Works closely with network actors to innovate products, services, processes, or technologies
Coordinator	a	Organises a group of participants
Dominator	b	Acquires organisations vertically or horizontally, impacting the ecosystem's wellbeing
Ecosystem leader	b	Sets a vision to unite organisations for comprehensive customer value, implements the ecosystem for innovation, and restructures it when necessary, with additional resources and connections
Enabler	c	Usually, an organisation that supplies the necessary resources for the Lab to operate

Table 1. (*Continued*)

Role	Source	Characteristics
Expert	b	Explores, creates and innovates
Facilitator	a	Provides resources for internet usage
	c	Is a member of the Lab and partnering NGOs who facilitates workshops as a mentor
Functional manager	b	Performs managerial tasks within the organisational hierarchy
Gatekeeper (similar to power promoter)	a	Has access to resources
Informant	a	Contributes users' insights to the LL
Instigator	a	Affects actors' decision-making processes
Integrator	a	Combines diverse knowledge, ideas, technologies, or outputs from various LL participants into a unified entity
Leader	c	Manage laboratory programs
Messenger	a	Shares and distributes information within the LL network
Opponent	b	Opposes development plans
Orchestrator	a	Supports and guides network activities, fostering trust to enhance collaboration towards the LL's goals
Planner	a	Engages in development processes, providing input through intangible resources
Producer	a	Participating in the development process
Provider	c	An individual who offers specialised knowledge or expertise to address specific issues or challenges
Regulator	b	Decides on legal disputes; sets policies; independently assesses the feasibility of innovations
Researcher	c	An academic participant studies a specific area and shares knowledge as an active participant, mentor, or prototype developer, promoting solutions based on knowledge
Sponsor	b	Allocates resources and initiates decisions to foster ecosystem growth
Supplier	b	Provides materials, technologies and services for use by other entities within the ecosystem to create a comprehensive product or service
Tester	a	Tests innovation in real-life settings like hospitals, school cafeterias and classrooms

2540020-9

Table 1. (*Continued*)

Role	Source	Characteristics
User	c	They identify themselves as either customers or end users of innovations. The data revealed that customers could be either utilisers or actual users within this context
	b	Obtains and applies an innovation for a specific purpose
Utiliser	c	Is a unique user who initiates innovation, advises during development, and finally manages its release to the wider community
Webber (similar to relationshippromoter)	a	Initiates and selects potential actors

term, midterm and long term. The second layer defines where the effects are seen: involved companies, consumers/users, society (Ballon *et al.*, 2018).

Beaudoin *et al.* (2022) suggested a research agenda for evaluating the effect and impact of LLs around the questions who, what, why, how, where, when and how effective. Aquilué *et al.* (2021) proposed a four-stage methodology (problem and ideation; development; implementation, testing and assessment; final proposal) to be evaluated with regards to feasibility impact; social impact; and spatial impact in a specific project. Molinari *et al.* (2023) concluded in their SWOT analysis that the strength of the impact of the university-driven LL under study was mostly around visibility and participation in the public discussion of the topic.

The success factors of LLs for collaborative innovation have been recently mapped by Valkokari *et al.* (2024). They mapped the success factors for LLs into shared vision; interaction between partners; actors, resources and activities; operational model and supporting structures. Their framework for the impact of collaborative innovation in LLs included impact on regional, national and global dimensions.

Even though sustainability is a focus area of LLs, the authors have not managed to identify previous research of the impact of SOI activities in LLs in the semiconductor industry. Hence, there is a clear research gap to be tackled.

Research Approach

Methodology

A qualitative multiple-case study was selected as the research method, as the goal was to generate new understanding by synthesising responses from multiple companies rather than to prove existing theories. A qualitative research approach is a suitable research method when investigating emerging phenomena (Yin, 2018). Semi-structured interviews were selected as the data collection method to allow for interactive data collection. Organisational procedures were complied with for research permission.

In total, 14 companies were selected for the research from the Finnish shared semiconductor infrastructure under study. In the shared semiconductor infrastructure, the RTO provides access for external companies to semiconductor equipment. User companies can also rent cleanroom space for their own use. The selected shared semiconductor infrastructure is an interesting research object as it has, over several decades, enabled the existence and growth of the regional semiconductor ecosystem around it. Several of the companies have been acquired abroad, making the regional ecosystem an interesting study object for impact on several dimensions.

The research was done at the end of 2023, when the interviews were conducted over Teams, recorded, transcribed and verified by the interviewees. The data was brought into NVivo 14 software tool for qualitative research and coded to support the research questions. The data was then analysed by our multidisciplinary research team, categorised and synthesised.

Table 2 shows the interviewed pseudonymised companies, the locations of their mother companies, the decade when they were established, whether they are SMEs or large companies, the interviewed people's titles, as well as the duration of the Teams interviews. The classification of companies into SMEs and large corporations was facilitated through supplementary data obtained from the Orbis company information portal. SMEs were defined as entities with an annual turnover of less than €50 million, including start-ups, and with employee numbers ranging from 7 to 300.

Table 2. Interviewed companies and people.

Company	Owner geography	Establishment period of time	Category	Interviewed people	Interview duration
A	Americas	1990–1999	SME	CTO, Quality manager	44 min
B	Americas	2000–2009	SME	CEO for Finland	52 min
C	Europe	–1989	SME	Managing director	42 min
D	Finland	2010–2019	Large	Senior process engineer, ESG manager	35 min
E	Finland	2010–2019	Large	Head of chip production, Sustainability director	28 min
F	Asia	2010–2019	SME	Operations manager, Head of finance	35 min
G	Asia	2000–2009	Large	R&D technology manager, Process development manager, Facility manager, Environmental manager	43 min

Table 2. (*Continued*)

Company	Owner geography	Establishment period of time	Category	Interviewed people	Interview duration
H	Asia	–1989	Large	Senior tech manager, Quality engineer	30 min
I	Europe	1990–1999	SME	Managing director for Finland, Research team leader	52 min
J	Finland	2010–2019	Large	CTO, Senior process development manager, Quality engineer	43 min
K	Finland	2020–	SME	Fabrication lead	23 min
L	Americas	2020–	SME	Senior technology director	47 min
M	Finland	–1989	Large	Senior R&D scientist, Sustainability manager	41 min
N	Americas	2000–2009	SME	Managing director for Finland	23 min

Conversely, large corporations were characterised by an annual turnover exceeding €50 million and an employee count of over 300.

The interviewees included employees with varied job functions and knowledge levels, as shown in Table 2. Large company representatives were often directly responsible for sustainability, while SME representatives had a broader range of responsibilities, also including sustainability. All were deemed the best participants by their companies, reflecting the industry's fragmented understanding of sustainability.

This research can be considered reliable in its specific context, as the interviewees had relevant titles and their answers became repetitive. Several of them also verified their responses within the companies to ensure high quality of their answers.

Data analysis

As the analytical framework, we used the ARA model that was originally proposed by Håkansson and Johanson (1992) and later used by Valkokari *et al.* (2016), for analysing the first research question, as shown in Fig. 1. This model was chosen for

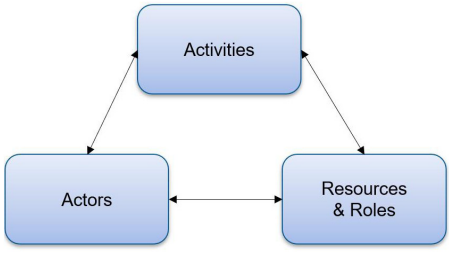


Fig. 1. Framework for analysing actors, resources and roles, as well as SOI activities in the LL.

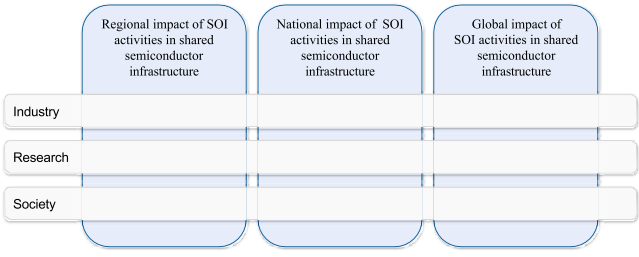


Fig. 2. Framework for analysing SOI impact in shared semiconductor infrastructure.

two reasons: (i) it supports describing the in-built dynamics of an LL, its actors and their resources and (ii) it highlights the ever-evolving nature of collaborative activities within the networked relationships between the actors of shared research infrastructure forming an LL. The corresponding author also used industry experience and know-how for the analysis. The co-author acted as an external observer in the analysis, ensuring the rightfulness of the findings.

For analysis of the second research question, we used the impact indicator framework of collaborative innovation proposed by Valkokari *et al.* (2024) as a basis and modified it to suit the specific case of SOI impact analysis in the semiconductor industry under study. The adopted framework used is shown in Fig. 2.

Findings and Discussion

Actors, resources and roles, and activities for SOI impact activities in the shared semiconductor infrastructure

This section analyses the actors, resources and roles, and activities in the shared semiconductor infrastructure. The ARA model findings are used to conclude on the first research question.

Actors

The facility itself and the semiconductor equipment can be considered as actors, as they affect SOI widely. In the facility, there are various active organisations. At the organisations active in the infrastructure, there are different kinds of individuals who affect the SOI activities in the shared infrastructure. In addition, the national, European and global legislations and regulations affect the SOI activities in the shared infrastructure. The funding parties decide what kind of SOI activities get funding. The entire supply chain affects SOI activities in several ways, as well as the industry standards and requirements. The actors in the shared semiconductor infrastructure for SOI impact are shown in Table 3.

Activities

The activities requested and undertaken by the actors of the shared semiconductor infrastructure are summarised in Table 4. There are both activities done individually by the organisations as well as collaboratively and these are described in more detail below in the sub-sections. The activities include such that are already done by the actors, and such that the actors wish would take place.

Individual activities

The different organisations in the shared infrastructure have individual activities. The facility must be entertained by the facility provider, the semiconductor equipment must be maintained by the equipment provider, the university conducts education and research in the infrastructure, and the user companies use the infrastructure for various own activities.

Most of the user companies mentioned that they do their own R&D, piloting and production in the shared infrastructure. Company A CTO said "Area must be safe and secured, own space must be only for our company people." Company C managing director was of the same opinion. Hence, the importance of keeping own activities confidential was of importance as they were linked to individual companies' business and competitiveness.

The companies develop their current or next-generation semiconductor technologies and products in the infrastructure and urge for the importance of technology and the contribution of technology to the digital society. Company L Senior director said that ". . . we should aim at sustainable products, good quality, small size −more environmentally friendly." And company K fabrication lead said that "Expectation and goal that with our technology [the application] can be done with less energy consumption than the current technology. . . it is important to keep focus on the technology that needs to be fabricated inside the facility."

Table 3. Actors in the shared semiconductor infrastructure.

Actors		
Infrastructure		Facility
		Semiconductor equipment
Organisations		Facility owner
		Facility operator
		Semiconductor equipment provider
		User companies
		User company owners
		University
		Customers
		Partners
		Regional ecosystem players
Individuals	Facility personnel	Facility management
		Facility maintenance personnel
	Semiconductor equipment provider	Management
		R&D personnel
		Operative personnel
		Maintenance personnel
		Quality personnel
	Infrastructure user companies	Management
		R&D personnel
		Operative personnel
		Sustainability and quality personnel
		Shareholders/owners
	University	Teaching personnel
		Students
Legislation and regulations		National
		European Union level regulations
		Global regulations
Funding parties		Government
		Investors
Supply chain		
Industry requirements		

Several user companies expected services and activities from the other parties. Company D ESG manager requested that the consumption data be tracked and shared: "We expect that all [consumption] numbers and reports should be publicly available so that we would know where we are in [infrastructure] operations."

Table 4. Activities in the shared semiconductor infrastructure.

Activities		
Individual activities	Facility	Provides own or shared cleanroom space for users
		Maintains facility and facility systems and solutions like water system, air conditioning, chemical and gas distribution
		Invests in facility technology
		Organises recycling and waste collection
		Provides facility-related consumption data
	Semiconductor infrastructure provider	Invests in new equipment
		Develops processes for semiconductor equipment
		Maintains equipment
		Provides access to equipment
		Implements R&D activities; own, joint and contract
		Builds expertise and experience on sustainability topic
		Provides equipment-related consumption data (new requested activity)
		Does individual, competitive R&D
	Semiconductor infrastructure user companies	Uses semiconductor infrastructure by own employees for R&D, piloting and production
		Uses the facility of the shared space and/or own space
		Recruits other infra users through encounters in infrastructure
	Universities	Provides education
		Does research
		Maintains own tools
Collaborative activities		Engaging into collaborative R&D among the users
		Engaging into other collaborative efforts between users
		Engaging in best practice sharing and training (new requested activity)
		Engaging in collaboration with European and Finnish players (new requested activity)
		Taking part in talent development
		Sharing information in meetings (new requested activity)
		Engaging in sporadic meetings in the cleanroom

This implies expectations both towards the facility provider as well as to the RTO. Companies B, F and N were of the same opinion. Company G Facility manager said: "Info sharing from the facility side should be implemented."

The user companies also expected deep sustainability consideration from the equipment and facility provider when planning and building the infrastructure expansion. Company I research team leader asked that "energy consumption should be considered when purchasing new equipment, e.g. pumps −favor less energy-consuming equipment." And Company F head of finance said that "We expect that sustainability is considered in every aspect; it has to be part of planning."

Some companies mentioned that their primary interest was in evaluating new technologies provided by the semiconductor equipment provider. Company G R&D technology manager said: "We are planning to use that for evaluating new technologies, if they are suitable for our future products, potentially ramping up some new technologies, not production, so research and early-phase R&D and new technology evaluation". Company H senior technology manager said: "It is important that [RTO/shared infrastructure] will study technologies that are not mature enough for [company] and do early development for [company]. . .. If it is found interesting, then [company] can invest in that technology." This implies that the equipment provider is in a central position to enable novel semiconductor development.

Collaborative activities

Most companies said that they participate in private and/or public collaborative projects where the shared infrastructure is the fabrication infrastructure for the project. Company G R&D technology manager said: "[Shared infrastructure] provides both facilities and know-how for joint research and development with [RTO] and [University] which helps us to develop our future technology and products." Company H Senior technology manager said: "We are part of R&D projects, like [publicly funded national] projects, so [shared infrastructure] is present in all R&D projects as the semiconductor facility." The infrastructure hence dictated what kind of semiconductor R&D projects could be done and served as an LL.

Company D senior process engineer hinted that they were looking for global collaboration through presence in the shared infrastructure: "Presence in [shared infrastructure] can possibly open doors to other [semiconductor fabrication lines] in Europe −can get connections for better discussions in Europe. Increased collaboration within Europe and in Finland."

Company B CEO requested more activities for and information sharing about environmentally friendly processing: "Any ways that operators could contribute to operations to make it more environmentally friendly would be nice to get info about. More energy or water-intensive processes – instructions about that. Training of operators for more environmentally friendly processing." This implies that the CEO asked for information and best practice sharing, which can be considered a degree of collaboration because the CEO's comment implied that company B was interested in learning from other shared infrastructure users.

Company I research team leader requested collaborative activities for reducing shared infrastructure footprint: "if we could reduce footprint/wafer in [shared infrastructure] we would be very happy to support it by helping [shared infrastructure] −we are willing to do that if there is some step that should or could be implemented to achieve that."

Company M senior R&D scientist also underlined the educational side by mentioning that the shared infrastructure has an "educational role." Company B CEO requested "good collective waste chemical handling in [shared infrastructure] and [shared infrastructure expansion]." Company I research team leader was of the same opinion and requested, in addition, training in recycling.

Company N managing director mentioned possible collaboration with other users: "Also we need to be open minded of what can be the capabilities that others can offer in the context of the ecosystem in [shared infrastructure]. If they provide technologies and services that can benefit us."

Roles for SOI

As highlighted by Valkokari *et al*. (2016), the roles the LL participants decide to take affect the resources they are willing to provide to the LL. Based on the actors and activities, we can now summarise the roles for driving SOI in the shared semiconductor infrastructure. The roles evolve over time and are heavily based on personal interest.

As the shared semiconductor infrastructure under study has not been initiated and set up with the purpose of being an LL but based on the need for such infrastructure, the identified roles differ from the previously identified ones. In addition, previously identified roles have not been identified for the use case of SOI activities.

Table 5 shows the identified roles for SOI activities in the shared semiconductor infrastructure. There are parties taking more active roles, whereas there are others being more passive, mainly wishing to benefit from other people's work. Some of the identified roles have been previously identified, as shown in Table 1, whereas some are newly identified for the case under study for the shared

Table 5. Resources and roles in the shared semiconductor infrastructure for SOI: (a) Nyström *et al.* (2014), (b) Dedehayir *et al.* (2022), (c) Darkwa (2025).

	Roles	Characteristics in the case under study	Actors
Previously identified	Advocate (a)	Considers SOI activities important and advances them proactively	Individuals
			Pioneering companies
			Legislators
	Contributor (a)	Participates in SOI activities	User companies
			Individuals
			Infrastructure provider
	Expert (b)	Is a SOI expert	Individuals
	Facilitator (a, c)	Provides the means for SOI activities	Equipment provider
	Informant (a)	Provides information from its perspective about SOI and how that can be advanced	Individuals
			Companies
			Infrastructure provider
			Equipment provider
			Teaching personnel
	Integrator (a)	Ensures that SOI activities are integrated into activities	Individuals
			Companies
	Messenger (a)	Shares SOI information within the LL	Individuals
			Infrastructure provider
	Provider (c)	Shares and offers SOI knowledge	Individuals
			Companies
			Infrastructure provider
	Researcher (c)	Academic sharing know-how on SOI	Individuals
	Sponsors (a)	Gives their support to SOI activities through e.g., funding or resources	Managers
			Funding parties
			Shareholders/owners
	User (b, c)	Uses SOI results	User companies
			Customer

Table 5. (*Continued*)

	Roles	Characteristics in the case under study	Actors
Newly identified	Benefiter	Companies only wishing to benefit from the results of the SOI activities, not participate in achieving the results	Ecosystem companies not participating in activities
	Educators	People wishing to share knowledge and educate others about SOI	Researchers and operators
	Exploiter	Takes advantage of SOI activities and their results by participating in them	R&D project participants/ customers
			Shared semiconductor infra user companies
	Innovator	The people actually doing SOI and commercialising it	Researchers and operators

semiconductor infrastructure with a focus on roles for SOI activities. The roles identified by Nyström *et al.* (2014) seem to have most similarities as our case under study mostly compares to an LL.

Many of the user companies requested the RTO, providing the semiconductor equipment, to be a forerunner and to make wise technology selections for the semiconductor infrastructure. Company G R&D technology manager said that "When you select technologies, I would like you to look into the future on e.g. where regulations will be limiting some technology, like PFAS – don't start doing something that is forbidden in three years or so." Hence, the equipment provider can be considered to have several roles there for SOI — sponsor, advocate, innovator, educator, informant, facilitator, and provider.

Company H senior technology manager reminded that, related to sustainability, "[shared infrastructure expansion] must of course follow government requirements and EU criteria since it receives public money." Company N managing director was of the same opinion and requested the shared infrastructure provider to consider sustainability with regards to "where legislation is going in EU level and national and global matters." The company G R&D technology manager took it further and said that, related to sustainability, "We expect you to take a long look

into the future, not only on legal requirements at the moment, prepare for what is expected in the future in 10 years from now. How to achieve future goals, be a forerunner." Hence, legislation can be seen as an SOI advocate.

The strength and dependency of sustainability on individual interests was mentioned by Company I research team leader who said: "Sustainability will influence our ways of working, and the direction will depend on individuals." As a result, based on individual interests, the users can take various roles in the LL for SOI.

The interest of companies to be benefiters related to SOI was implied by several companies indirectly. Company H senior technology manager, for example, said: "We are in general more interested in knowledge about sustainability than in the actions of what is happening because then we can utilize that in our company." And company G facility manager said: "Information should be shared within the users of [shared infrastructure] on e.g. efficient ways to use the energy, how to handle chemicals, new ways to reduce emissions of semiconductor factories." Many companies wanted to be benefiters and exploiters instead of contributors. This implies that many SOI activities were not seen as competitive topic or innovations but as information that should be widely available for the common good. There were also several requests for training and education of SOI topics from the shared infrastructure operator side to the user companies, making the equipment provider an educator.

The accountability or responsibility of companies was mentioned by company A and company C, implying the Advocate and Informant roles. Company A CTO said "[We] feel responsibility for making wafer fabs more sustainable. It is our role to be a leader and show how these things could be done in a more environmentally friendly manner. Sustainability is a big thing in our corporate strategy." Not all companies were, however, leaders, some had just started sustainability activities like company F who said that they were just about to start to consider sustainability. Company K senior technology director, on the other hand, saw sustainability just as technology and not as separate actions. Hence, they become exploiters of the SOI actions in the shared infrastructure.

Company M sustainability manager brought forward the encouragement for sustainability coming from different shareholders: "We have stakeholder pressure, investors and customers are demanding more and more each year." Shareholders and owners are hence clear sponsors for SOI actions.

Discussion around the first research question

The identified roles in the LL differ from the ones previously identified in the literature. Every LL is specific. Depending on the aim of the LL, the roles might

differ. The semiconductor LL under study has not been specifically set up for the purpose of doing SOI, but SOI activities are part of the other activities within the LL. Hence, the roles differ from the ones identified by Leminen *et al.* (2014), Nyström *et al.* (2014), Dedehayir *et al.* (2022) and Darkwa (2025).

Whether the shared infrastructure functions as an LL is debatable. There seems to be collaborative activities between the different users within R&D projects, but wider sporadic collaboration for SOI seems to be lacking. Hence, we can agree with (Paskaleva and Cooper, 2021) on that it is questionable whether this LL promotes innovation or not. It certainly advances individual actor's innovation thanks to the infrastructure available, but collaborative innovation would require additional engagement.

Engaging activities and funding were identified by Compagnucci *et al.* (2021) to be crucial for the LL's success. This can also be seen to be focal here, as most of the user companies said that they participate in privately and publicly funded collaborative projects. Hence, the sponsors become central as well as ecosystem-building activities.

The infrastructure provider and semiconductor equipment operator were widely considered to be the SOI sponsor, advocate, innovator, educator, informant and facilitator. The importance of individuals taking the role as sustainability advocates was obvious. The user companies were relying on the infrastructure provided to select which technologies should be used and to show the direction of the future.

Some user companies considered themselves SOI advocates, some were clear exploiters or benefiters. None of the interviewees mentioned anything about an ecosystem or LL orchestrator; this role was clearly lacking from the shared infrastructure. The infrastructure provider was seen as an expertise and technology provider, but not as an ecosystem builder. The shared semiconductor facility was referred to as "the bub". The lack of a clear LL orchestrator explains, at some level, the lack of intensified collaborative SOI activities.

Impact of SOI activities in the shared semiconductor infrastructure

The impact of SOI activities is summarised in Table 6. The impact framework is a modified version of the one recently presented by Valkokari *et al.* (2024).

Industry

As user companies benefit from SOI in the shared infrastructure, such SOIs become naturally integrated into their operations and products and integral parts of their offering. Hence, the SOI activities in the shared infrastructure affect directly the regional industry, IP created in the region and the region's image. Company D

Table 6. Impact of SOI activities on the shared semiconductor infrastructure.

	Regional	National	Global
Industry	Shared semiconductor infrastructure's SOI activities become naturally integrated into user companies' products and services, making SOI an integral part of their offering. Affects the competitiveness and image of the regional industrial ecosystem	Diffusion of SOI activities through technology transfers or collaborative R&D projects to national industry, integrating SOI into new applications, ensuring long-term competitiveness, and enabling the development of more sustainable solutions. IP creation secures long-term competitiveness on the national level and attracts foreign investment	Diffusion and knowledge exploitation of SOI into global mother companies' operations and technology, affecting long-term competitiveness of global companies and hence the global semiconductor industry. SOI activities affect global mother companies' investment decisions as well as possibilities to reach net-zero targets. Impact on making the global semiconductor industry more sustainable
Research	Available technologies and operational models dictate the capabilities of the infrastructure for microfabrication R&D activities, where the infrastructure is used as the fabrication facility, either in private or collaborative R&D. Long-term impact on how and to what level sustainability is included in the regional ecosystem's R&D activities. Impact on the regional know-how and expertise development of SOI. Impact on SOI diffusion to the industry	Available technologies and operational models dictate the capabilities of theinfrastructure formicrofabrication R&D activities in collaborative national R&D projects, where the infrastructure is used for fabrication. Long-term impact of how SOI activities are included in national R&D activities, as well as R&D target applications. Impact on the know-how development and expertise of SOI inmicrofabrication industry on a national level,ecting hence the long- term development of the national industry and its attractiveness.	Available technologies and operational models dictate the capabilities of the infrastructure for microfabrication R&D activities in collaborative wider R&D projects, where the infrastructure is used for fabrication. Long-term impact on what kind of R&D projects the shared infrastructure users can participate in and hence what kind of SOI activities and expertise are advanced at a global level. Participation in global SOI know-how development

Table 6. (*Continued*)

	Regional	National	Global
Society	Shared semiconductor infrastructure is a role model, responsible for evaluating the right sustainability-related options, setting the engagement level, showing the future direction, and disseminating best practices to the regional ecosystem. Contributes to regional sustainability transition	SOI activities in shared semiconductor infrastructure affect the national-level activities through engagement and information exchange with other regional semiconductor ecosystems. Affects the national semiconductor industry's sustainability image, know-how and direction, and has an influence on long-term national public funding decisions. Contributes to the sustainability transition on the national level. Affects employment development of the national semiconductor industry	Impact on global sustainability discussion through various networks. SOI activity dissemination increases global awareness of best practices to implement a sustainable semiconductor industry. Strengthening of image that Finland and Europe are sustainability forerunners. Contributes to UN SDGs and enables the sustainable development of our digital society

senior process engineer said: "It's about being competitive, about having a competitive advantage." The technology developed by the user companies directly affects SDGs, as company L Senior director said that they "try to have cutting edge technology, utilize new technology with silicon to replace older generation technology ... – that will make society more sustainable."

On the national level, the SOI activities of the shared infrastructure diffuse to a wider industry through collaborative R&D projects, making them part of new applications, and creating IP to Finland for long-term competitiveness.

In case of user companies that have global mother companies, SOI from the shared infrastructure can also be diffused to the global companies' activities, affecting the global companies' competitiveness, affecting global companies' net zero targets and contributing to making the semiconductor industry more sustainable and contributing to the global SDGs.

Research

The SOI activities in the shared infrastructure impact on the long-run research activities on regional, national and global levels. The shared semiconductor infrastructure defines the fabrication capabilities for R&D projects and hence what kind of SOIs can be done in private or public research projects on different levels. Through the research activities, SOI implemented into the shared infrastructure operations also spread to the different geographies.

The research of SOI also affects the know-how and expertise development in the different dimensions. Company M senior R&D scientist said: "*Company constantly recruits personnel of micro-fabrication expertise. Many of them have gained support to develop their personal skills and expertise, as well as in some cases a formal academic degree, through work-years done in [shared infrastructure]*."

Society

On a societal dimension, the SOI activities in the shared semiconductor infrastructure affect the regional ecosystem, the national ecosystem as well as the global ecosystem. On the regional level, it contributes to the local sustainability transfer.

On the national level, it also contributes to long-term public funding decisions. Company H senior technology manager said that: "The biggest sustainability effect of [shared infrastructure] on Finnish society is solutions and ideas of what can be implemented in [shared infrastructure], then the info will be spread to the Finnish industry spill-off effect."

On the global level, SOI activities are spread through different networks, affecting the implementation of SOI in the semiconductor industry and building awareness. SOI activities hence affect how the UN SDG's are reached at a global level.

Discussion around the second research question

It is possible to identify the impact of SOI activities in the shared infrastructure on reginal, national and global levels. In contrast to the framework suggested by Valkokari *et al.* (2024), we did not find that the SOI activities directly impact e.g., the employment levels nor create new spin-offs. SOI has the biggest impact when integrated seamlessly into research activities and industry offerings. On the societal level, SOI activities in the shared infrastructure impact most the sustainability transition of the semiconductor industry and build awareness of the topic.

Our results are aligned with the ones by Molinari *et al.* (2023), as we concluded that the impact of SOI activities on the societal level comes through awareness raising and diffusion into ecosystems and networks of different dimensions. Our result serves as an answer to Hansen *et al.* (2022), who questioned whether SOI really drives for sustainability transition: we conclude that SOI should be integrated seamlessly into research and businesses in order to effectively drive for sustainability transition as part of industry offering. In this way, SOI can both enable the development of our digital society as well as contribute to UN SDGs.

The developed semiconductor technology itself contributes to eight SDGs, as mentioned by Hsieh *et al.* (2023), making the impact of SOI activities in a shared semiconductor infrastructure a complexly analysed topic. Should the general semiconductor technology development for applications affecting SDGs be considered SOI activities? The authors argue that yes — if the developed product directly contributes to one or several of the UN's SDGs it is an SOI activity, even though it has not been explicitly stated that the activity is done as an SOI activity.

Impact on different horizons can hence be said to be created within the LL and diffused to different dimensions. Impact of SOI activities, i.e., longer-term benefit from the SOI activities than what is described with values is then captured through the sustainable development of our digital society as well as through contribution to the UN SDGs.

Conclusions

The SOI activities of a Finnish shared semiconductor LL were analysed through the ARA-model. The answer to the first research question on the roles for SOI in the shared infrastructure was presented in Table 5.

The impact of SOI activities in the shared semiconductor infrastructure was deduced based on a framework adapted from the one proposed by Valkokari *et al.* (2024). The result was summarised in Table 6. We conclude that the SOI activities in the semiconductor LL have an impact on different geographical levels, both related to research activities, industry development and society in general.

SOI activities have the biggest impact when integrated into industrial offerings, research activities and diffused to the global semiconductor industry. Next-generation semiconductor devices themselves are SOIs and affect eight of the UN's SDGs. Hence, while impact is created by activities in the LL, the impact is captured through the development of our digital society as well as through contributions to UN SDGs.

The outcomes and results of this study contribute to the current understanding of roles for SOI activities as well as for the impact of SOI-related activities in a semiconductor LL. The theoretical contribution of this study includes the definition of roles for SOI activities in an LL, as well as a framework for the impact paths of SOI activities in a semiconductor LL. The findings widen the current LL impact discussion into the deep tech side and showcase the complexity of the impact pathways of SOI actions in a technology-intensive industry, affecting SDGs in various manners.

The managerial implications of this study include a new understanding of what roles different LL actors have in SOI and how SOI activities of an LL create impact. Managers can use the results to analyse their activities in LLs; RTOs will be able to better quantify their impact related to SOI.

Funding parties will be able to better understand the impact of funding SOI activities, and the research community can use the results to understand the impact of SOI in general.

This empirical research is based on a case study of one semiconductor LL undergoing co-evolution within a shared research infrastructure. Consequently, the findings are tentative and not generalisable, but they suggest directions for further studies. Future research should include complementary investigations into the impact paths of other (international) LLs within the semiconductor industry, as well as into the success factors of LLs for achieving maximum impact.

ORCID

Piia Konstari https://orcid.org/0009-0000-9630-8939
Katri Valkokari https://orcid.org/0000-0003-3577-2855

References

Abi Saad, E and M Agogué (2024). Living labs in science-industry collaborations: Roles, design, and application patterns. *Technovation*, 135, 103066, doi:10.1016/j.technovation.2024.103066.

Adams, R, S Jeanrenaud, J Bessant, D Denyer and P Overy (2016). Sustainability-oriented innovation: A systematic review. *International Journal of Management Reviews*, 18(2), 180–205, doi:10.1111/ijmr.12068.

Alexandrakis, J, J Hein and J Kratzer (2022). Living labs and small and medium-sized enterprises: A symbioses propelling sustainable innovation. *Sustainability*, 14(19), 12729, doi:10.3390/su141912729.

Aquilué, I, A Caicedo, J Moreno, M Estrada and L Pages (2021). A methodology for assessing the impact of living labs on urban design: The case of the furnish project. *Sustainability*, 13(8), 4562, doi:10.3390/su13084562.

Ballon, P and D Schuurman (2015). Living labs: Concepts, tools and cases. *Info*, 17(4).

Ballon, P, M Van Hoed and D Schuurman (2018). The effectiveness of involving users in digital innovation: Measuring the impact of living labs. *Telematics and Informatics*, 35(5), 1201–1214, doi:10.1016/j.tele.2018.02.003.

Beaudoin, C, S Joncoux, J-F Jasmin, A Berberi, C McPhee, RS Schillo and VM Nguyen (2022). A research agenda for evaluating living labs as an open innovation model for environmental and agricultural sustainability. *Environmental Challenges*, 7, 100505, doi:10.1016/j.envc.2022.100505.

Berberi, A, C Beaudoin, C McPhee, J Guay, K Bronson and VM Nguyen (2023). Enablers, barriers, and future considerations for living lab effectiveness in environmental and agricultural sustainability transitions: A review of studies evaluating living labs. *Local Environment*, doi:10.1080/13549839.2023.2238750.

Carrara, F and E Freisinger (2024). Actors' activities, and interactions in innovation ecosystems: A systematic literature review and typology. *International Journal of Innovation Management*, 28(03–04), doi:10.1142/S1363919624300022.

Compagnucci, L, F Spigarelli, J Coelho and C Duarte (2021). Living labs and user engagement for innovation and sustainability. *Journal of Cleaner Production*, 289, 125721, doi:10.1016/j.jclepro.2020.125721.

Darkwa, I (2025). Innovation: Actor heterogeneity and linkages in humanitarian innovation ecosystems. *Innovation and Development*, 15(1), 63–89, doi:10.1080/2157930X.2023.2234222.

Dedehayir, O, SJ Makinen and JR Ortt (2022). Innovation ecosystems as structures: Actor roles, timing of their entrance, and interactions. *Technological Forecasting and Social Change*, 183, 121875, doi:10.1016/j.techfore.2022.121875.

Eusebio, EJG (2024). How eco-innovation affects sustainable performance: A systematic review. *Multidisciplinary Reviews*, 8(6), 2025166, doi:10.31893/multirev.2025166.

Fatoki, O (2019). Sustainability-oriented innovation and performance of small and medium enterprises in South Africa. *Journal of Environmental Management and Tourism*, 10(1), 231, doi:10.14505//jemt.v10.1(33).23.

Fauth, J, K De Moortel and D Schuurman (2024). Living labs as orchestrators in the regional innovation ecosystem: A conceptual framework. *Journal of Responsible Innovation*, 11(1), doi:10.1080/23299460.2024.2414505.

Goodman, J, M Halme and JK Juntunen (2023). Sustainability-oriented innovation for system-level impact. *Academy of Management Proceedings*, 2023(1), doi:10.5465/AMPROC.2023.141bp.

Guzmán, JG, AF del Carpio, R Colomo-Palacios and MV de Diego (2013). Living labs for user-driven innovation: A process reference model. *Research-Technology Management*, 56(3), 29–39, doi:10.5437/08956308X5603087.

Håkansson, H and J Johanson (1992). A model of industrial networks. In *Industrial Networks*, B Axelsson and G Easton (Eds.), 1st edn. Routledge.

Håkansson, H and I Snehota (1997). *Developing Relationships in Business Networks*. International Thomson Business Press.

Hansen, E, J Korhonen, R Panwar and M Hakovirta (2022). The quandary of sustainability-oriented innovations. In *The Role of Business in Global Sustainability Transformations*, pp. 185–200. Routledge, doi:10.4324/9781003003588-15.

Hossain, M, S Leminen and M Westerlund (2019). A systematic review of living lab literature. *Journal of Cleaner Production*, 213, 976–988, doi:10.1016/j.jclepro.2018.12.257.

Hsieh, S, P-Y Lin, I-H Lin, DE Beck and C-H Lin (2023). Assessing the contribution of semiconductors to the sustainable development goals (SDGs) from 2017 to 2022. *Heliyon*, 9(11), e21306, doi:10.1016/j.heliyon.2023.e21306.

Huang, JH, TA Iakovleva and J Bessant (2024). Fostering user involvement in collaborative innovation spaces: Insights from living labs. *International Journal of Innovation Management*, 28(07–08), doi:10.1142/S1363919624500324.

Kalmakova, D, Y Bilan, A Zhidebekkyzy and R Sagiyeva (2021). Commercialization of conventional and sustainability-oriented innovations: A comparative systematic literature review. *Problems and Perspectives in Management*, 19(1), 340–353, doi:10.21511/ppm.19(1).2021.29.

Klimas, P and W Czakon (2022). Gaming innovation ecosystem: Actors, roles and co-innovation processes. *Review of Managerial Science*, 16(7), 2213–2259, doi:10.1007/s11846-022-00518-8.

Konstari, P and K Valkokari (2024). Drivers and barriers for open innovation for sustainability in a shared semiconductor infrastructure. *Journal of Open Innovation: Technology, Market, and Complexity*, 10(4), 100395, doi:10.1016/j.joitmc.2024.100395.

Konstari, P and K Valkokari (2025). Value creation and capture from sustainability-oriented innovations in a shared semiconductor infrastructure. *Sustainable Technology and Entrepreneurship*, 4(2), 100104, doi:10.1016/j.stae.2025.100104.

Lakatos, ES, RL Pacurariu, AL Birgovan, LI Cioca, A Szilagy, A Moldovan and EC Rada (2024). A systematic review of living labs in the context of sustainable development with a focus on bioeconomy. *Earth*, 5(4), 812–843, doi:10.3390/earth5040042.

Leminen, S, A-G Nyström and M Westerlund (2020). Change processes in open innovation networks – Exploring living labs. *Industrial Marketing Management*, 91, 701–718, doi:10.1016/j.indmarman.2019.01.013.

Leminen, S, M Rajahonka, M Westerlund and M Hossain (2021). Collaborative innovation for sustainability in nordic cities. *Journal of Cleaner Production*, 328, 129549, doi:10.1016/j.jclepro.2021.129549.

Leminen, S, M Westerlund and A-G Nyström (2012). Living labs as open-innovation networks. *Technology Innovation Management Review*, 2(9), 6–11, doi:10.22215/timreview/602.

Leminen, S, M Westerlund and A-G Nyström (2014). On becoming creative consumers – User roles in living labs networks. *International Journal of Technology Marketing*, 9(1), 33, doi:10.1504/IJTMKT.2014.058082.

Lu, H, Y Zhang, J Jiang and G Cao (2025). Do market-based environmental regulations always promote enterprise green innovation commercialization? *Journal of Environmental Management*, 375, 124183, doi:10.1016/j.jenvman.2025.124183.

Molinari, M, J Anund Vogel, D Rolando and P Lundqvist (2023). Using living labs to tackle innovation bottlenecks: The KTH live-in lab case study. *Applied Energy*, 338, 120877, doi:10.1016/j.apenergy.2023.120877.

Morsy, M, F Znid and A Farraj (2025). A critical review on improving and moving beyond the 2 nm horizon: Future directions and impacts in next-generation integrated circuit technologies. *Materials Science in Semiconductor Processing*, 190, 109376, doi:10.1016/j.mssp.2025.109376.

Nyström, A-G, S Leminen, M Westerlund and M Kortelainen (2014). Actor roles and role patterns influencing innovation in living labs. *Industrial Marketing Management*, 43(3), 483–495, doi:10.1016/j.indmarman.2013.12.016.

Paskaleva, K and I Cooper (2021). Are living labs effective? Exploring the evidence. *Technovation*, 106, 102311, doi:10.1016/j.technovation.2021.102311.

Ruberti, M (2024). Environmental performance and trends of the world's semiconductor foundry industry. *Journal of Industrial Ecology*, 28(5), 1183–1197, doi:10.1111/jiec.13529.

Ståhlbröst, A (2012). A set of key principles to assess the impact of living labs. *International Journal of Product Development*, 17(1/2), 60, doi:10.1504/IJPD.2012.051154.

Ståhlbröst, A and BB Kareborn (2011). Exploring users motivation in innovation communities. *International Journal of Entrepreneurship and Innovation Management*, 14(4), 298, doi:10.1504/IJEIM.2011.043051.

Toffolini, Q, M Capitaine, M Hannachi and M Cerf (2021). Implementing agricultural living labs that renew actors' roles within existing innovation systems: A case study in France. *Journal of Rural Studies*, 88, 157–168, doi:10.1016/j.jrurstud.2021.10.015.

Valkokari, K, CC Amitrano, F Bifulco and T Valjakka (2016). Managing actors, resources, and activities in innovation ecosystems – A design science approach. In *IFIP Advances in Information and Communication Technology*, Vol. 480, pp. 521–530, doi:10.1007/978-3-319-45390-3_44.

Valkokari, K, K Hyytinen and J Levasluoto (2024). Living labs as enablers for collaborative innovation – Exploring success factors and impacts. *Journal of Innovation Management*, 12(3), 158–174, doi:10.24840/2183-0606_012.003_0007.

von Wirth, T, L Fuenfschilling, N Frantzeskaki and L Coenen (2019). Impacts of urban living labs on sustainability transitions: Mechanisms and strategies for systemic change through experimentation. *European Planning Studies*, 27(2), 229–257, doi:10.1080/0965 4313.2018.1504895.

Voytenko, Y, K McCormick, J Evans and G Schliwa (2016). Urban living labs for sustainability and low carbon cities in Europe: Towards a research agenda. *Journal of Cleaner Production*, 123, 45–54, doi:10.1016/j.jclepro.2015.08.053.

Yin, RK (2018). *Case study Research and Applications*, L Fargotstein (Ed.), 6th edn. SAGE Publications, Inc.

Publication V

Konstari, P., and Valkokari, K.
Integration of multi-disciplinary environmental sustainability aspects into early-phase microelectronics research and development

Reprinted with permission from
Discover Sustainability
6, 1089

Discover Sustainability

RESEARCH Open Access

Integration of multi-disciplinary environmental sustainability aspects into early-phase microelectronics research and development

Piia Konstari[1*] and Katri Valkokari[2]

*Correspondence:
Piia Konstari
piia.konstari@vtt.fi
[1]Microelectronics and Quantum Technology, VTT Technical Research Centre of Finland, PO Box 1000, 02044 Espoo, Finland
[2]Foresight and Data Economy, VTT Technical Research Centre of Finland, PO Box 1300, 33101 Tampere, Finland

Abstract
The environmental impact of a device is to a large content defined in the device design phase. Hence, it is of importance that the researchers understand how they can affect the environmental sustainability of a microelectronics device and what are the relevant topics that can be affected during the early phases of research and development of new microelectronics devices. Through participatory and multi-disciplinary design science research, we develop a design science artifact for knowledge integration of how environmental sustainability can be considered during the early phases of microelectronics research and development projects in a research and technology organization. In addition, we present different aspects that during the design science research was found to affect efficient knowledge utilization of sustainability related knowhow from other departments of the research and technology organization. Our design science artifact is a practical innovation management tool for how environmental sustainability could be brought into every microelectronics researcher's awareness without costly additional work. In addition, we highlight aspects that are important to consider for successful knowledge integration within multi-disciplinary organizations. Managers can use our results as a starting point in working out a cost-efficient approach for how to consider environmental sustainability in early-stage research and development projects in their microelectronics departments.

Keywords Design science, Early-phase sustainability evaluation, Environmental sustainability, Innovation management, Knowledge utilization, Research and development, Research and technology organization

1 Introduction

Semiconductors contribute to eight of the United Nation's (UN) Sustainable Development Goals (SDGs) and are hence needed for the sustainable transition of our society [1]. The advancement of our digital society, particularly with the increased adoption of artificial intelligence (AI) and the rising demand for substantial computing capacity, will significantly amplify the need for semiconductor chips over the next decade [2]. Semiconductor technology is based on a variety of materials that have been selected for their

unique properties and contributions to device performance [3], of which several are critical raw materials (CRM) [4, 5]. Integrated circuits (ICs) made with semiconductor technology are complex devices needing state of the art semiconductor manufacturing technology, the costs of which can be tens of billions of dollars [6].

Semiconductor manufacturing is heavily energy, water and CRM consuming [5]. Energy can constitute up to 30% of the semiconductor companies' costs, underlining the importance of energy for semiconductor manufacturing. Semiconductor manufacturing causes green-house gas (GHG) emissions that contribute to the climate change [7] among other environmental impacts. Some nitrogen and phosphorous acids used in the manufacturing get mixed with water and contribute to water eutrophication. In addition, semiconductor processing uses several rare materials [8] of which many are highly poisonous.

Global and regional regulations have been put in place since 1997 to reduce GHGs, including carbon taxes and emission trading systems, as well as environmental, social, and governance (ESG) management practices and the Corporate Sustainability Reporting Directive (CSRD). Semiconductor manufacturing companies are deeply engaged into these [9]. Decarbonization of the scope 3 emissions in the semiconductor industry can be grouped to four levels: supplier decarbonization, waste reduction, material optimization and product specification. Of these, the last one is the most complex to implement [10]. Downstream and upstream supply chain strategies have been found to be both important in general for sustainability and circularity [11]. The resource optimization of semiconductor supply chains is important for minimizing their environmental impact [5].

Product sustainability examines how products can generate economic advantages for businesses while simultaneously delivering environmental and social benefits to society as a whole [12]. The semiconductor industry is expected to achieve reductions in greenhouse gas emissions while simultaneously increasing product performance and reducing costs. A more sustainable material or manufacturing option cannot always be used without compromising the device performance.

According to current understanding, the environmental impact of a product is widely defined in the early product design phase [12]. Hence, environmental sustainability related topics should be considered as early as possible when it is still possible to affect the design [13]. There is space for innovative approaches and solutions for reducing scope 3 emissions through product design choices. Product design choices include factors related to material, production, use and end of life [13]. In the semiconductor field, practical examples for more environmentally sustainable options include alternative computing architectural solutions to the complementary metal–oxide–semiconductor (CMOS) technology are suggested to be one possibility [14], and environmentally friendly electronics materials has long been another active research area [15].

For environmental sustainability assessment of products, life cycle assessments (LCAs) [16, 17] or life cycle assessment based eco-tools [18–20] are the most common ones. In addition, there are some qualitative sustainability assessment tools available [21]. In specific industries, for example early-phase automotive product development checklists for sustainable product development have been suggested [22], and for chemical process development sustainability indicators [23]. Circular economy methods such as design for reduce, reuse and recycling, are likewise a widely studied concept [24, 25].

Most of the previously suggested approaches are, however, developed for mass produced end products, and require a magnitude of life cycle inventory data and understanding and consideration of the entire product life cycle. The tools are best suited for mass manufactured products with a clear end use application and known manufacturing place. The tools are not designed to be used for early-phase device development for multiple use cases, that can be part of several different end products and hence lack accurate inventory data. In addition, the continuous technology development makes it difficult to obtain lifetime inventory data for semiconductor devices and hence faster assessment methods are required for the R&D phase [5]. Recent studies recognize the lack of and urge for development of early-phase industry-specific new product development tools for sustainability facets integration [26].

Multi-disciplinary research and technology organizations (RTOs) coordinate and participate in large research and development (R&D) projects with public and private entities at both national, European and global level. Consequently, RTOs with microelectronics departments significantly influence innovation activities and the development of the global electronics industry. They play a crucial role in promoting sustainability and innovation within their organizations and the broader ecosystem as they develop next generation technologies for companies. The sustainability-oriented innovation (SOI) activities at European RTOs have recently been studied and their role in the green innovation ecosystems around them discussed [27].

The R&D projects at RTOs typically have a defined budget and a detailed statement of work. Hence, to include some level of environmental sustainability consideration into every R&D project, increasing sustainability awareness among RTO researchers is of importance for making the electronics industry more sustainable. Even though every R&D project does not directly concern sustainability, there should be ways to include sustainability consideration into every microelectronics R&D project in an RTO in a cost-efficient manner. Hence, it is of importance that the researchers understand the environmental impact of their choices and can evaluate these aspects of the future product in their R&D work [28–30].

Multi-disciplinary RTOs have several departments with deep expertise in different fields. Microelectronics departments concentrate typically on microelectronics development and might lack deep knowledge of for example sustainability related topics. Earlier research has shown that in the semiconductor field only a small number of employees have specific deep know-how and knowledge to design certain semiconductor devices as the required know-how is so specialised [31]—they are deep tech experts. Within the microelectronics industry it is a rather new topic to consider sustainability in R&D due to the demand of superior technical performance [32, 33]. A small number of technical experts recognizes the necessity of adapting their work practices and thought processes in response to environmental sustainability. A significant number of these deep tech professionals remain unaware about what sustainability means and how it could potentially be considered in their work as they have traditionally focused only on their field. Therefore, new approaches for including sustainability consideration in microelectronics R&D projects and for increasing sustainability awareness among researchers are essential to foster a sustainability-oriented innovation (SOI) approach in microelectronics R&D projects.

The research gap this study tackles is to develop a cost-efficient approach for how environmental sustainability can be considered in early-phase microelectronics R&D at an RTO when only a limited amount of information about the end product or its life cycle is available, there is no funding for LCAs, and the developed device must meet clear technical performance targets. This research also investigates what aspects affect efficient multi-disciplinary environmental sustainability knowledge integration into microelectronics R&D. Even though there are research of early-phase approaches in other industries, the authors have not managed to identify any prior research related to this specific topic. The main research questions (RQs) for this study are:

RQ1: How can environmental sustainability be considered at an RTO during early-phase R&D of microelectronics devices?

RQ2: What aspects affect multi-disciplinary environmental sustainability knowledge integration into microelectronics R&D at an RTO?

This study is conducted using a longitudinal participatory design science approach within a Finnish RTO's microelectronics department during a 2-year period from spring 2023 to spring 2025. The purpose of this design science study is to develop an artifact for how environmental sustainability could be considered in a cost-efficient manner in early-phase microelectronics R&D when sustainability assessment as such is not necessarily included in the R&D project scope. The study also investigates aspects affecting efficient environmental sustainability knowledge utilization from the multi-disciplinary RTO for this purpose. In addition to workshops, bi-yearly surveys are used as supporting material to map the researchers' thoughts about sustainability in general.

The main theoretical contribution of this study is the design science artifact—an approach for how environmental sustainability could be evaluated in a cost-efficient manner during early-phase microelectronics R&D projects, as well as understanding of the aspects affecting utilization of environmental sustainability knowledge siloed into other departments of a multi-disciplinary RTO. The study provides evidence of how challenging it is to evaluate environmental sustainability cost efficiently in the R&D phase when there is no specific funding available for sustainability assessment, as well as to how challenging it might be to exploit knowledge siloed into different parts of the organization. However, the study also provides evidence that through the developed artifact, an innovation management tool, relevant topics for the microelectronics RTO can be brought to discussion to raise environmental sustainability related awareness among the researchers.

The structure of this paper is as follows: Section 2 present the most relevant literature findings for this study. Section 3 presents the research design and data analysis. Section 4 presents the findings and discusses them. Section 5 concludes the study, explains its limitations and gives suggestions for further research.

2 Literature review

This research is multi-disciplinary and combines deep understanding of semiconductor technology R&D with environmental sustainability assessment, as well as knowledge utilization related to innovations that promote environmental sustainability. This section presents the most important findings from the literature for this research.

2.1 Sustainability and sustainability assessment in the semiconductor industry

The current academic discussion of sustainability in the semiconductor industry is on sustainable semiconductor industry supply chains and their management [7, 34, 35], on green energy and water efficiency [36], efficient manufacturing [37–40], waste management [41], and sustainability-oriented innovations (SOI) and the value creation and capture of them in shared semiconductor infrastructure [32, 33], as well as green innovation ecosystems [27]. Recent reports from consulting firms on sustainability within the semiconductor sector emphasize the importance of addressing the supply chain and mitigating greenhouse gas (GHG) emissions across Scope 1, 2, and 3 categories [10, 42–44].

On an organizational and more general level, different conceptual frameworks for sustainable innovation in organizations has been suggested in the literature [45, 46]. In addition, there is a vivid discussion about integration of sustainability into organizational strategy, projects and project management, and products [47–52]. These papers consider, however, sustainability on a more general—organizational-level, and does not deal with the topic now in our hands.

Life cycle assessments (LCAs) is the most common sustainability assessment method also for semiconductors [17, 53–56]. However, LCAs are rather time-consuming and laborious to conduct. To give accurate results, they require good quality inventory data over the entire product life cycle that is most often difficult to obtain [57]. Methods for how to simplify the LCA process have been suggested by e.g. modular approaches [58]. Other LCA-based tools have been suggested in the semiconductor field, e.g. [18, 59], with focus on the manufacturing side. In addition, other qualitative eco-tools have been suggested for e.g. the printed electronics field [21]. A questionnaire-based approach has been suggested for the automotive industry [22], ad an indicator based for early-phase process development in the chemical industry [23].

Even though there are several LCAs, green- or eco tools available, none of them addresses the specific case under study in this paper. The suggested tools are mainly LCA based and the inventory data they require is not available in microelectronics R&D projects, making their outcomes unreliable. The most promising candidate for further study is the green tool develop for printed electronics as it is based on discussions [21] and addresses an industry that is providing building blocks for several end applications. Nevertheless, there is a clear research gap to tackle on this practical level that this paper addresses.

2.2 Knowledge sharing and knowledge exploitation

Knowledge utilization includes knowledge sharing, knowledge exploitation and -exploration. Thereby, knowledge utilisation aims to incorporating complementary knowledge into a body of existing knowledge with a multidisciplinary setting, i.e. knowledge integration process between researchers from the different units of the RTO.

2.2.1 Knowledge sharing

The ability to effectively share knowledge within organizations is key for the organization's competitiveness [60]. In the technology industry, the barriers for knowledge sharing in the software industry have been identified to be knowledge-, individual-, or organization related [61]. An alternative grouping for barriers for knowledge sharing has been proposed as individual/personal, organisational, and technological barriers [62].

Factors mostly affecting knowledge sharing within organizations are trust, communication, reward systems, and leadership [63]. Trust, appreciation, management support, and organisational goals have been identified to facilitate collaboration in knowledge sharing through face-to-face meetings, a chief knowledge officer, technology to support knowledge sharing, and collaboration via a weblog [64].

Successful tacit knowledge sharing in knowledge intensive high-tech companies is crucial. Factors affecting this are related to the individuals and the environment, and effective knowledge sharing requires often change of organizational structure, focus on interpersonal relationships, motivation and evaluation mechanisms, and informal organizations [65]. Knowledge sharing through personal interaction is key for enhancing the innovation capability, whereas ICT-based mechanisms are of secondary importance [66].

Identified factors hindering knowledge sharing in engineering organisations were communication among employees, trust, task interdependence, organisational structure, reward and recognition, and attitudes. Gender and job level significantly affected knowledge sharing, highlighting vertical organisation structure and gender bias [67].

Knowledge sharing in complex R&D projects faces barriers such as codification, inadequate information technology (IT) support, lack of initiative and strategy, and insufficient time and resources. Collaboration within large international R&D teams, consisting of diverse organizations operating in different locations, encounters challenges like information exchange and retrieval, communication barriers, interdependence of knowledge and skills, and varying technical terminology [68].

2.2.2 Knowledge exploitation and exploration

Knowledge exploitation is the use and further development of existing competencies, whereas knowledge exploration is the development of new ones. These need to be balanced within organization to stay competitive [69]. Knowledge exploration is mainly affected by learning culture, autonomy, and IT systems, whereas knowledge exploitation is closely linked to collaborative leadership and learning culture of organizations [70].

The challenges with economic, environmental and social sustainability knowledge exploitation for SOIs have been recognized and one of the main factors has been identified to be linked to challenges with knowledge acquisition [71]. Strategic exploitation and exploration of knowledge is of importance for the development and deployment of sustainable technologies [72].

There exists numerous prior research related to knowledge sharing and exploitation, highlighting important factors affecting those. However, the authors have not managed to locate any prior research related to multi-disciplinary knowledge integration within an RTO for sustainability evaluation. Hence, there is a research gap in the intersection of the microelectronics R&D and RTO that requires further investigation—what aspects affect the knowledge utilization in deep tech R&D projects in a multi-disciplinary RTO.

3 Design science research approach

The aim of this study is to develop an artifact which enables cost-efficient evaluation of environmental sustainability topics in all early-phase microelectronics R&D projects in an RTO. In addition, as sustainability is a multi-disciplinary topic, this study investigates

the aspects affecting effective environmental sustainability knowledge integration from different departments of the RTO.

A design science approach was selected as the research method as the aim is to discover and solve a problem and to bridge practice to theory [73]. Design science approach was considered the best option as the microelectronics department wanted to tackle the topic in practice together through an engaging discussion, taking advantage of in-house multi-disciplinary knowhow and to involve key experts in the process. The role of the corresponding author was to drive the knowledge integration process forward.

The result of the design science research is an artifact for how sustainability can be considered in early-phase microelectronics R&D. The aim is that the artifact will be taken into use as an evaluation tool in the R&D projects at the department to make informed decisions and choices in projects with the aim to find a balanced option with regards to environmental sustainability. In addition, aspects affecting knowledge integration from the different departments at the RTO were mapped as they became evident during the design science research process.

The research was done as participatory research [74] in the microelectronics department of a Finnish RTO. The specific department includes around 230 researchers in the field of microelectronics and quantum technologies and about 20 managers. Of these, in total a core group of 15 persons were involved in the design science research. The specific department was selected for this study as the corresponding author is part of it and could conduct and drive the study as participatory research, affect the outcome thanks to her industry experience and insights, and access also confidential information relevant for this study.

Data was collected in three ways: (1) as a research diary of discussions, events and decisions affecting the research questions, (2) through engaging workshops, and (3) through anonymous surveys during bi-yearly department meetings. Figure 1 illustrates the research workshop stages and timing of survey data collection. The research diary was collected by the corresponding author during the entire two-year period.

The design science research artifact for environmental sustainability evaluation was configured through several engaging workshops including around 15 persons including both microelectronics department researchers as well as experts from other departments on sustainable electronics, biodegradable electronics, material design and sustainable supply chains. Table 1 summarises the content and outcome of the multi-disciplinary workshops that were held in three stages. These stages reflect the thought process and goal setting at the microelectronics department, and they correspond to the real development need and work done at the RTO.

Possible environmental sustainability aspects for microelectronics were evaluated and debated among the multi-disciplinary workshop participants: fabrication related topics like number of lithography layers versus device area on the wafer, amount of used raw

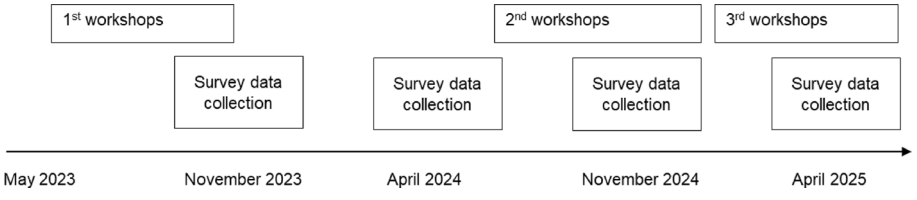


Fig. 1 Illustration of the research data collection stages

Table 1 Summary of the workshop stages and their outcomes

Design Stage	Timing	Core development team	Target	Outcome
1st workshops	June 2023–September 2023	Microelectronics department core management team, around 5 persons	Define preliminary sustainability approach for the research area based on literature review and discussions	Understanding that the research area should consider sustainability on multiple levels: manufacturing, material selection, device design, system architecture, and choice of target application
2nd workshops	August 2024–February 2025	Around 15 scientists including experts for microelectronics and electronics design and processing, chemists, material design and supply chain specialists, recycling generalists and innovation management specialists	Adopt the Green Tool for the microelectronics field from [21]	Understanding that adoption of the green tool for microelectronics will not serve the research areas purposes as it is too time consuming, and the life cycle data needed is not available in the early-phase R&D phase at RTOs, and the researchers cannot affect the categories in the tool
3rd workshops	March 2025–April 2025	Microelectronics department management team, around 6 persons	To find a solution for how sustainability should be considered in the research areas early-phase work without a digital tool to increase sustainability awareness and make it a competitive advantage	Decision to move the sustainability discussion to research projects with help of an identified set of key questions and management sparring: project application, design, fabrication, lifecycle perspective, and raw materials

Table 2 Summary of survey participation

Survey	Number of answers
8.11.2023	76
24.4.2024	73
28.11.2024	50
24.4.2025	25

materials and their sustainability, type of equipment needed etc. The main discussion was about what can a researcher affect and what should he or she consider in an early-phase microelectronics R&D project that affects environmental sustainability when the project has a clear budget and scope that does not necessarily include sustainability assessments.

The challenges with LCAs, as well as the Green Tool developed by Hakola et al. [21] were recognized for this specific field: they require understanding of the entire life cycle, they require detailed inventory data, they are better suitable for mass produced devices or products, and as the effect of one microelectronics device on the entire life cycle of an end product is negligible, is alternative approaches needed. Hence, during the workshops it became clear that a simpler more engaging approach was needed to meet the goals of the microelectronics department.

The results of the workshops were presented to the microelectronics department bi-yearly and feedback on the suggested approach was collected through surveys in bi-yearly department meetings. The number of anonymous survey results are summarized in Table 2. The surveys were held always after a presentation of the sustainability topic and workshop outcomes. Summary of the survey results are presented in Appendix.

The survey results were reviewed by the department management and considered in the workshops.

4 Findings and discussion

This section presents the key findings and discusses them.

4.1 Developing an approach for how environmental sustainability can be addressed in early-phase microelectronics R&D

Through an active and inclusive design science approach during the workshops presented in Table 1, and consideration of both the survey feedback in Appendix as well as general comments and discussions within the management team and the researchers of them microelectronics department, finally an approach for how environmental sustainability should be considered in microelectronics R&D at the RTO was formed. Next, the process behind it is explained.

There are a limited number of topics that the researcher can affect in early-phase R&D projects. The R&D project has a clearly defined budget and statement of work with expected outcomes. As it is common that sustainability assessment as such is not part of the statement of work, it would bring additional value and impact to the project outcomes if the researchers were sufficient aware of how environmental sustainability could be considered during the R&D project and if they were able to independently do the evaluation.

In the first workshops, the team recognized that in early-phase R&D work, there is no exact understanding available of how and where the entire end product will finally be built, about its use phase, lifetime or disposal phase. What can be affected at early-phase R&D is especially choice of materials, the device design, the effect of the device design on the system architecture of the end product, as well as the device fabrication options.

While doing R&D of next-generation microelectronics devices, the researcher makes a multitude of decisions related to what materials he or she uses, how is the layout of the device, how is it fabricated and tested etc. All these aspects include decisions that affect the energy consumption of the device, the probability of reaching technical performance requirements, energy consumption of the fabrication and testing processes, materials used, and the amount of material needed for the fabrication etc. These should be thoroughly considered and evaluated to minimize the environmental impact without compromising the technical performance requirements set forth in the statement of work of the project. Based on this, the first workshops ended up with suggesting the approach shown in Fig. 2.

In the second workshops, the idea of moving the first workshop results to the Green Tool categorization developed in-house by Hakola et al. [21] for printed electronics was investigated: raw materials, manufacturing, logistics, installation & maintenance, use, end-of-life, sustainability maturity. The aim was to make a digital tool that the researchers could use independently for the environmental sustainability evaluation. However, the feedback received from researchers already in the workshops and then in the surveys (see Appendix) was that they did not wish for any digital tool but for discussion and awareness sharing—they did not feel that they had enough knowledge about sustainability and digital tools were only seen as laborious and time consuming.

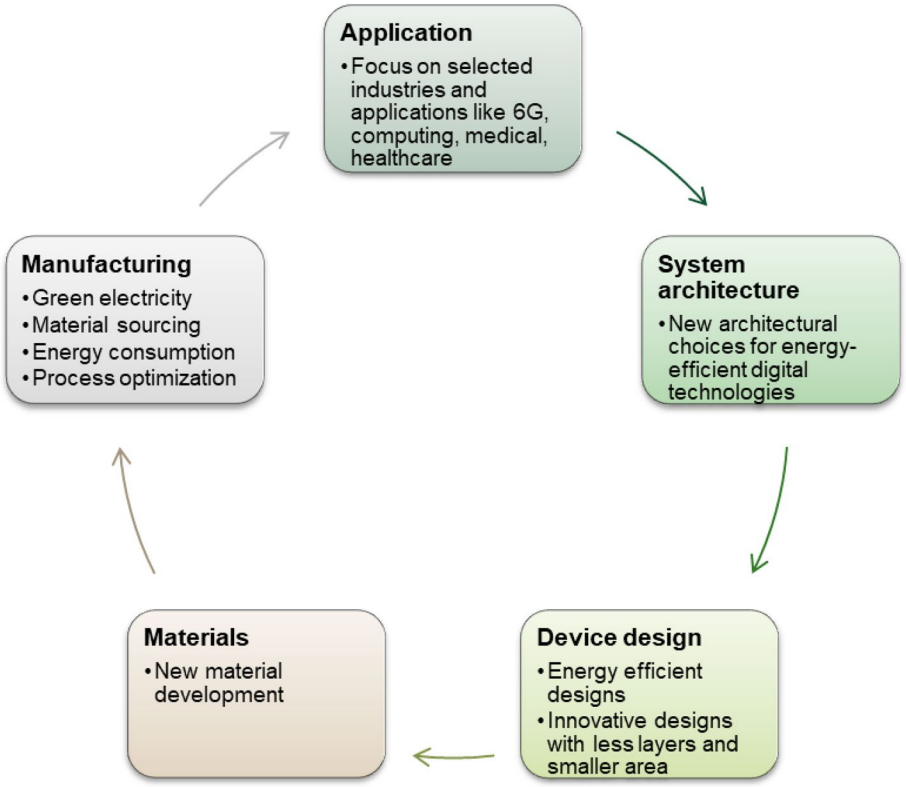


Fig. 2 The result of the first workshops: In microelectronics R&D projects environmental sustainability should be considered on multiple levels: application, system architecture, device design, materials, manufacturing. manufacturing, materials selection, device design, system architecture, and choice of target application

Furthermore, as the Green Tool by Hakola et al. [21] was tried out in the second workshops on certain microelectronics devices like quantum circuits, it became clear that the life cycle evaluation outcome resulted in pretty much similar results for all devices—the study was on a too high level compared to the work done in early-phase microelectronics R&D. The differences came from things like e.g. are the devices batch manufactured or does the devices require single-wafer manufacturing steps. This difference is similar to that is the device under development ready for volume manufacturing or not and does hence not fulfil the requirements for the environmental sustainability assessment that the management was looking for. Hence, another approach was needed.

In addition, after discussions in the workshops, the Green Tool is a qualitative comparative tool, and hence it was not considered suitable for evaluation of typical early-phase R&D projects at the RTO. The RTO most often develops next generation technologies, which have a different performance requirement than current generations. If, for example, the power transfer requirement in the next generation devices is triple the one of the current generations, is the sustainability comparison with such a comparative tool irrelevant.

Consequently, in the third and final workshops, the design science artifact took form as interactive discussion questions, to be addressed together with the researchers. This approach is shown in Fig. 3. In addition to the topics already identified in the first workshops, the workshop participants considered it important to discuss also some additional aspects in the R&D projects. First of all, target of R&D work—the application, its importance and impact for the future digital society, and to be able to describe it. And

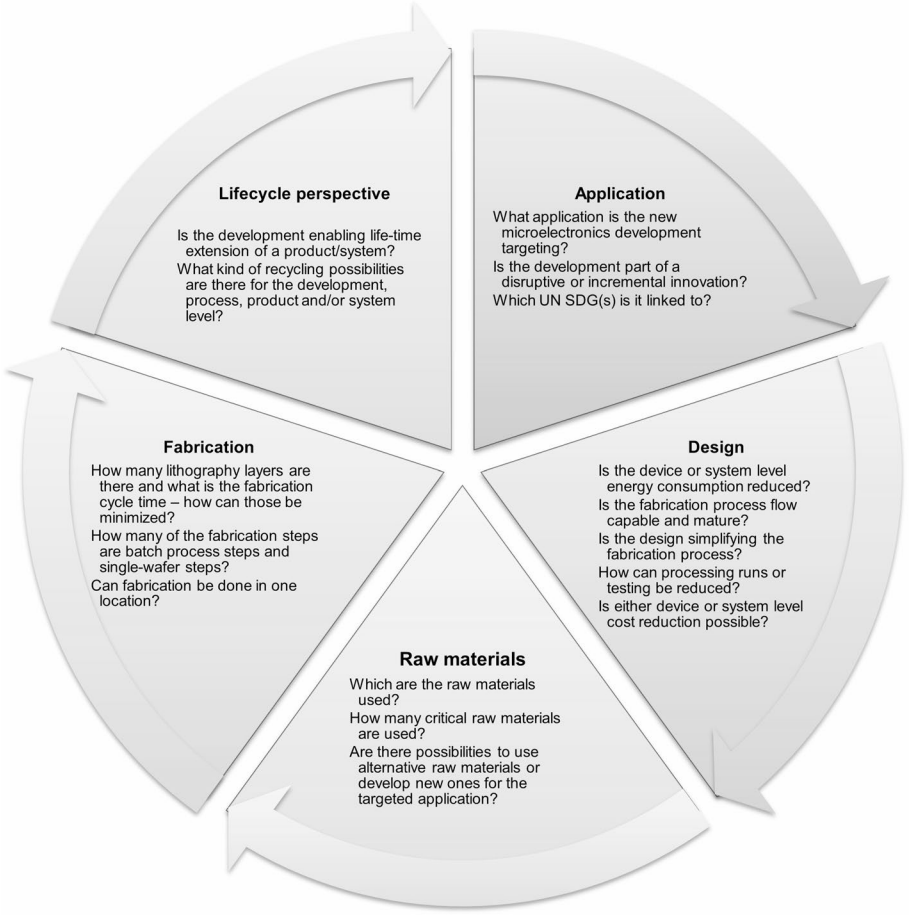


Fig. 3 The design science artifact for how environmental sustainability should be discussed and evaluated through practical aspects that can be affected in early-phase microelectronics R&D projects at an RTO

secondly, lifetime perspective in the extent that possible—can the lifetime of the end product somehow be affected at all through the project under work?

The researchers and management representatives were strongly in favour of an inclusive approach, aiming at knowledge integration of knowhow that is already available both in the own department but also in other departments of the RTO. The key for this design research artifact in Fig. 3 is that it makes environmental sustainability an interactive evaluation and discussion topic into all research projects, motivating to pull in experts from other departments and integrate knowledge that is available elsewhere in the organization on for example CRMs and sustainable supply chains. The aspects to consider are rather practical ones and discussing through these should not consume enormous amounts of time and are hence a cost-efficient evaluation approach. In addition, the approach raises awareness and builds bridges between the different RTO departments, paving the way for discussions with a common vocabulary.

The answer to our first research question is hence that environmental sustainability should be considered in microelectronics R&D projects at an RTO by discussing and evaluating the aspects shown in Fig. 3.

Earlier research has suggested different kinds of eco- or green tools for sustainability assessment of semiconductor products, most of them based on LCA analysis [16, 18, 55]. On product sustainability level, the evaluations are, on the other hand on an innovation

management level [75]. None of these explores the possibilities of bringing sustainability on every researcher's table to make all employees accountable and increase sustainability awareness among the microelectronics researchers during early-phase R&D projects. There are sustainability assessment tools at different levels in the organization, and our artifact in Fig. 3 suggests an approach for the operational level.

Our design science artifact in an innovation management tool for knowledge integration of environmental sustainability and technical semiconductor device development knowhow. With technology development moving forward, deep knowhow of different disciplines will be necessary for the development of new technology generations. This design science artifact is one step towards making a practical guide for how all microelectronics researchers could consider environmental sustainability related aspects in their early-phase R&D projects.

4.2 Aspects affecting multi-disciplinary knowledge integration in an RTO

As was seen in the previous section, evaluation of environmental sustainability in microelectronics R&D projects requires expertise in several disciplines. During the workshop phases, the following knowledge aspects were found to be important for the evaluation of microelectronics environmental sustainability: knowledge about semiconductor technology, knowledge about electronics, knowledge about chemistry, knowledge about material sciences, knowledge about sustainability, as illustrated in Fig. 4. This expertise is not always available within the same organizational department of the RTO but located somewhere else in the organization somewhat siloed. Various aspects affect the finding and integration of required knowledge for the purpose of environmental sustainability evaluation of microelectronics R&D projects.

Our design science study indicates a genuine interest in engaging with and understanding the topic of sustainability. However, it was found that a digital tool alone is insufficient due to the complexity of the subject. For complex, multi-disciplinary topics like how to consider environmental of sustainability in microelectronics R&D, leadership, coaching and interaction turned out to be key for successful multi-disciplinary knowledge integration from other RTO departments. Several other aspects were also seen to affect efficient knowledge exploitation within the RTO. These aspects were encountered during the participatory research in daily work and during the workshop phases.

Figure 5 presents the aspects recognized during this study that affect multi-disciplinary environmental sustainability knowledge integration from other departments within the RTO to the microelectronics department and forms the answer to the second

	Application	Design	Raw materials	Fabrication	Lifecycle perspective
Chemistry					
Electronics					
Materials science					
Semiconductor technology					
Sustainability					

Fig. 4 Knowledge required for the evaluations of the environmental sustainability aspects for microelectronics R&D

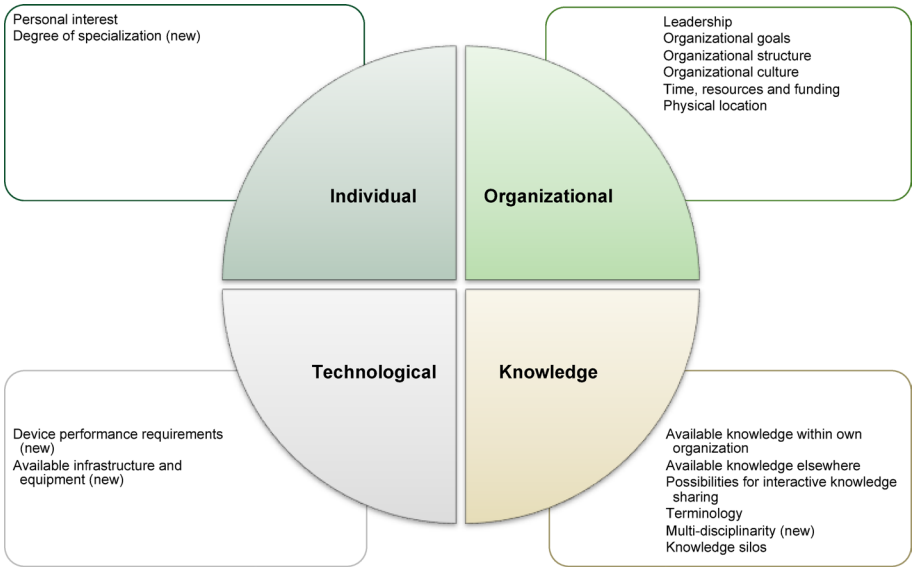


Fig. 5 Aspects affecting multi-disciplinary environmental sustainability knowledge integration from different RTO departments. The newly recognized ones are marked with (new)

research question. Figure 5 includes both aspects earlier identified in the literature but introduces also new ones specific for our study, as explained next.

The level of individual interest in sustainability clearly affects the engagement of employees in sustainability related activities. The importance of personal engagement for knowledge sharing was identified earlier also by e.g. Riege [62] and Wei [65]. Survey responses showed that many researchers were not either interested in sustainability or did not see any practical ways in how they could affect sustainability. During workshops, it became clear that employees who were deeply specialised in one specific topic—something that is very typical in the semiconductor industry [31]—had challenges with absorbing and adopting new ways of thinking and seeing the broader picture and impact. The aspect of degree of specialization has not been highlighted in earlier research as affecting knowledge utilization.

On the organizational level, leadership commitment is the key for inclusion of sustainability in the R&D work. The survey results show a drop in engagement and responses between April 2024 and November 2024, and even further drop to April 2025. During this time, there was also less push from management on the sustainability topic. In case the organizational goals do not reflect the importance of sustainability, it is difficult to motivate the organization to engage, look for or utilize knowledge. This was identified also by Gonzalez and de Melo [76] and Saénz et al. [66].

The organizational structure affects which employees come into discussions with each other. This finding is line with Mushtaq and Rizwan [67] and Santos et al. [68]. And the organizational culture affects the way employees interact over organizational boundaries and how eager they are to suggest novel solutions, hence playing an important role for adoption of new practices. Available time, available resources and available funding heavily affects where employees put their efforts, and the physical location of the employees can for example favour sporadic information exchange and brainstorming,

affecting engagement in sustainability topics. The challenge with time, resources and different locations had been earlier identified also by Santos et al. [68].

Knowledge, its availability or lack of it, the possibilities to share it, and access to cross-disciplinary information, all play a crucial role in introducing sustainability into an organization. Tura et al. [71] earlier also encountered the challenge with knowledge acquisition. Integration of sustainability into a deep tech field like microelectronics or semiconductor technology requires deep understanding of several disciplines. It is not enough to be expert in one field; it is important to have deep understanding of both sustainability as well as of the deep tech field to be able to include sustainability consideration into daily R&D work. Different terminologies between different disciplines might become a challenge, if the researchers do not understand each other—something that was recognized by Santos et al. [68].

During workshops the communication was sometimes challenging as the deep tech experts did neither talk the same language, nor understand the basics of each other's disciplines to be able to evaluate feasible sustainability approach possibilities for the microelectronics industry. For example, it is not possible to stop use hydrogen fluoride (HF) in semiconductor technology just because its hazardousness, as the entire industry is built around the etching properties of silicon and silicon dioxide in HF. Hence, multi-disciplinary understanding is a must for efficient knowledge exploitation of relevant fields for being able to consider environmental sustainability related aspects in microelectronics R&D projects. This aspect has not been highlighted earlier in the academic literature but forms a clear barrier for knowledge utilization. The barrier can be overcome by defining relevant concepts early in the workshops and by utilizing an intermediator for running the workshops who understand different disciplines and can translate the used vocabulary between those.

In addition, sustainability knowledge siloing in the organization results in that it is not exploited in other parts of it—i.e. siloing is a barrier for knowledge utilization. There is a need of interactive encounters and discussions, something that was also identified by Saénz et al. [66]. This could be affected through management practices and through e.g. organizing RTO level knowledge sharing and networking events where different departments could share information about their expertise and sporadic encounters could take place.

Lastly, technology limits the possibilities for efficiently putting into use and exploiting knowledge. This aspect was not encountered in any of the previous studies, except in the form of availability of digital tools that were mentioned by Riege [62], Sensuse et al. [64], and Saénz et al. [66], and the last one of these claimed that the digital tools were in any case of secondary importance. Microelectronics devices often have such advanced performance requirements that R&D work must be done with a performance first attitude, and optimization for sustainability can only be considered at a later stage of the development process when the technology has already matured somewhat and is being mass manufactured.

In addition, available manufacturing equipment and tools in many ways dictate the possibilities for environmental sustainability actions. Researchers are not eager

to explore alternative paths for R&D practices if they can barely meet the minimum requirements set forth by performance expectations in disruptive developments in project's statement of works. The case is naturally different if sustainability is the focus of a project and the key topic of the development in question. In any case, environmental sustainability can only be considered within the limits dictated by available manufacturing equipment related to e.g. energy consumption, and hence the technology affects the possible level of efficient knowledge utilization and implementation in practice.

Our findings coincide in many ways with previous research, by underlining the importance of interaction and leadership. Digital tools are after all a secondary priority when the aim is to change ways of working and exploit existing knowledge. Our findings bring forward also new aspects affecting knowledge utilization form different departments in RTOs for the use of considering environmental sustainability in microelectronics R&D projects and highlights the challenge of siloed knowledge and challenges for researchers from different disciplines to use common terminology.

5 Conclusions

This study has been conducted as a longitudinal participatory research study in a microelectronics department of a Finnish RTO during a period of two years in 2023–2025. The first focus of this study was on developing an approach for how multi-disciplinary environmental sustainability knowledge could be integrated in early-phase microelectronics research and development projects. We presented the answer to this research question in Fig. 3. In addition, this study looked for understanding which aspects affect the efficient multi-disciplinary environmental sustainability knowledge integration from different departments in the RTO into microelectronics R&D. We presented the identified aspects in Fig. 5.

Our paper is among the first longitudinal studies of how environmental sustainability could be considered in early-phase microelectronics R&D projects in a cost-efficient manner, bringing the sustainability subject on every researcher's table. Our design science artifact is important for advancing environmental sustainability awareness in the specific Finnish microelectronics RTO under study. Our results will help researchers to consider environmental sustainability related aspects in their early-phase R&D projects and hence help them to learn to evaluate the impact of their choices for the electronics industry. Our results indicate key aspects that management should consider to prevent barriers for multi-disciplinary knowledge integration between different RTO departments.

The main contribution of this study is the environmental sustainability artifact presented in Fig. 3, as well as the aspects affecting knowledge utilization in Fig. 5, that are linked to a specific context and discipline. These are innovation management tools for multi-disciplinary knowledge integration. Academics can use these results to understand the practical challenges researchers encounter in microelectronics R&D projects when aiming for considering environmental sustainability on a very practical level in their work. Managers can use the results as basis for consideration and discussion about how they could raise environmental sustainability awareness through interactive discussions

in their R&D departments, and what aspects they should consider facilitating increased knowledge utilization in their organizations. The suggested approach brings environmental sustainability consideration on every researcher's table and increases awareness, but the results also highlight the need of strong leadership and coaching for reaching the goals.

This study is limited to a specific discipline, organization, geography and culture, and cannot be generalized. The artifact has not been piloted outside of the RTO yet but is presented here for the first time for the academic community to allow for continued discussion and improvement of early-phase R&D sustainability consideration in the semiconductor industry. The study was conducted as a response to a specific need in the microelectronics department of a Finnish RTO. However, the results can be exploited and applied into different contexts and other RTOs in different geographies.

Additional research is necessary to understand how environmental sustainability can be integrated into early-phase microelectronics R&D projects across different organizations, geographical locations, and disciplines to build up generalizable understanding. Moreover, further studies are needed to provide practical examples of the application of the approach outlined in Fig. 3, and of the use of it outside of the RTO in other RTOs and other geographies. Additionally, there is a need for research focused on developing knowledge transfer pathways within organizations to effectively disseminate siloed sustainability knowledge.

Appendix: Survey results

See Tables 3, 4, 5, 6, 7, 8, 9.

Table 3 Survey results for the question "I consider sustainability in my daily R&D work."

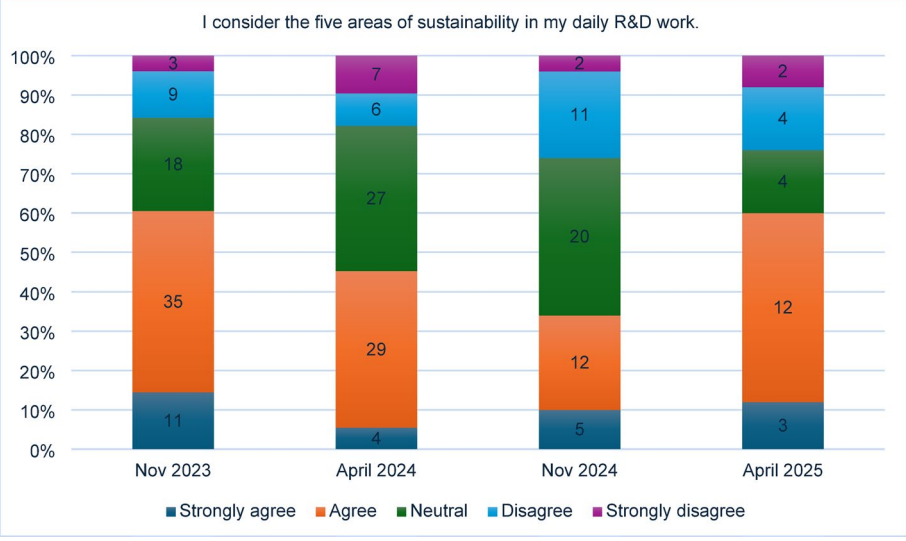


Table 4 Survey results for the question "I understand the research areas sustainability approach for R&D work."

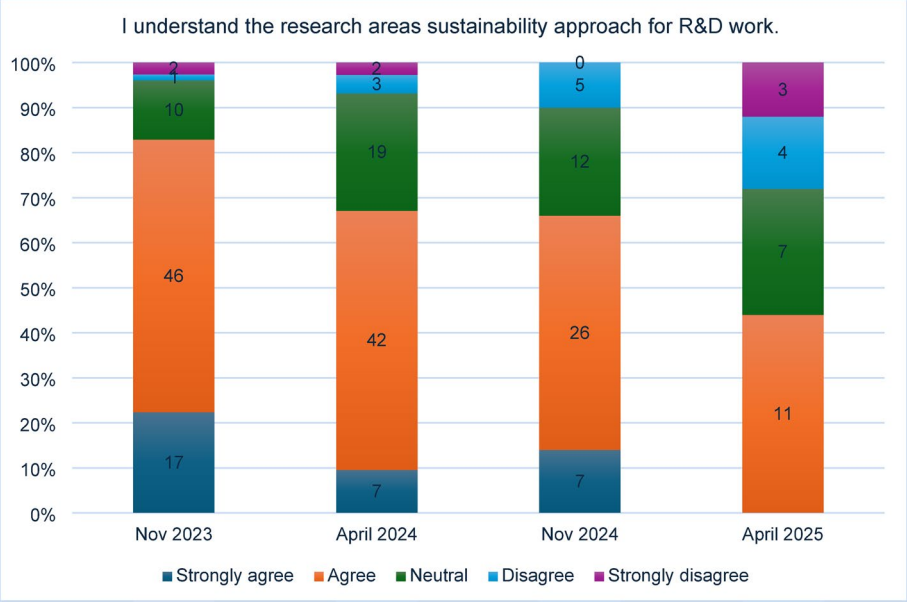


Table 5 Survey results for the question "I consider sustainability when writing project proposals and selecting topics for jointly funded project proposals."

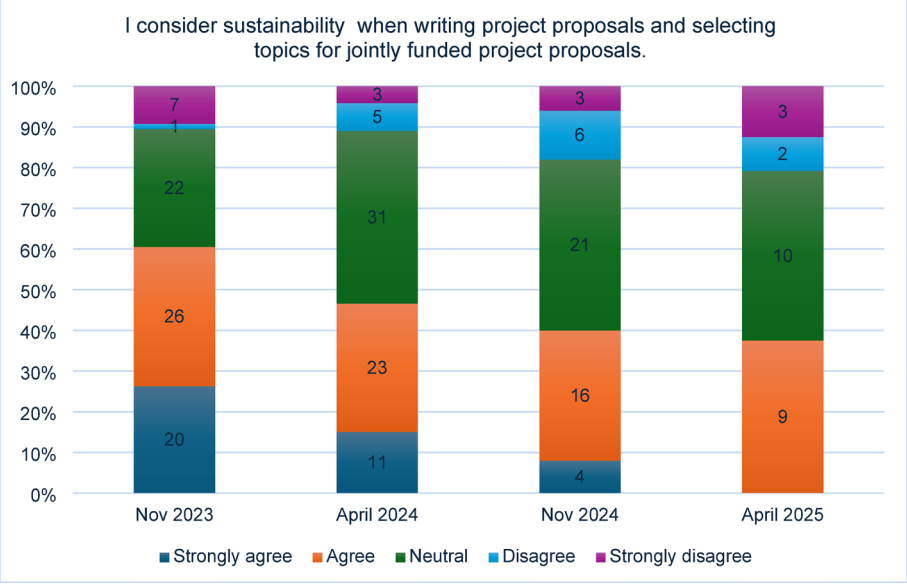


Table 6 Survey results for the question "I get requests from customers relating to sustainability."

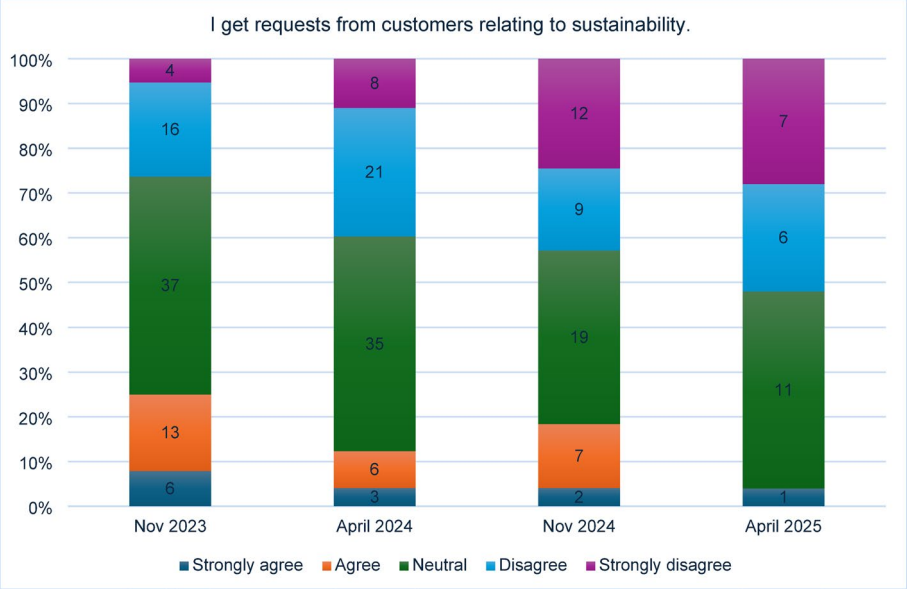


Table 7 Summarized and categorized survey results for the question "Give a concrete example of how you have considered sustainability in your research or project plans during the last 6 months."

November 2023	April 2024	November 2024	April 2025
Operational optimization			
Operational efficiency Energy efficiency and energy consumption Remote work Reduced consumption of energy, electricity, materials Investment selection Waste reduction Recycling	Alternative materials Operational optimization and efficiency Reduced resource consumption of energy, electricity, chemicals and materials Recycling and reuse Waste reduction Pollution reduction Facility and investment planning, equipment reuse Processing efficiency Test material reuse	Waste reduction Less energy consuming processes Operational efficiency Investment consideration Alternative materials Capable processes improving yield and reducing waste Reuse Recycling	Alternative materials Energy efficiency and energy consumption Facility planning Waste reduction Recycling Processing time optimization Reduced number of testing and monitoring
New technology development			
Project topic, application selection Alternative materials, replacement of critical raw materials System architecture Novel technology Design, simplified design	Development topic and application selection Energy and power efficient developments Novel designs Layout footprint decrease New architectural solutions, modular approaches UN SDG linkage Reduction of testing in projects Reduction of processing in projects Sustainable high-performance material development Reduction of harmful substances Impact and sustainability assessment	Not used some raw materials long-term sustainability impact analysis low-energy designs Sustainability goals for projects	Avoiding use of critical raw materials Choice of research topics

Table 8 Summary of survey results for the question "What kind of guidance would you like that the Green Tool would give you?"

What kind of guidance would you like that the Green Tool would give you?
Understanding
Best practices
Sustainability targets vs other criteria
How to make wise selections
Suggestion of roadmaps
No more bureaucracy

Table 9 Summary of survey results for the question "How do you think the research project specific discussions will help you?"

How do you think the [research project] specific sustainability discussion will help you?
Get ideas how to introduce sustainability into my daily work
I don't think that the solution helps us "baseline" researchers and engineers in any way
I think it's difficult to fully assess the sustainability issues when considering long term items on the roadmap
Input on what to consider in the fabrication work going forward
It is a thought process
It makes it an official target for RTO and gives some kind of commitment
The discussion needs to move to handprint and sustainability impact of the tech we develop
We may find opportunities to sell sustainable solutions and possibly compare their feasibility with real life capabilities

Acknowledgements
The authors would like to acknowledge the colleagues that contributed to the artifact development.

Author contributions
Piia Konstari: Conceptualization, Methodology, Formal analysis and investigation, Writing—original draft preparation. Katri Valkokari: Methodology, Supervision.

Funding
No funds, grants, or other support was received.

Data availability
Data used for this research is confidential and contains partly trade secrets of the organization. The data generated during and analysed during the current study are not publicly available due to confidentiality reasons but are available from the corresponding author on reasonable request like co-authorship.

Declarations

Ethical approval and consent to participate
Review or approval by an ethics committee was not needed for this study because it does not cover patient information or animal testing. The surveys were conducted using Microsoft Forms. The surveys were answered anonymously and voluntarily upon statement that we do research on the topic. Only the questions listed in the Appendix were asked and no information was collected that could identify the responders. Consent for the research was received from the leader of the department.

Consent for publication
Consent to publish this research was received from the leader of the department according to organizational policies.

Competing interests
The authors declare no competing interests.

Received: 10 May 2025 / Accepted: 17 September 2025
Published online: 15 October 2025

References

1. Hsieh S, Lin P-Y, Lin I-H, Beck DE, Lin C-H. Assessing the contribution of semiconductors to the sustainable development goals (SDGs) from 2017 to 2022. Heliyon. 2023;9(11):e21306. https://doi.org/10.1016/j.heliyon.2023.e21306.
2. Kusters J, Bhattacharjee D, Nicholas JT, Stewart D, Ramachandran K. Semiconductor industry outlook. Accessed: Apr. 16, 2025. [Online]. Available: https://www2.deloitte.com/us/en/insights/industry/technology/technology-media-telecom-outlooks/semiconductor-industry-outlook.html.
3. Mei Y, Geng Y, Chen Z, Xiao S, Gao Z. Ensuring the sustainable supply of semiconductor material: a case of germanium in China. Int J Prod Econ. 2024;271:109231. https://doi.org/10.1016/j.ijpe.2024.109231.

4. Althaf S, Babbitt CW. Disruption risks to material supply chains in the electronics sector. Resour Conserv Recycl. 2021;167:105248. https://doi.org/10.1016/j.resconrec.2020.105248.
5. Holdeman CJ, Howarter JA. Benchmarking energy, emissions, and resource sustainability in semiconductor manufacturing. Miner Met Mater Ser. 2025. https://doi.org/10.1007/978-3-031-80688-9_2.
6. Singh KB, Misra SC. Manufacturing of semiconductor chips: from their origins to the current automotive chip crisis. IEEE Eng Manag Rev. 2024. https://doi.org/10.1109/EMR.2024.3491302.
7. Lu W, Lo S, Hung S, Yo J. Semiconductor industry supply chain productivity changes: incorporating corporate green performances. Manag Decis Econ. 2023;44(8):4232–47. https://doi.org/10.1002/mde.3945.
8. Tian S, Wang M, Wu L, Kumar A, Tan KH. Sustainability diffusion in the Chinese semiconductor industry: a stakeholder salience perspective. Int J Prod Econ. 2025;279:109470. https://doi.org/10.1016/j.ijpe.2024.109470.
9. Chen M-C, Pang S, Su S-Y. Sustainable global semiconductor supply chain network design considering ESG. Technol Soc. 2025;81:102829. https://doi.org/10.1016/j.techsoc.2025.102829.
10. McKinsey & Company. Beyond the fab: decarbonizing scope 3 upstream emissions, 2023. Accessed: Oct. 30, 2024. [Online]. Available: https://www.mckinsey.com/industries/semiconductors/our-insights/beyond-the-fab-decarbonizing-scope-3-upstream-emissions#/.
11. Almelhem M, Buics L, Süle E. Comparison of sustainability and circularity indicators: downstream vs. upstream supply chain strategies. Discov Sustain. 2025;6(1):302. https://doi.org/10.1007/s43621-025-01158-0.
12. Dyllick T, Rost Z. Towards true product sustainability. J Clean Prod. 2017;162:346–60. https://doi.org/10.1016/j.jclepro.2017.05.189.
13. Han J, Jiang P, Childs P. Metrics for measuring sustainable product design concepts. Energies (Basel). 2021;14(12):3469. https://doi.org/10.3390/en14123469.
14. Monakhov KYu, et al. Molecular approach to semiconductors: a shift towards ecofriendly manufacturing and neuroinspired interfaces. Pure Appl Chem. 2024;96(9):1313–31. https://doi.org/10.1515/pac-2024-0242.
15. Irimia-Vladu M, et al. Environmentally sustainable organic field effect transistors. Org Electron. 2010;11(12):1974–90. https://doi.org/10.1016/j.orgel.2010.09.007.
16. Boyd SB. Life-cycle assessment of semiconductors, vol. 9781441999887. New York, NY: Springer, New York; 2012. https://doi.org/10.1007/978-1-4419-9988-7.
17. Delhaye TP, Le Brun G, Flandre D, Raskin J-P. Bottom-up life-cycle assessment of MEMS piezoresistive pressure sensors. In 2021 symposium on design, test, integration & packaging of MEMS and MOEMS (DTIP), IEEE, August 2021, pp. 1–6. https://doi.org/10.1109/DTIP54218.2021.9568683.
18. Villard A, Lelah A, Brissaud D, Mantelli M. An eco-design tool for manufacturers of semiconductor technologies: looking for environmental opportunities in the design phase. In 2012 IEEE international symposium on sustainable systems and technology (ISSST), IEEE, May 2012, pp. 1–6. https://doi.org/10.1109/ISSST.2012.6228013.
19. Şengül H, Theis TL. An environmental impact assessment of quantum dot photovoltaics (QDPV) from raw material acquisition through use. J Clean Prod. 2011;19(1):21–31. https://doi.org/10.1016/j.jclepro.2010.08.010.
20. Huang C-Y, Hu AH, Yin J, Wang H-C. Developing a parametric carbon footprinting tool for the semiconductor industry. Int J Environ Sci Technol. 2016;13(1):275–84. https://doi.org/10.1007/s13762-015-0869-z.
21. Hakola L, Smolander M, Orko I, Sokka L, Välimäki M. Development of a qualitative tool for sustainability assessment and application of the tool to benchmark electronic smart labels. Circ Econ Sustain. 2023. https://doi.org/10.1007/s43615-023-00280-3.
22. Schöggl J-P, Baumgartner RJ, Hofer D. Improving sustainability performance in early phases of product design: A checklist for sustainable product development tested in the automotive industry. J Clean Prod. 2017;140:1602–17. https://doi.org/10.1016/j.jclepro.2016.09.195.
23. Saavalainen P, et al. Developing and testing a tool for sustainability assessment in an early process design phase—case study of formic acid production by conventional and carbon dioxide-based routes. J Clean Prod. 2017;168:1636–51. https://doi.org/10.1016/j.jclepro.2016.11.145.
24. Reike D, Vermeulen WJV, Witjes S. The circular economy: new or refurbished as CE 3.0? Exploring controversies in the conceptualization of the circular economy through a focus on history and resource value retention options. Resour Conserv Recycl. 2018;135:246–64. https://doi.org/10.1016/j.resconrec.2017.08.027.
25. Yuan Qh, Tang LY. The principles in green design. E3S Web Conf. 2021;259:02002. https://doi.org/10.1051/e3sconf/202125902002.
26. Hunger T, Arnold MG, Engesser S, van den Boogaart KG. Integrating sustainability facets into the early stages of new product development using multi-criteria tools—a critical review. J Clean Prod. 2025. https://doi.org/10.1016/J.JCLEPRO.2025.145834.
27. Konstari P, Valkokari K. Green innovation ecosystems in the semiconductor industry—the role of European research and technology organisations. Sustain Futures. 2025;10:101127. https://doi.org/10.1016/j.sftr.2025.101127.
28. Mengistu AT, Dieste M, Panizzolo R, Biazzo S. Sustainable product design factors: a comprehensive analysis. J Clean Prod. 2024;463:142260. https://doi.org/10.1016/j.jclepro.2024.142260.
29. Reichard JJ, Martin A. Sustainable design evaluation—integration of sustainability in product development processes. Proc Des Soc. 2023;3:3275–84. https://doi.org/10.1017/pds.2023.328.
30. Sheldrick L, Rahimifard S. Evolution in Ecodesign and sustainable design methodologies. In Re-engineering manufacturing for sustainability, Singapore: Springer Singapore, 2013, pp. 35–40. https://doi.org/10.1007/978-981-4451-48-2_6.
31. Donnellan B. Knowledge management in the semiconductor industry: dispatches from the front line. In Lecture notes in artificial intelligence (subseries of lecture notes in computer science), vol. 3336, 2004, pp. 282–291. https://doi.org/10.1007/978-3-540-30545-3_27.
32. Konstari P, Valkokari K. Drivers and barriers for open innovation for sustainability in a shared semiconductor infrastructure. J Open Innov Technol Mark Complex. 2024;10(4):100395. https://doi.org/10.1016/j.joitmc.2024.100395.
33. Konstari P, Valkokari K. Value creation and capture from sustainability-oriented innovations in a shared semiconductor infrastructure. Sustain Technol Entrep. 2025;4(2):100104. https://doi.org/10.1016/j.stae.2025.100104.
34. Chaudhuri R, Singh B, Agrawal AK, Chatterjee S, Gupta S, Mangla SK. A TOE-DCV approach to green supply chain adoption for sustainable operations in the semiconductor industry. Int J Prod Econ. 2024;275:109327. https://doi.org/10.1016/j.ijpe.2024.109327.

35. Mugoni E, Kanyepe J, Tukuta M. Sustainable Supply Chain Management Practices (SSCMPS) and environmental performance: a systematic review. Sustain Technol Entrep. 2024;3(1):100050. https://doi.org/10.1016/j.stae.2023.100050.
36. Liu Y-Z, Lu W-M, Tran PP, Pham TAK. Sustainable energy and semiconductors: a bibliometric investigation. Sustainability. 2024;16(15):6548. https://doi.org/10.3390/su16156548.
37. Qi E, et al. Sustainability model for semiconductor manufacturing. In 2024 35th Annual SEMI advanced semiconductor manufacturing conference (ASMC), IEEE, May 2024, pp. 1–4. https://doi.org/10.1109/ASMC61125.2024.10545500.
38. Narayanaswamy V, Muthusamy K. Sustainability index benchmarking in a semiconductor manufacturing environment. Adv Mater Res. 2011;383–390:3377–81. https://doi.org/10.4028/www.scientific.net/AMR.383-390.3377.
39. Hsieh C-C, Rachmawati NL, Lin Y-C. Coordinating remanufacturing efforts for sustainable chemical supply in semiconductor supply chains. Comput Ind Eng. 2025. https://doi.org/10.1016/j.cie.2025.110895.
40. Venkataswamy R, et al. Environmental impact assessment of chemical mechanical planarization consumables: challenges, future needs, and perspectives. ACS Sustain Chem Eng. 2024;12(32):11841–55. https://doi.org/10.1021/acssuschemeng.4c03195.
41. Shen C, Tran PP, Minh Ly PT. Chemical waste management in the US semiconductor industry. Sustainability. 2018;10(5):1545. https://doi.org/10.3390/su10051545.
42. McKinsey & Company. Keeping the semiconductor industry on the path to net zero, 2022. Accessed: Apr. 20, 2024. [Online]. Available: https://www.mckinsey.com/industries/semiconductors/our-insights/keeping-the-semiconductor-industry-on-the-path-to-net-zero.
43. McKinsey & Company. Exploring new regions: The greenfield opportunity in semiconductors, 2024. Accessed: Apr. 20, 2024. [Online]. Available: https://www.mckinsey.com/industries/semiconductors/our-insights/exploring-new-regions-the-greenfield-opportunity-in-semiconductors.
44. Semi. Scope 3 Category 1 GHG assessment guideline for the semiconductor sector. Semi-Semiconductor Climate Consortium (SCC), Semiconductor Climate Consortium Report, 2023. Accessed: Apr. 20, 2024. [Online]. Available: https://www.semi.org/sites/semi.org/files/2024-01/SCC%20Prospectus%20Jan%202024.pdf.
45. Varadarajan R. Innovating for sustainability: a framework for sustainable innovations and a model of sustainable innovations orientation. J Acad Mark Sci. 2017;45(1):14–36. https://doi.org/10.1007/s11747-015-0461-6.
46. Bautista-Puig N, Lozano R, Barreiro-Gen M. Developing a sustainability implementation framework: insights from academic research on tools, initiatives and approaches. Environ Dev Sustain. 2023;25(10):11011–31. https://doi.org/10.1007/s10668-022-02516-y.
47. Silvius G, Marnewick C. Interlinking sustainability in organizational strategy, project portfolio management and project management: a conceptual framework. Procedia Comput Sci. 2022;196:938–47. https://doi.org/10.1016/j.procs.2021.12.095.
48. Vilochani S, McAloone TC, Pigosso DCA. Consolidation of management practices for sustainable product development: a systematic literature review. Sustain Prod Consum. 2024;45:115–25. https://doi.org/10.1016/j.spc.2024.01.002.
49. Vilochani S, McAloone TC, Pigosso DCA. Bridging the gap: exploring the effect of sustainable product development practices into product sustainability performance in manufacturing companies. J Environ Manag. 2025;378:124821. https://doi.org/10.1016/j.jenvman.2025.124821.
50. Schipper RPJR, Silvius AJG. Towards a conceptual framework for sustainable project portfolio management. Int J Proj Organ Manag. 2018;10(3):191. https://doi.org/10.1504/IJPOM.2018.093977.
51. Aghajani M, Ruge G, Jugdev K. An integrative review of project portfolio management literature: thematic findings on sustainability mindset, assessment, and integration. Proj Manag J. 2023;54(6):629–50. https://doi.org/10.1177/87569728231172668.
52. Hallstedt SI, Isaksson O, Nylander JW, Andersson P, Knuts S. Sustainable product development in aeroengine manufacturing: challenges, opportunities and experiences from GKN Aerospace Engine System. Des Sci. 2023;9:e22. https://doi.org/10.1017/dsj.2023.22.
53. Krishnan N, Boyd S, Somani A, Raoux S, Clark D, Dornfeld D. A hybrid life cycle inventory of nano-scale semiconductor manufacturing. Environ Sci Technol. 2008. https://doi.org/10.1021/es071174k.
54. Boyd SB. Semiconductor LCA: the road ahead. In Life-Cycle Assessment of Semiconductors, New York, NY. Springer New York, 2012, pp. 109–112. https://doi.org/10.1007/978-1-4419-9988-7_8.
55. Kuo T-C, Kuo C-Y, Chen L-W. Assessing environmental impacts of nanoscale semi-conductor manufacturing from the life cycle assessment perspective. Resour Conserv Recycl. 2022;182:106289. https://doi.org/10.1016/j.resconrec.2022.106289.
56. Kuo C-H, Hu AH, Hung LH, Yang K-T, Wu C-H. Life cycle impact assessment of semiconductor packaging technologies with emphasis on ball grid array. J Clean Prod. 2020;276:124301. https://doi.org/10.1016/j.jclepro.2020.124301.
57. Karuppiah K, Sankaranarayanan B, Ali SM. Evaluating the challenges to life cycle assessment using best-worst method and decision-making trial and evaluation laboratory. Environ Prog Sustain Energy. 2023. https://doi.org/10.1002/ep.13991.
58. Kiemel S, Rietdorf C, Schutzbach M, Miehe R. How to simplify life cycle assessment for industrial applications—a comprehensive review. Sustainability. 2022;14(23):15704. https://doi.org/10.3390/su142315704.
59. Villard A, Lelah A, Brissaud D. Drawing a chip environmental profile: environmental indicators for the semiconductor industry. J Clean Prod. 2015;86:98–109. https://doi.org/10.1016/j.jclepro.2014.08.061.
60. Szulanski G. Exploring internal stickiness: impediments to the transfer of best practice within the firm. Strateg Manag J. 1996;17(S2):27–43. https://doi.org/10.1002/smj.4250171105.
61. Akgün AE, Keskin H, Ayar H, Okunakol Z. Knowledge sharing barriers in software development teams: a multiple case study in Turkey. Kybernetes. 2017;46(4):603–20. https://doi.org/10.1108/K-04-2016-0081.
62. Riege A. Three-dozen knowledge-sharing barriers managers must consider. J Knowl Manag. 2005;9(3):18–35. https://doi.org/10.1108/13673270510602746.
63. Cormican K, Meng C, Sampaio S, Wu Q. Towards sustainable knowledge sharing practices: an analysis of organizational level enablers. Sustainability. 2021;13(23):12934. https://doi.org/10.3390/su132312934.
64. Sensuse DI, Lestari PI, Hakim SA. Exploring factors influencing knowledge sharing mechanisms and technology to support the collaboration ecosystem: a review. DESIDOC J Libr Inf Technol. 2021;41(3):226–34. https://doi.org/10.14429/djlit.41.3.16609.

65. Wei Y. Analysis on influencing factors of tacit knowledge sharing and solutions for high-tech enterprises. In 2010 3rd international conference on information management, innovation management and industrial engineering, IEEE, Nov. 2010, pp. 310–313. https://doi.org/10.1109/ICIII.2010.80.
66. Sáenz J, Aramburu N, Blanco CE. Knowledge sharing and innovation in Spanish and Colombian high-tech firms. J Knowl Manag. 2012;16(6):919–33. https://doi.org/10.1108/13673271211276191.
67. Mushtaq I, Rizwan A. Obstacles to knowledge sharing in engineering organisations: a quantitative approach. Int J Knowl Manag Stud. 2018;9(3):293. https://doi.org/10.1504/IJKMS.2018.094216.
68. Santos VR, Soares AL, Carvalho JA. Knowledge sharing barriers in complex research and development projects: an exploratory study on the perceptions of project managers. Knowl Process Manag. 2012;19(1):27–38. https://doi.org/10.1002/kpm.1379.
69. Liu W. Knowledge exploitation, knowledge exploration, and competency trap. Knowl Process Manag. 2006;13(3):144–61. https://doi.org/10.1002/kpm.254.
70. Gonzalez RVD, de Melo TM. Inovação por exploração e explotação do conhecimento: um estudo empírico do setor automobilístico. Gestão & Produção. 2017;25(1):1–15. https://doi.org/10.1590/0104-530x3899-17.
71. Tura N, Ojanen V, Hanski J. Innovations for sustainability: challenges of utilising sustainability-related knowledge. Int J Innov Sustain Dev. 2019;13(3/4):452. https://doi.org/10.1504/IJISD.2019.100371.
72. Chassagnon-Haned N, Hamani A. Enabling Sustainability. In The European environmental conscience in the EU, London: Routledge, 2025, pp. 163–180. https://doi.org/10.4324/9781032656359-12.
73. Holmström J, Ketokivi M, Hameri A. Bridging practice and theory: a design science approach. Decis Sci. 2009;40(1):65–87. https://doi.org/10.1111/j.1540-5915.2008.00221.x.
74. Yin RK. Case study research and applications, Sixth Edition. SAGE Publications, Inc. 2018.
75. Vilochani S, Borgianni Y, McAloone TC, Pigosso DCA. An investigation into the extent to which sustainable product development practices are implemented in manufacturing companies. Sustain Prod Consum. 2024;50:155–67. https://doi.org/10.1016/j.spc.2024.07.022.
76. Gonzalez RVD, de Melo TM. The effects of organization context on knowledge exploration and exploitation. J Bus Res. 2018;90:215–25. https://doi.org/10.1016/j.jbusres.2018.05.025.

Publisher's Note

ACTA UNIVERSITATIS LAPPEENRANTAENSIS

1225. LAURÉN, MIKA. Computationally efficient modeling of internal combustion engine for system-level studies of vehicle power trains. 2025. Diss.

1226. PALU, RIINA. A framework for assessing national maritime supply chain resilience. 2025. Diss.

1227. LILJESTRÖM, TOM. Informal governance in small and medium-sized companies as a systematically managed activity : an owner, board and management perspective. 2025. Diss.

1228. KAREINEN, ELISA. Possibilities of personal carbon trading to tackle greenhouse gas emissions in the passenger mobility sector. 2025. Diss.

1229. TELKKÄ, JOONAS. Experimental characterization of open loop passive heat removal. 2025. Diss.

1230. ZAIKOVA, ANNA. Navigating the transition in municipal solid waste management systems. 2025. Diss.

1231. VIERU, KAARINA. SME internationalisation in smaller towns. 2025. Diss.

1232. KARKI, BISHAL RAJ. Towards sustainable digital maintenance services. 2025. Diss.

1233. SAARNI, KATI. Reducing software ecosystem failure : planning activities, conceptualizing digital services, and understanding failure factors. 2025. Diss.

1234. PHADNIS, NIKHIL. Enhancing innovation portfolio management : towards a pragmatic process centric approach. 2025. Diss.

1235. XUE, QIWEI. Human factors modeling using machine learning for fusion energy applications. 2025. Diss.

1236. HINA, MARYAM. Blockchain for sustainability : a multilevel perspective connecting consumers and organisations. 2025. Diss.

1237. RAUTIO, JUUSO. On the reliability of power semiconductor modules in corrosive environments. 2025. Diss.

1238. SCHERMAN, EERO. Dissimilar metal joining for rotors of high-speed axially laminated anisotropic synchronous reluctance machines. 2025. Diss.

1239. SUOMALAINEN, SARI. Urban open spaces for sustainability transformation — capturing citizens' perceptions with arts-based methods. 2025. Diss.

1240. KORPINEN, KATRIINA. On the electrochemical migration of copper in electronics – effects of frequency. 2025. Diss.

1241. GALIMOVA, TANSU. Renewable electricity-based fuels and chemicals: demand, trading, and transportation. 2025. Diss.

1242. ADISA, MIKHAIL. Aligning ICT, civic engagement, and policy directives : a multi-level approach to sustainable practices and organizational compliance. 2025. Diss.

1243. MYERS, ALEXANDER. Strategizing through uncertainty in deep technology ventures : a design science approach. 2025. Diss.

1244. GYAWALI, ARUN. Utilisation of remote sensing, machine learning, and agent-based simulation for biophysical assessment of young boreal forest. 2025. Diss.

1245. NIELSEN, IBEN BOLUND. Business perspectives for enabling circular economy. 2025. Diss.

1246. SALCEDO PUERTO, ORLANDO ENRIQUE. Valorization of agricultural and industrial side streams : energy potential and environmental assessment. 2025. Diss.

1247. TERESHCHENKO, ELIZAVETA. Student-centered university-industry collaboration in software engineering : a modern multi-stakeholder model. 2025. Diss.

1248. TURKCU, DENIZ. Battling with the tensions in sustainable packaging. 2025. Diss.

1249. PARTANEN, LAURA. Environmental sustainability in software-intensive companies in Finland : towards actionable understanding. 2025. Diss.

1250. MARÍN CORTÉS, OSCAR ALBERTO. Advancing green mining : integrating sustainable water and tailings management in the copper mining industry. 2025. Diss.

1251. YALDAIE, ASHKAN. From research to living rooms : evaluating smart home technologies through systematic reviews, user studies, and practical implementations. 2025. Diss.

1252. HEINONEN, JARMO. Conjoint-fMRI in neuromarketing research. 2025. Diss.

1253. QUINTEROS CONDORETTY, AMERICA. Lock-ins and enablers in the transition towards a circular lithium economy for electric vehicle batteries. 2025. Diss.

1254. GURZHII, ANASTASIIA. Blockchain for credential verification : insights into decision-making in recruitment. 2025. Diss.

1255. TYLOSKY, NATASHA. Designing data exploration for non-expert audiences. 2025. Diss.

1256. SATYMOV, RASUL. Techno-economic analysis of energy transition pathways and renewable energy technologies for a sustainable energy-industry system. 2025. Diss.

1257. IBÁÑEZ RIOJA, ALEJANDRO. Simultaneous optimization of dimensioning and control in green hydrogen production systems based on water electrolysis. 2025. Diss.

1258. CHRISTENSEN, EMILY. Hybrid work in agile software development. 2025. Diss.

1259. NIEMINEN, JOONA. Charge-induced modifications for enhanced membrane performance in water treatment. 2025. Diss.

1260. ABDULLAI, LARRY. Orchestrating ICT ecosystem for sustainability transition : strategies, models and empirical evidence from the Finnish ICT sector. 2025. Diss.

1261. ADIBE, PIA. Navigating the in-between : exploring individuals' different meanings of creating space for collaborative innovation. 2025. Diss.

1262. ELO, TIMO. Synthesis of novel functionalized and exfoliated hexagonal boron nitrides filler and their compatibilization chemistry for high-performance biocomposites. 2025. Diss.

LUT University

ISBN 978-952-412-380-8
ISBN 978-952-412-381-5 (PDF)
ISSN 1456-4491 (Print)
ISSN 2814-5518 (Online)
Lappeenranta 2025