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LIFE CYCLE SUSTAINABILITY ASSESSMENT FOR RESEARCH AND INNOVATION

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502 - Životní prostředí a jeho ochrana [2]

To my dearest Pavel, David & Julie
And to all those whose curiosity, questions, and generosity allow ideas to grow…

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PREFACE

At the core of this book is human experience. Life cycles, living in harmony with nature, and what we now call Life Cycle Thinking have shaped human life for generations. Yet, as our lifestyles have changed and industrial production and consumption have expanded, the relationship between people, nature, and resources has become increasingly complex. This complexity has led us to draw together three concepts that have shaped our academic and professional work: sustainability, life cycle, and assessment.

Time is central to sustainability. A temporal perspective reminds us to look beyond immediate results, connect present decisions with future consequences, and consider how local actions contribute to global change. Life Cycle Thinking adds another important principle: avoiding the transfer of burdens between life-cycle stages, locations, impact categories, stakeholder groups, or generations. Moving from environmental Life Cycle Assessment (LCA) towards Life Cycle Sustainability Assessment (LCSA) expands this perspective to economic and social considerations.

The book takes a step-by-step learning journey. It begins with sustainability and Life Cycle Thinking, continues through environmental LCA, Life Cycle Costing, and Social LCA, and concludes with the integration of these methods and a discussion of current developments and remaining challenges. It provides a starting point for studying and applying LCSA. Relevant sources are provided throughout to support further study and help readers address these challenges in their own research.

Above all, we hope this book encourages readers to ask: How can we make sustainability an integral part of how we think, assess, innovate, and decide?

1/
FOUNDATIONS OF SUSTAINABILITY

Sustainability is a term that is often interpreted in different ways, sometimes misunderstood and frequently associated with environmental protection, yet its scope extends beyond single concern. It concerns how resources are used and how benefits and risks are distributed, now and in the future. These considerations apply to decisions at every level: choosing what to eat or buy; designing a product or selecting suppliers; or planning infrastructure or setting public policy. While these decisions may appear disparate at first, they share common features and involve trade-offs (for example, price versus quality), create effects that extend beyond the immediate decision (often not directly calculated in cost), and reflect diverse values and horizons (fairness, long-term thinking).

Every decision we make is shaped by a way of thinking, whether or not we are aware of it. These ways of thinking, called paradigms, act as lenses through which we see problems, interpret information, and decide priorities. In sustainability, paradigms influence why and what we assess, who benefits, and who carries the burden. If these assumptions remain hidden, decisions can appear logical on the surface but lead to unintended consequences. The same project can be seen as efficient in one case and problematic in another, depending on the perspective used.

The chapter begins with the idea that sustainability is a way of seeing problems, then continues with the foundations of sustainability, and finally examines the various actors in sustainability transitions and innovations.

The project meeting where everyone is right

An international consortium composed of scientists, administrators, technicians, and other experts is preparing a research proposal for a new battery technology project. The materials scientist discusses energy density and stability; the engineer focuses on scale-up; the economist emphasises the need for cost reduction and market competitiveness. Finally, the policy expert cites strategic autonomy and clean energy targets.

Each of these experts has a point, but they are not all looking at the same problem, for example, the environmental engineer asks: *What environmental impacts will the new materials have?* The social scientist also has questions: *Where will the materials come from? What risks might be created along the supply chain? Who benefits if the technology succeeds? What factors might influence public acceptance of the new technology?*

The discussion shifts: the technology itself has not changed, but the way people look at it has. For some of the experts, sustainability means better performance with lower emissions. For others, it means responsible sourcing, fairer distribution of benefits, safer production, or recyclability.



THE CONCEPTUAL FOUNDATIONS OF SUSTAINABILITY

Ideas related to what today is called "sustainability" did not emerge recently. Many past civilisations developed practices to manage resources over long periods, driven by necessity and local environmental conditions. Agricultural systems have evolved by an understanding that overexploitation could threaten the survival of certain species, including humans. These practices were not labelled as "sustainability," but they did reflect a certain awareness of limits.

An important historical root of sustainability lies in Hans Carl von Carlowitz's Sylvicultura oeconomica (1713)[1], which advocated managing forests to maintain a lasting supply of timber. His work helped establish the principle that resource use should remain within nature's capacity for renewal and is recognised as a precursor to modern sustainability thinking.

This relationship changed through industrialisation and became more pronounced in the *Anthropocene***,** a widely used term for the present period in which human activity has become a major force shaping Earth system processes[2]. A significant finding was the surge in human impact from around 1950 onwards, a phenomenon called the *Great Acceleration*[3]**.** The term reflects the interconnected nature of post-1950 changes across socio-economic and biophysical spheres.

Technological innovation accelerated economic growth and increased reliance on fossil energy. Living standards improved in many regions, but the transformation also intensified resource extraction, pollution, and the geographical separation of production and consumption. As sustainability concerns shifted from resource use to Earth system stability, the concept of *resilience* became important for understanding how social-ecological systems absorb disturbance, adapt to change, and maintain essential functions under pressure[4]**.**

These concerns were brought to global attention by *The Limits to Growth* (1972), the first Club of Rome report, which used system dynamics modelling to warn that continued exponential growth in population, industrial output, and resource use could exceed the Earth's finite capacity within a century[5]. In a later update, *Beyond the Limits* (1992), the authors argued that catastrophic outcomes were not inevitable, but could be avoided if societies shifted toward forms of development compatible with long-term ecological and social stability[6]. This work continued with *Limits to Growth: The 30-Year Update*[7]. More recently, researchers have revisited the World3 model using empirical data: Herrington[8] compared observed global trends with its scenarios, while Nebel et al.[9] recalibrated its parameters to better reflect historical developments. These studies have renewed discussion of ecological overshoot and the conditions under which societies might move towards more sustainable trajectories.

Along with these works, a recognised sustainability formulation was introduced in the report Our Common Future which defines specifically sustainable development as "meeting present needs without compromising the ability of future generations to meet their own needs"[10]. Although it is relatively broad, the definition established two essential ideas. First, it introduces a temporal dimension: decisions are not limited to present outcomes but extend into the future. Second, it prioritises needs, suggesting that development should be evaluated in terms of what is necessary for human well-being. Although the terms sustainability and sustainable development are often used interchangeably, they are not identical: Sustainability describes a desired long-term condition, while sustainable development refers to pathways towards that condition.

Sustainability also has a normative side, concerned with fairness and with the scale of human demand. Justice is therefore closely connected to sustainability, because environmental harms and risks are distributed unevenly across populations and over time. Environmental justice focuses on who is exposed to pollution, ecological degradation, and resource loss, while social justice addresses how benefits, burdens, and opportunities are shared within society[11]. Intergenerational justice extends this concern to future generations, arguing that present development should not undermine their ability to meet their own needs[12]. Also closely linked to these ideas is the concept of *sufficiency*, which shifts attention from unlimited consumption toward what is enough for a good life within ecological limits[13].

As these concepts evolved, different interpretations emerged regarding their interrelationship, with one key distinction arising between weak and strong sustainability[14,15]. *Weak sustainability* permits substitution between forms of capital, provided that the total capital stock does not decline. For instance, the depletion of natural resources may be justified if it leads to improved infrastructure, knowledge, or innovation. This view aligns with traditional economics, in which efficiency and optimisation dominate.

Advocates of *strong sustainability* emphasise the protection of critical natural capital that cannot be adequately replaced. Climate regulation and ecosystem functions provide conditions on which economic and social systems depend. Once these systems are degraded beyond certain thresholds, the resulting losses may become irreversible. According to this view, maintaining the integrity of these systems is essential–not substituting them with human-made alternatives.

A further development in sustainability thinking comes from the *degrowth* perspective[16]. Degrowth challenges the assumption that continuous economic growth is necessary or even desirable, i.e., increasing production and consumption do not automatically lead to greater well-being and can conflict with environmental limits. Proponents call for a reorientation towards sufficiency and quality of life.

Degrowth also highlights the social dimension of sustainability, particularly issues of inequality.

Yet these concepts do not specify how trade-offs should be handled or which dimensions should take precedence. This openness has enabled different approaches to develop, which is why sustainability is often understood in multiple, sometimes conflicting, ways. These debates produced different ways of representing the environmental, social and economic dimensions of sustainability. The following section contrasts the three-pillar model with approaches that place society and the economy within ecological limits.

The three pillars and beyond

Environmental, social, and economic dimensions became gradually established in sustainability thinking. In the 1990s, Elkington popularised the three-dimensional logic in business as the *triple bottom line* (3BL) (Figure 1.1)[17,18]. The economy operates within society, and both depend on ecological systems. Sustainability dimensions are not static; rather, they shift with ecological, political, and social change.

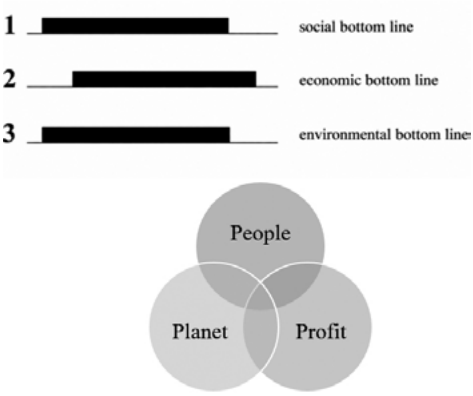

Figure 1.1 From triple bottom line to the 3Ps (People, Planet, Profit)[17]

The framework opened the perspective beyond environmental protection by emphasising that economic activity, social conditions, and environmental systems are interconnected. Economic activity enables livelihoods, but it relies on stable environmental systems and functioning societies. Social well-being requires both economic resources and a healthy environment, while environmental protection cannot be sustained without viable economic and social structures.

Although the three-pillar model has been highly influential, it has also been criticised for presenting environmental, social, and economic dimensions as if they

were separate and potentially exchangeable domains. In practice, these areas overlap and co-evolve: environmental degradation affects health, livelihoods, and inequality; social exclusion shapes access to resources and exposure to environmental harm; and economic structures influence both ecological pressures and social well-being.

For this reason, later scholarship moved away from viewing the pillars as three parallel boxes, towards understanding sustainability as an embedded system, a view in which the economy is a subsystem of society that cannot be separated from ecological systems. This shift affects not only how sustainability is visualised, but also how it is assessed and practically applied[4,19].

The discussion on limits was further developed through the concept of *planetary boundaries*, a framework that identifies key Earth system processes and defines precautionary borders within which humanity can operate with relatively low risk[20,21]. The approach seeks to translate sustainability into measurable limits, such that crossing a planetary boundary increases the risk of abrupt or even irreversible Earth system change. Climate change and biodiversity loss are among the most prominent examples of such boundaries.

Building on these ideas, the concept of *Doughnut Economics* emerged[22]. The doughnut model combines environmental limits with social foundations, creating a space in which sustainable development can occur[23]. As shown in Figure 1.2, the model takes the form of a circular diagram with two concentric rings. The inner green ring represents the social foundation—a set of minimum social conditions that must be met, including access to water, food, health, education, income and work, political voice, social cohesion, equality, housing, connectivity, and energy. The outer green ring represents the ecological ceiling, equivalent to planetary boundaries, beyond which environmental limits are breached. These boundaries include climate change, ocean acidification, chemical pollution, nutrient pollution, air pollution, freshwater disruption, land conversion, biodiversity breakdown, and ozone layer depletion. The safe and just space for humanity lies in the green band between these two rings.

Within the diagram, social wedges extend inward from the social foundation threshold toward the centre, with their length representing the degree of *social shortfall*—the extent to which minimum social needs are not being met. Ecological wedges extend outward beyond the ecological ceiling, represented by the red petal-shaped segments, with their length representing the degree of *ecological overshoot*—the extent to which human activity exceeds environmental limits. However, because the visualisation scales area quadratically, small differences may appear more pronounced than they are.

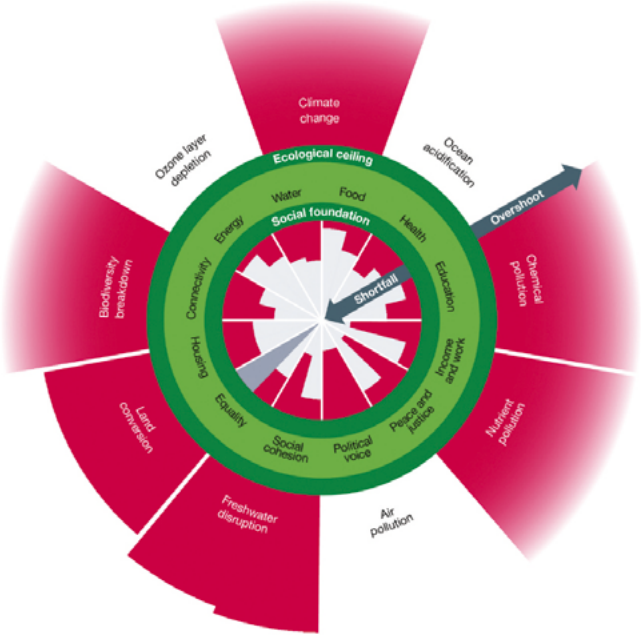

Figure 1.2 Global shortfalls and overshoots across doughnut boundaries[24]

Concepts such as planetary boundaries and Doughnut Economics represent a move from disaggregated sustainability dimensions toward more integrated and circular concepts. This shift sits alongside a *circular economy*, one in which resource use, production, consumption, and recovery are understood as interconnected parts of wider systems compared to linear and isolated stages. Circular economy concepts build on that logic by seeking to maintain material value, and design systems that regenerate natural capital. That said, making an economy more circular does not automatically make it more sustainable —circularity must be evaluated against broader ecological thresholds and social conditions[25].

SUSTAINABILITY TRANSITIONS AND INNOVATION

Sustainability transitions are long-term processes of systemic change through which societies move towards more sustainable ways of producing, consuming, and organising social and economic life[26]. Such transitions cannot be explained by technological change alone. The socio-technical perspective therefore examines

how technologies interact with institutions, practices, behaviours, and cultural norms to shape large-scale societal change[27,28].

One of its most widely used frameworks is the *Multi-Level Perspective*, which explains transitions as interactions between niche innovations, socio-technical regimes, and the wider landscape[27]. *Niche innovations* refer to emerging technologies or practices; regimes represent established systems, infrastructures, and institutions; and the landscape includes broader developments such as macroeconomic trends. Transitions occur when pressures at the landscape level and innovations emerging in niches begin to destabilise established regimes. Beyond the technical, transitions are also social, and political processes shaped by questions of justice, participation, and the distribution of benefits and burdens, especially in energy and industrial systems[29,30].

While the Multi-Level Perspective explains how transitions unfold, Triple Helix and Quadruple Helix models examine how different innovation actors interact within these processes. The *Triple Helix* explains innovation as the result of interaction between three main spheres: research, industry, and government[31]. In this view, universities and research organisations generate knowledge, industry applies innovations, and government provides regulation, funding, and strategic direction. Innovation emerges through exchanges between science, markets, and public institutions, through which research, industry, and government contribute different resources, priorities, and forms of authority. The *Quadruple Helix* extends the model by adding a fourth sphere: society[32,33]. The Quadruple Helix therefore offers a way to understand how sustainability transitions are actually driven, by Government and Policy, Industry and Markets, Civil Society, and Research and Academia.

Government and policy

Government and policy influence sustainability transitions by defining priorities, setting targets, and creating the institutional conditions for change. However, policy design is rarely straightforward—it involves trade-offs, and competing priorities, making sustainability governance inherently uneven and contested. It can be especially visible in relation to the so-called *Commons*—shared resources such as climate stability, water systems, or biodiversity that are vulnerable to overuse unless governed by collective rules and institutions[34].

One prominent global policy reference is the United Nations framework *Transforming Our World: The 2030 Agenda for Sustainable Development*[35], which introduced the 17 *Sustainable Development Goals (SDGs)* as an integrated agenda connecting environmental protection, social well-being, and economic development within a single framework[36].

The idea is illustrated by the *SDG wedding cake* model (Figure 1.3), which places the biosphere as the ecological foundation, society as dependent on this foundation, and the economy as embedded within both[37]. Environmental goals—such as climate, and biodiversity underpin social goals including health, education, equality, and peace, with economic activity understood as operating within these wider conditions. This perspective frames the economy as embedded within society and dependent on ecological stability (Figure 1.3).

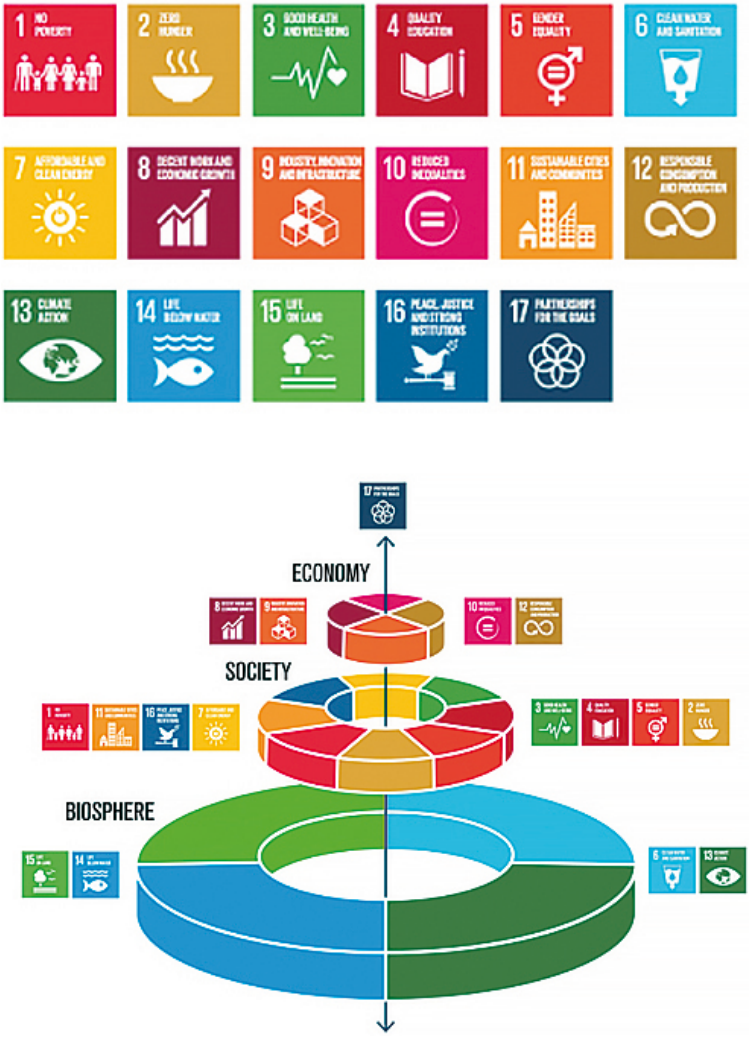

Figure 1.3 SDG wedding cake (Azote for Stockholm Resilience Centre)[37]

Industry and markets

Industry shapes production systems, innovation pathways, investment strategies, and global value chains. Yet, many sustainability problems persist because markets do not automatically reward environmentally and socially desirable outcomes.

Sustainability problems are often associated with several forms of market failure[38]. Climate change is a widely used example, as efforts to reduce harmful emissions generate benefits for everyone, regardless of who pays, which makes climate stability a global *public good*[39]. This creates incentives for free-riding, since firms or countries may prefer that others bear the cost of mitigation while they continue to benefit. Environmental harms such as greenhouse gas emissions are also *externalities*—meaning that their costs are shifted onto other people, other regions, or future generations[38]. As a result, a company may appear economically efficient while transferring environmental and social burdens elsewhere. Markets can also fail because of *imperfect competition* and *imperfect information,* leaving consumers and decision-makers without reliable data about environmental and social impacts[40]. In such cases, even well-intentioned choices may not lead to sustainable outcomes. These challenges are further compounded by dynamics resembling the prisoner's dilemma in game theory: while collective action would lead to better outcomes, individual incentives favour non-cooperation.

These failures help explain why sustainability transitions require more than voluntary market adjustments. Firms influence the direction and pace of change through issues such as investment choices or supply-chain practices[41].

In response to these challenges, firms have adopted concepts such as Corporate Social Responsibility (CSR), Environmental, Social, and Governance (ESG) programs, and sustainability reporting. CSR emerged as an early framework emphasising that companies have multivalent responsibilities: economic, legal, ethical, and philanthropic[42].

Civil society

Civil society represents the societal dimension of the Quadruple Helix and includes citizens, users, communities, non-governmental organisations, grassroots initiatives, and the media. As a heterogenous sphere, its actors vary in their interests, resources, influence, and access to decision-making. They influence which solutions are considered acceptable, and how transition processes unfold in practice, making society an active participant in shaping sustainability pathways[29].

A technically and economically viable solution may still fail if it lacks public trust or is perceived as unfair. *Social acceptance* depends on participation, transparency, and whether benefits and burdens are distributed in ways that people consider

just. This is why sustainability transitions call for public engagement, co-creation, and more inclusive forms of governance[43].

Civil society also shapes sustainability through *behavioural change* and *social practices*. Consumption patterns, mobility choices, household energy use, and everyday routines all influence the achievement of sustainability goals. Underlying these dynamics are questions of environmental and energy justice: who benefits from transition processes, who bears the costs, and whether vulnerable groups have a meaningful voice in decision-making[44].

Research and academia

Within the Quadruple Helix, research and academia contribute to sustainability transitions by producing knowledge, developing methods, and questioning the assumptions that shape decision-making. It can be understood in at least three ways:

- *research on sustainability*, which studies sustainability problems and transitions;
- *research for sustainability*, which supports solutions; and
- *sustainable research*, which reflects on how research itself is conducted in socially and environmentally responsible ways.

The breadth is reflected in the emergence of sustainability science, which examines the dynamic interactions between nature and society[45] and brings together contributions from the natural sciences, engineering, medicine, and the social sciences and humanities[46]. An evolving field defined by complexity and real-world relevance, sustainability science depends on transdisciplinary forms of knowledge production that connect scientific expertise with stakeholder knowledge and societal needs[47].

The shift is also visible in frameworks such as Responsible Research and Innovation[48,49] which emphasise anticipation, inclusion, reflexivity, and responsiveness as conditions for aligning research and innovation with societal needs[50]. The Societal Readiness approach complements Technology Readiness Levels by encouraging researchers to consider how their work responds to societal needs, values and expectations[51]. Related concepts such as living labs and real-world laboratories similarly emphasise that sustainability knowledge is created through interaction with users, policymakers and communities.

It is particularly relevant in emerging technologies, where key design and development decisions are often made before evidence on long-term impacts is available. In such cases, sustainability functions as a forward-looking orientation for research and innovation—creating a need for anticipatory and participatory approaches that guide innovation under incomplete knowledge. The following research frontier box illustrates the challenge and introduces Responsible Research and Innovation, Constructive Technology Assessment, and the Collingridge dilemma

as concepts for sustainability-oriented decision-making (Figure 1.4, based on TwinVECTOR project[*1]) [47,52,53].

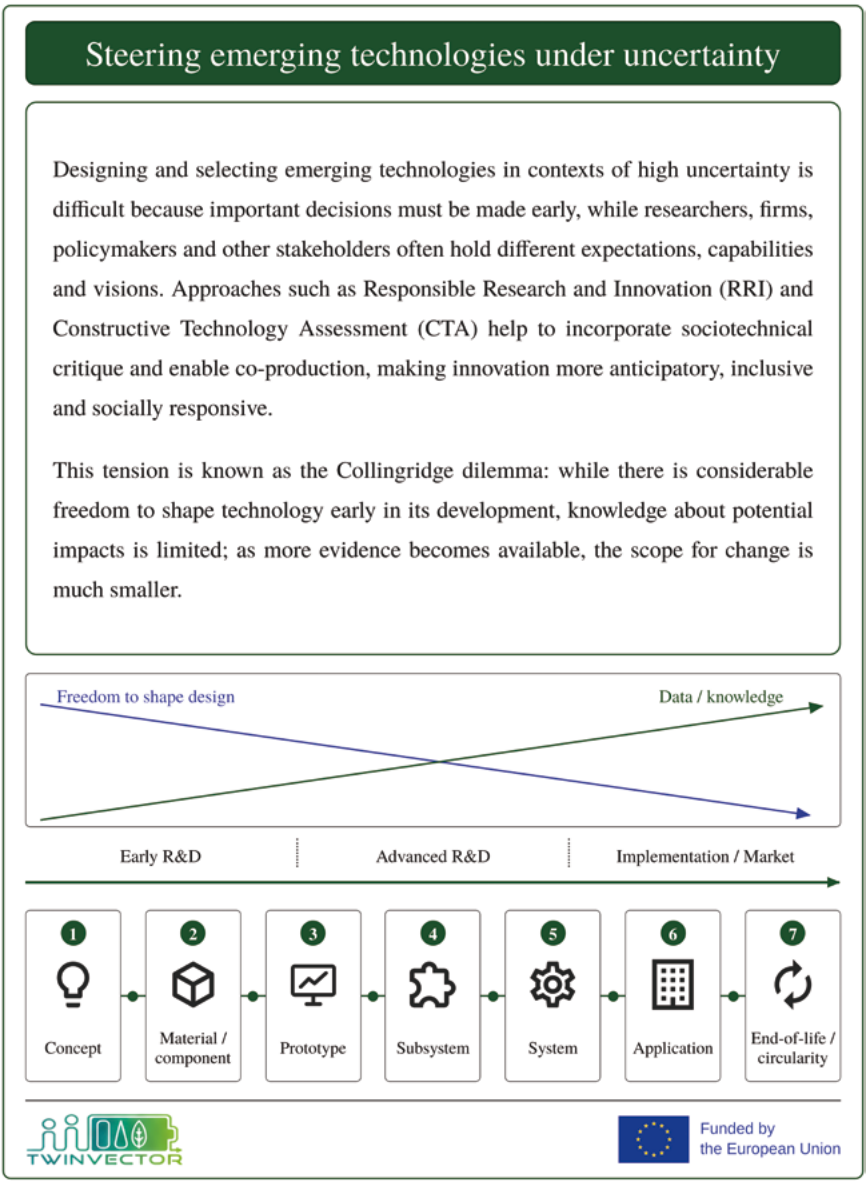

Figure 1.4 Research Frontier Box based on EU TwinVECTOR project Deliverable Guidelines for sustainability assessment[54]

*1 Horizon Europe, Grant No. 101078935

THE ROLE OF SUSTAINABILITY IN RESEARCH AND INNOVATION

Beyond the role of research as an actor in sustainability transitions, sustainability provides a strategic orientation for how research and innovation are designed, evaluated, and steered. Many impacts are determined before technologies reach the market, as early decisions on materials and design can lock in resource use and supply-chain risks.

This reorientation moves attention from whether an innovation can be developed to whether, and under what conditions, it should be pursued. It encourages researchers to question underlying assumptions and consider their consequences.

Since these functions require impacts to be examined across raw material extraction, production, use, and end-of-life stages, the next chapter introduces life cycle thinking as a structured approach for translating broad sustainability principles into the assessment of products, technologies, and systems across all phases.

RECOMMENDED READINGS

Topic	Recommended reading
Foundations of sustainable development	World Commission on Environment and Development (1987). *Our Common Future*[10].
Weak and strong sustainability	Neumayer (2010). *Weak versus Strong Sustainability: Exploring the Limits of Two Opposing Paradigms*[14].
Ecological limits and social foundations	Rockström et al. (2024). *Planetary Boundaries guide humanity's future on Earth*[21]; Raworth (2017). *Doughnut Economics: Seven Ways to Think Like a 21st-Century Economist*[22].
Environmental and intergenerational justice	Schlosberg (2007). *Defining Environmental Justice: Theories, Movements, and Nature*[11]; Brown Weiss (1989). *In Fairness to Future Generations: International Law, Common Patrimony, and Intergenerational Equity*[12].
Sustainability transitions	Geels (2002). *Technological transitions as evolutionary reconfiguration processes: A multi-level perspective and a case-study*[27]; Geels and Schot (2007). *Typology of sociotechnical transition pathways*[28].
Collective action and resource governance	Ostrom (1990). *Governing the Commons: The Evolution of Institutions for Collective Action*[34].
Responsible research and innovation	Stilgoe, Owen and Macnaghten (2013). *Developing a framework for responsible innovation*[48].
Transdisciplinary sustainability research	Lang et al. (2012). *Transdisciplinary research in sustainability science: Practice, principles, and challenges*[47].

REFLECTION & EXERCISES

Exercise 1. Planetary boundaries

Which statement best describes the role of planetary boundaries in sustainability thinking?

A. They define the maximum level of economic growth that each country should achieve.

B. They identify global biophysical boundaries beyond which the risk of abrupt or irreversible Earth system change increases.

C. They measure only carbon emissions and are mainly used in climate policy.

D. They replace the need for social indicators by focusing on environmental performance alone.

E. They allocate equal environmental impacts to all technologies regardless of context.

Answer: B

Why: Planetary boundaries define a safe operating space for humanity. Crossing a boundary does not necessarily trigger an immediate tipping point, but increases the risk of large-scale, potentially irreversible environmental change.

Reflection: Why is it difficult to translate planetary boundaries from the global level to individual countries, products, or technologies?

Exercise 2. Emerging technologies and planetary boundaries

Choose one emerging technology, product, or industrial activity, for example, a lithium-ion battery, an electric vehicle, hydrogen technology, food packaging material, a data centre, or a renewable energy system. Using Figure 1.2, analyse how this technology may interact with at least three planetary boundaries. For each selected boundary, answer:

A. Which planetary boundary is relevant?

B. How could the selected technology contribute to pressure on this boundary?

C. How could research and innovation reduce this pressure?

Answer guidance: Connect each boundary to a specific life cycle stage; identify concrete mechanisms such as energy use, emissions, land use, water use, toxic releases, material extraction, or waste; propose realistic responses, such as material substitution, design for durability, circular strategies, improved process efficiency, or better recovery systems. Suggested output format: | planetary boundary | main pressure created | life cycle stage | possible mitigation

Exercise 3. How would you decide?

You are part of a multidisciplinary team evaluating an emerging technology. Preliminary results indicate strong economic potential and moderate environmental benefits, but evidence about social impacts in the supply chain remains limited. How would you proceed?

A. Continue development based on the available economic and environmental evidence and address social impacts if concerns emerge.

B. Continue through a staged process combining social and environmental screening, stakeholder engagement, and clear review points.

C. Pause development until more comprehensive life cycle and supply-chain data are available.

D. Prioritise an alternative with better-understood impacts, even if its current technical or economic performance is lower.

Answer guidance: There is no single correct answer. Justify your choice by considering uncertainty, precaution, substitution between sustainability dimensions, affected stakeholders, and opportunities to adapt the technology.

Reflection:

Which sustainability paradigm does your decision reflect?

Who benefits and who bears the remaining risks?

What evidence could cause you to reconsider your decision?

Exercise 4. Identifying externalities in sustainability decisions

Choose one product, technology, or activity, such as a lithium-ion battery, a data centre, air travel, fast fashion, or plastic packaging. Identify at least two negative externalities and, if relevant, two positive externalities associated with it.

For each externality, explain: who creates it, who is affected by it, why it is not fully reflected in the market price, how it could influence sustainability assessment or policy decisions.

Answer guidance: distinguish clearly between internal and external costs; identify affected stakeholders across time and / or geography; explain why the impact is external to the market transaction; suggest at least one implication for regulation, taxation, design, and / or sustainability assessment.

Optional answer frame: | externality | Who creates it? | Who is affected? | Why is it external? | policy assessment relevance

Exercise 5. Quadruple Helix case analysis

Select one emerging technology or innovation area, such as new battery technology, solar energy, AI, bio-based materials, or carbon capture.

A. Identify the role of: government and policy, industry and markets, civil society, research and academia.

B. Then explain how interaction among these four spheres could either accelerate or hinder a sustainability transition.

Answer guidance: Describe each actor as a distinct but interacting sphere; explain at least one enabling and one constraining interaction; connect the example to innovation, legitimacy, regulation, markets, and / or public acceptance.

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2/
LIFE CYCLE THINKING

The sustainability impacts of modern products and services are rarely confined only to the moment of use. These impacts begin long before products and services reach the user and often continue after they are no longer in use. A battery or a cup of coffee may appear simple from the consumer's point of view, but each is linked to a chain of material extraction, processing, transport, manufacturing, use, maintenance, and end-of-life treatment. Moreover, design choices made within the research and development (R&D) phase substantially influence subsequent impacts across the value chain.

Consequently, broader questions arise concerning where many future impacts are likely to be determined. Where do the materials come from, and under what environmental and social conditions are they produced? Will scaling up from laboratory research to industrial application require more water, greater use of hazardous substances, or more complex waste management? Could an R&D choice that improves one parameter generate higher burdens elsewhere in environmental, social, or economic terms? What appears in laboratory testing to be a sustainability improvement may thus prove less favourable when assessed from a life cycle perspective.

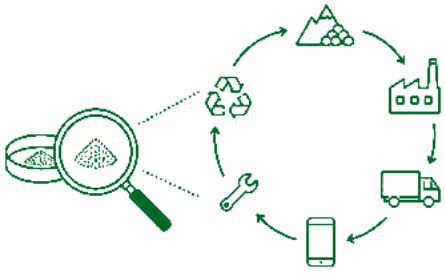
The origins, core concepts, levels of application, and links to sustainability assessment within life cycle thinking (LCT) are introduced in this chapter. The themes covered include: why the LCT perspective matters, how life cycles are structured, along with how a life cycle perspective helps avoid burden shifting between stages, places, or sustainability dimensions. This discussion further lays the groundwork for the more detailed methods introduced in the subsequent chapters.

From one successful experiment to a whole supply chain

In the laboratory, the new material looks excellent. The sample is small, the experiment is controlled, and the result is promising, even better than expected. The team has good reasons to celebrate. The laboratory, however, is only one small part of the story.

To produce the material at larger scale, precursors must be sourced, transported and processed. Solvents may be needed. Energy demand may increase. Some materials may be lost during synthesis. Waste streams may appear. A process that seems simple in a laboratory notebook may become more complex in pilot production.

Life cycle thinking encourages researchers to zoom out, connecting the experiment on the bench with extraction, production, use, repair, recycling and disposal. Researchers should systematically anticipate where important impacts may appear as the technology matures.



THE ORIGINS OF LIFE CYCLE THINKING

The term *life cycle thinking (LCT)* emerged from efforts to examine products and processes across their life cycles. The roots of LCT are usually traced to the 1960s and 1970s, when early studies began comparing products such as packaging systems, containers, and industrial materials in terms of total energy demand, resource use, and waste generation[1]. These early efforts challenged the narrow assumption that environmental performance could be assessed only at one stage, introducing the idea that products should be viewed as chains of interconnected stages, from raw material extraction to disposal[2].

However, these first approaches remained fragmented and non-standardised. Different studies applied different assumptions, which made results difficult to compare[3]. Some focused mainly on energy, others on waste or emissions, and many lacked a common methodology. During this period, life cycle scope was largely environmental: the dominant concerns were resource depletion, pollution, and energy efficiency, while social and economic dimensions had not yet been systematically integrated[4].

The late 1980s and early 1990s marked the consolidation of practice. *The Society of Environmental Toxicology and Chemistry* (SETAC) became a major scientific platform for developing terminology and methodological guidance. The 1991 SETAC Technical Framework for Life Cycle Assessments is regarded as a milestone in the definition of the key phases that underpin LCA[5]. This was followed by the 1993 SETAC Code of Practice, which further strengthened methodological consistency in life cycle studies.

This consolidation was later formalised through the *International Organization for Standardization (ISO)*. The ISO 14040 series transformed life cycle-based reasoning into an internationally recognised framework by defining the principles and phases of LCA, including goal and scope definition, inventory analysis, impact assessment, and interpretation[6,7]. ISO standardisation provided LCA with unified methodology and enabled its broad application in research, business, product policy, and environmental declarations[8].

A further milestone occurred in 2002, when the United Nations Environment Programme (UNEP) and SETAC established the International Life Cycle Partnership, commonly known as the *Life Cycle Initiative*[9]. UNEP's road map on life cycle approaches presents the development as part of a move toward sustainable consumption and production, linking it to international policy, including the Malmö Declaration (2000) and the World Summit on Sustainable Development in Johannesburg (2002).

Over time, life cycle work evolved from a relatively narrow focus on company-centred environmental accounting and compliance towards a broader systems perspective that informed policy[10]. From the early 2000s onward, life cycle approaches

became more firmly embedded in *European policy* development (i.e. the European Commission's Green Paper on Integrated Product Policy in 2001; Communication on Integrated Product Policy in 2003). In 2005, the European Platform on Life Cycle Assessment was established, while thematic strategies on waste prevention, recycling, and the sustainable use of natural resources further strengthened the policy relevance of life cycle approaches.

The period after 2008 also saw a rapid expansion of life cycle-based methods and applications. The EU Sustainable Consumption and Production and Sustainable Industrial Policy Action Plan, together with the publication of PAS 2050, contributed to the diffusion of carbon footprinting and life cycle-based product evaluation. In 2010, the European Commission launched the ILCD Handbook, which provides detailed methodological guidance for consistent LCA practice.

In the following decade, LCT expanded further through Product Environmental Footprint (PEF) and Organisation Environmental Footprint (OEF) methods, updated social LCA guidance, improved global access to life cycle inventory databases, and new regulatory applications, including battery carbon footprinting and digital product information systems. Selected milestones in the development of LCA are summarised in Table 2.1 below[11].

Table 2.1 Selected milestones in LCT and assessment[2,5,6,9,11,30]

Year	Milestone
1963	Early resource and environmental profile studies
1969	Coca-Cola comparative packaging study
1991	SETAC technical framework for LCA
1993	SETAC Code of Practice published
1996–2000	First ISO standards for LCA developed
2001	EU Green Paper on Integrated Product Policy
2002	UNEP/SETAC Life Cycle Initiative launched
2005	European Platform on LCA established
2008	EU SCP/SIP Action Plan; PAS 2050 published
2010	ILCD Handbook released by the European Commission
2013	First EU recommendation on Environmental Footprint methods
2020	GLAD network launched; updated UNEP Social LCA Guidelines
2021	EU recommendation on PEF and OEF updated
2022	Safe and Sustainable by Design EU framework initiated
2023	EU Battery Regulation adopted
2024	EU Ecodesign for Sustainable Products Regulation

CONCEPTS IN LIFE CYCLE THINKING

Concepts in LCT build on the idea that products, services, and technologies are treated as parts of wider systems that deliver functions and generate consequences across multiple stages. To this end, *systems thinking, LCT, and functional thinking* provide the conceptual foundation for later assessment choices, including *functional units* and the treatment of *trade-offs*.

Systems thinking

A system is defined as an interconnected set of elements organised to achieve a particular function or purpose[12]. The description is central to LCT, as products and technologies are parts of systems composed of linked flows. One core strength of LCT is that it applies a systems perspective to see sustainability problems, for instance by examining how decisions in one part of a product system affect other processes and stages across the value chain[13].

Technical improvements can also involve sustainability trade-offs. Lightweight materials, for example, may reduce fuel use in transport but increase production burdens; recyclable materials may require more energy-intensive processing; automation may improve efficiency, although certain forms of employment may be reduced; and lower-cost sourcing may reduce direct costs while increasing exposure to environmental or social risks in global supply chains.

In this sense, systems thinking helps identify and reduce *burden shifting*, a phenomenon which occurs when an apparent improvement in one place creates a larger burden elsewhere in the system. This may happen in terms of:

- *life cycle stages*, for example when impacts are reduced during the use stage but increased in the manufacturing stage;
- *geographical locations*, for example when pollution-intensive activities are outsourced abroad;
- *impact categories*, for example when climate change impacts are reduced but toxicity or water scarcity increase;
- *sustainability dimensions*, for example when lower costs are achieved at the expense of poorer labour conditions.

The role of LCT is therefore to ensure that the trade-offs are more visible[14].

A related systems challenge is the *rebound effect*, which refers to a change in overall consumption and production that results from behavioural or other systemic responses to changes in economic variables. These include factors such as income, prices, and the financial gains or costs associated with product or material

substitution[15]. Such changes may be triggered by improvements in the technical efficiency of providing an energy service.

More specifically, rebound effects arise when expected environmental gains from efficiency improvements are partially or fully offset by behavioural or systemic responses. For example, a more energy-efficient product may become cheaper to use and therefore be used more intensively, reducing the expected net environmental benefit. From a life cycle perspective, rebound effects demonstrate how final sustainability outcomes also depend on socio-technical dynamics[16].

Life Cycle Thinking

LCT can be understood as a way of thinking that considers the environmental, social and economic impacts of the decisions we make[17]. Because it encompasses all three dimensions of sustainability, it is sometimes referred to as *Life Cycle Sustainability Thinking*. It is primarily a qualitative approach used to identify relevant life cycle stages and impacts of decisions made at one stage on another[18].

Figure 2.1, adapted from the Life Cycle Initiative, presents research and development (R&D) as a central influence across the product *life cycle*, from raw material extraction and production to distribution, use, maintenance, and end-of-life treatment. It also illustrates circular flows through reuse, recycling, and material recovery, which can return products, components, or recovered resources to earlier life cycle stages and reduce reliance on virgin natural resources.

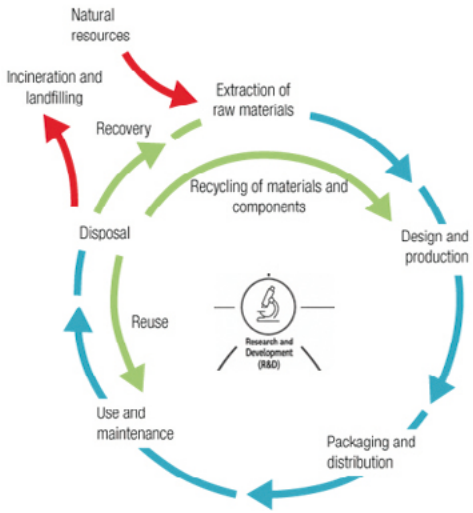


Figure 2.1 Life cycle stages (adapted from the Life Cycle Initiative[19])

LCT becomes practical in organisations through *Life Cycle Management (LCM)*, a management approach that applies life cycle tools and methods to steer the environmental burdens of products across their entire life cycle[17]. If economic and social dimensions are included, it can be referred to as *Life Cycle Sustainability Management*.

LCM provides a framework for integrating sustainability into product management, informed by data and within the relevant policy context, and it follows a continuous improvement logic similar to the *plan-do-check-act model* used in ISO 9000 and ISO 14000 systems. By using LCM, companies can stimulate innovation, improve existing products and services, and communicate performance through instruments such as Environmental Product Declarations[20].

LCA is a concrete tool through which the life cycles of a product or system can be examined, the exclusion of important processes prevented, and environmental impacts captured across scales ranging from local to global[21]. LCSA extends the life cycle perspective by integrating environmental LCA, life cycle costing, and social LCA, although other integration approaches are also emerging. Life Cycle Impact Assessment (LCIA) methodologies are designed to represent impacts in relation to specific *Areas of Protection (AoPs)*. In traditional LCA, these AoPs are usually understood as three recognised areas: *human health, ecosystem quality,* and the abiotic *natural resources*[22]. Accordingly, a central aim of LCA, and of the LCIA phase in particular, is to identify and assess all relevant potential impacts that may contribute to damage in these AoPs.

In simple terms, LCT is the mindset, LCM is the practice, and LCA is the analytical tool. The logic can also be extended toward sustainability more broadly through the related concepts of Life Cycle Sustainability Thinking, Life Cycle Sustainability Management, and Life Cycle Sustainability Assessment[23]. While LCSA is already well established, LCST and especially LCSM are less standardised terms. Figure 2.2 thus sets out the conceptual progression from thinking to management and assessment, and from environmental life cycle focus toward life cycle sustainability.

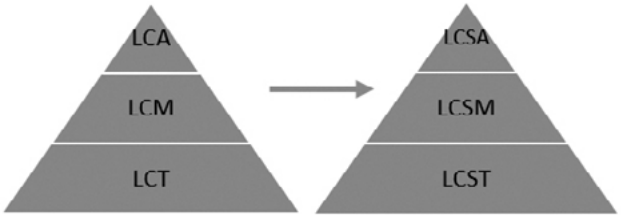


Figure 2.2 Life cycle based concepts (adapted from the UNEP/SETAC Life Cycle Initiative)[23]

Functional thinking

Functional thinking extends life cycle approaches by moving the focus away from the product as a standalone physical item and toward the function or service it delivers. Under this perspective, human needs can be met more effectively through service-oriented systems. This idea is reflected in the concept of the Product-Service System (PSS), where value is generated primarily by providing access to a function rather than ownership of a product[24]. Such approaches can be found across sectors including ICT, energy, mobility, and food, for example in remanufacturing, car-sharing, chemical management services, or demand-side management. Functional thinking is associated with sustainability improvements across the entire product chain as well as support for system innovation[25].

For example, comparing a paper cup and a ceramic mug by weight alone would be meaningless. While the function of each is to provide beverage service, a fair comparison would require a reference that reflects equivalent service, such as "serving 1,000 cups of hot drinks." Such a reference is called the *functional unit*, which defines what exactly is being assessed and provides a more precise basis for comparison. The functional unit is the quantified description of the function delivered by a product system and serves as the reference basis for relating inputs, outputs, and impacts in LCA[7].

LEVELS OF LCT APPLICATION

LCT can be applied at several levels—materials, products, projects or technology development processes, organisations, and policy— with the appropriate level depending on the purpose of the assessment and the maturity of the system being studied.

At the *material level*, life-cycle approaches are utilised in early design and ecodesign decisions, where alternative materials or components are screened before a final product configuration is fixed[26]. In contrast, at the *product level*, LCA has been more firmly established, and is used to compare product designs, variants, or supply-chain configurations.

The *project level* is less standardised as a formal category, but it is supported in practice through innovative pilot and scale-up studies for emerging technologies[27] project-level assessment functions as decision support within R&D and demonstration projects, often bridging material- and product-level analysis across technologies at different stages of maturity[28].

At the *organisation level*, assessment expands from an individual product to a company, portfolio, or value chain, as formalised in Organisational LCA (O-LCA) and the Organisation Environmental Footprint (OEF)[29]. At the *policy level*, life-cycle approaches support sustainable consumption and production and evaluation of regulatory or societal options.[30].

Figure 2.3 summarises these levels, their main purposes, and their most suitable applications. A distinction is drawn between objects of assessment, such as materials, products, and organisations, and decision contexts, including research projects.

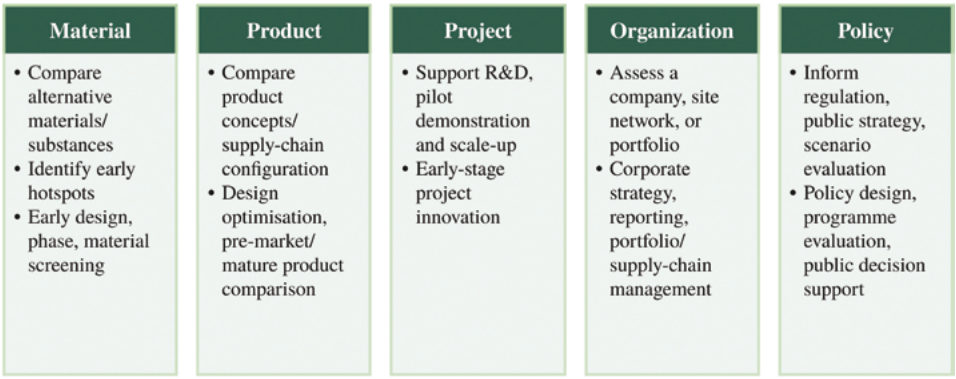


Figure 2.3 Levels of LCT application

SUSTAINABILITY ASSESSMENT AND LIFE CYCLE TOOLS

Sustainability assessment

Decisions can be evaluated across environmental, social, and economic dimensions through *sustainability assessment*[31]. As in a health check-up a doctor would not assess health through blood pressure alone, sustainability cannot be judged only by carbon emissions, costs, or a single social indicator. Similarly, sustainability assessment has been described as a complex appraisal method that supports decision-making in environmental, economic, and social context by providing an integrated picture of performance and consequences.

A widely cited definition describes sustainability assessment as any process that directs decision-making toward sustainability. This definition is intentionally broad, as such evaluations may be applied to projects, products, technologies, organisations, plans, programmes, or policies, provided that its purpose is to guide choices in a more sustainable direction[32].

Figure 2.4 (based on TwinVECTOR[*2] project) presents this process as a decision-support exercise guided by adequate scope and essential environmental, social and economic considerations. The procedure begins by defining values, sustainability principles and targets, followed by the object of assessment. The decision context—including policies, institutions, and systems—are then addressed. Scenario-oriented 'what if' analysis and target-oriented 'what to' assessment inform the selection of an appropriate framework, methodology, and indicators.

*2 Horizon Europe, Grant No. 101078935

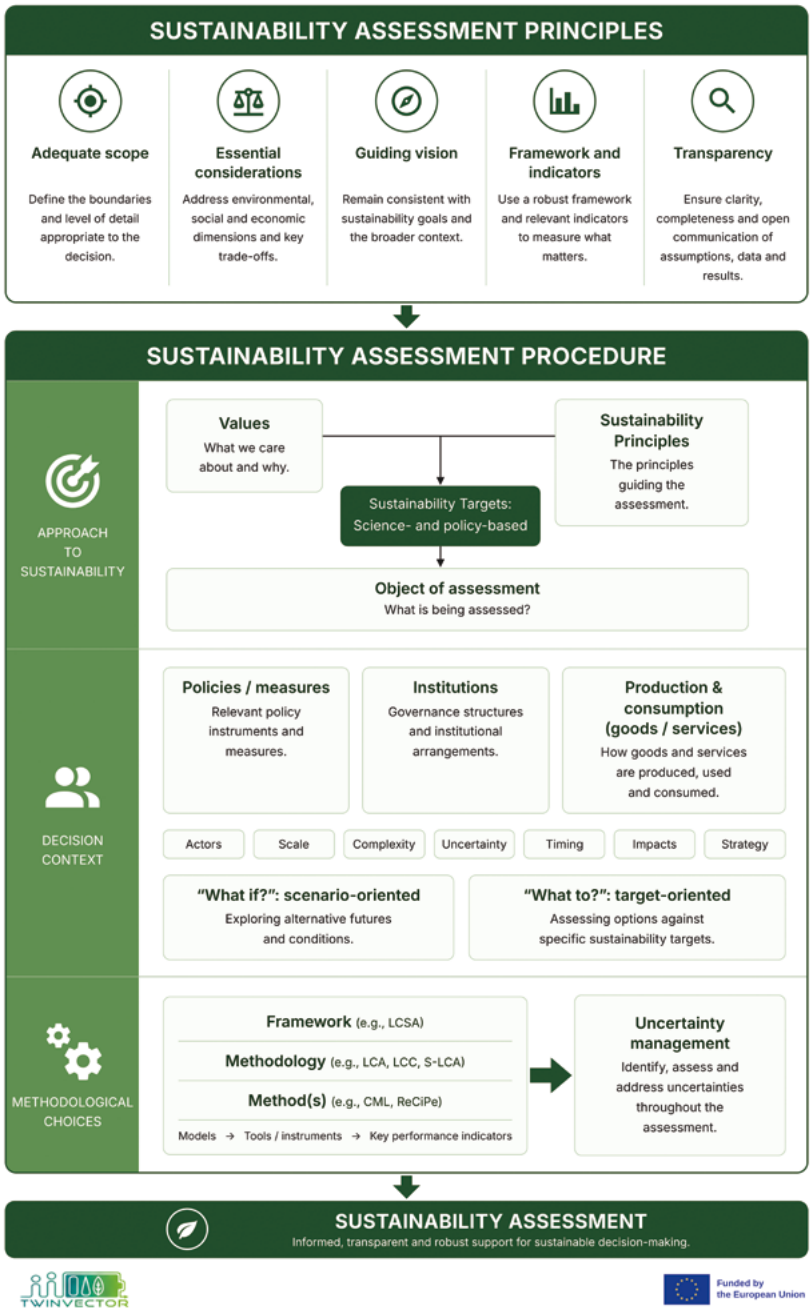


Figure 2.4 Sustainability assessment principles, AI-adapted from the Horizon Europe TwinVECTOR project Deliverable Guidelines for sustainability assessment[33]

Selected life cycle approaches

The main life cycle–based approaches and tools that support sustainability-oriented decision-making can be grouped into three basic categories[34]. The first group is mostly analytical in focus, while the second and third categories focus more on application and implementation.

The first category—*assessment approaches*—includes methods used to analyse impacts, burdens, or system performance, including LCA, footprints, MFA, EEIO, S-LCA, LCSA, O-LCA, LCC, and related analytical approaches. These tools are primarily used to generate evidence, compare alternatives, and identify hotspots or trade-offs across the life cycle. As such, they form the analytical backbone of life cycle practice by enabling users to understand what kinds of impacts occur, where they arise, and how they may shift across stages, places, or sustainability dimensions.

Management and communication approaches include instruments such as eco-design, eco-labels, EPDs, PEF, sustainable supply chain management, product-service systems, green purchasing, and extended producer responsibility. These approaches translate life cycle insights into decisions in product development, procurement, market communication, and value-chain coordination.

The final category—*organisational and reporting approaches*—places life cycle elements within broader organisational governance, including environmental management systems, auditing, CSR, and sustainability reporting. These approaches constitute a set of tools connecting assessment, management, communication, and organisational practice.

Table 2.2 Selected life cycle approaches[34]

Assessment approaches
LCA (materials and energy systems)
Environmental footprints, including carbon and water footprints
Materials flow analysis (MFA)
Environmentally extended input–output analysis (EEIO)
Social life cycle assessment (S-LCA)
Life cycle sustainability assessment (LCSA)
Life cycle costing (LCC)
Chemicals assessment
Risk assessment, hazard assessment
Emerging tools for biodiversity, land-use, and landscape assessment
Management and communication approaches
Eco-design
Eco-labels
Environmental product declarations (EPDs)
Product environmental footprint (PEF) method
Sustainable supply chain management (SSCM)
Circular materials management
Product-service systems (PSS)
Sustainable and circular public procurement
Green purchasing
Extended producer responsibility (EPR)
Organisational and reporting approaches
Environmental management systems (EMS, EMAS)
Organisational LCA (O-LCA)
Environmental impact assessment (EIA)
Environmental auditing
Corporate social responsibility (CSR)
Sector-specific management codes
Sustainability reporting (for example, GRI)
Emergency and disaster planning and preparedness

LCT across society, policy, business, and research

LCT informs decision-making across society, policy, business, and research by tracing how choices affect sustainability throughout the life cycle.

In *society*, LCT helps understanding of sustainable consumption, connecting everyday products and services with patterns of resource use, emissions, waste generation, and global value chains[35]. In this way, it relates to debates on resource productivity and more responsible consumption, which are also reflected in the 2030 Agenda for Sustainable Development[36].

In *policy*, LCT provides an analytical basis for a range of sustainability-related instruments, including environmental product declarations, eco-design requirements, green public procurement, carbon footprinting approaches, and waste and recycling strategies. Its main strength in policy is that it supports more coherent interventions by reducing the risk of burden shifting[37].

In *business*, companies use LCT for hotspot identification, product redesign, supply-chain risk screening, sustainability reporting, eco-innovation, and strategic decisions. LCT also complements circular economy strategies[38] by helping firms assess whether circular solutions truly reduce overall burdens across the system.

In *research*, LCT scope extends beyond technical performance alone. Early research and development decisions on materials and processes often determine future sustainability outcomes, including reparability and recyclability[39].

THE ROLE OF LCT IN RESEARCH AND INNOVATION

LCT provides a conceptual foundation for understanding products, services, and technologies as parts of wider systems. Examining impacts across raw material extraction, production, use, repair, and end-of-life reveals trade-offs and reduces the risk of burden shifting between life cycle stages, locations, impact categories, and sustainability dimensions. LCT also clarifies why methodological choices influence assessment results.

Laboratory performance and technical efficiency provide only partial evidence of sustainability. Early decisions concerning materials, process design, scale-up, durability, reparability, and recyclability can shape impacts across the future value chain. LCT connects early-stage experiments with the systems in which technologies may eventually operate, prompting researchers to consider whether an innovation works, which resources it requires, which burdens it may create or shift, who may be affected, and how its performance could change beyond controlled conditions.

The next chapter addresses environmental life cycle assessment (E-LCA), which translates this conceptual perspective into a systematic method for quantifying potential environmental impacts across the life cycle.

RECOMMENDED READINGS

Topic	Recommended reading
Introduction to life cycle thinking	European Commission and Joint Research Centre (2010). *Making Sustainable Consumption and Production a Reality: A Guide for Business and Policy Makers to Life Cycle Thinking and Assessment*[11].
Systems thinking	Meadows (2008). *Thinking in Systems: A Primer*[12]; Onat et al. (2017). *Systems thinking for life cycle sustainability assessment: A review of recent developments, applications, and future perspectives*[13].
Life cycle management in organisations	UNEP (2007). *Life Cycle Management: A Business Guide to Sustainability*[20].
Life cycle assessment methods	Hauschild, Rosenbaum and Olsen (eds., 2018). *Life Cycle Assessment: Theory and Practice*[21].
Organisational assessment	UNEP/SETAC (2015). *Guidance on Organizational Life Cycle Assessment*[29].
Life cycle thinking in product and service design	Vezzoli et al. (2014). *Product-Service System Design for Sustainability*[24]; Pollini and Rognoli (2021). *Early-stage material selection based on life cycle approach: Tools, obstacles and opportunities for design*[26].
Rebound effects	Font Vivanco and van der Voet (2014). *The rebound effect through industrial ecology's eyes: A review of LCA-based studies*[15].
Assessment across technology maturity levels	Bergerson et al. (2020). *Life cycle assessment of emerging technologies: Evaluation techniques at different stages of market and technical maturity*[28].

REFLECTION & EXERCISES

Exercise 1. Life cycle thinking

Which statement best describes life cycle thinking?

A. It measures the carbon emissions of a product during use.

B. It focuses mainly on factory-level efficiency and excludes upstream supply chains.

C. It reflects how environmental, social, and economic impacts are shaped across the life cycle of products and systems.

D. It replaces the need for sustainability assessment by providing one final indicator.

E. It is relevant only for mature industrial products, not for research and innovation.

Answer: C

Why: Life cycle thinking broadens analysis beyond a single process, stage, or indicator. It captures how decisions influence impacts across extraction, production, use, repair, and end-of-life, and can be extended across environmental, social, and economic dimensions.

Follow-up reflection: Why is life cycle thinking especially important in research and innovation, where technologies are often assessed first under controlled laboratory conditions?

Exercise 2. Functional unit identification

A research team is comparing two options for delivering the same service:

Option one 100 single-use paper cups for serving hot drinks

Option two: 20 ceramic mugs, each used five times in total.

Which of the following is the most appropriate functional unit?

A. One cup

B. 20 mugs

C. Serving 100 hot drinks

D. The total mass of packaging material

E. One kilogram of ceramic or paper

Answer: C

The function being compared is not the physical object itself, but the service delivered. A fair comparison therefore requires a functional unit that reflects equivalent service.

Follow-up reflection: How would the interpretation change if the ceramic mugs were used only twice instead of five times?

Exercise 3. Identifying problem shifting

A food producer replaces a glass container with lightweight multilayer plastic packaging. The new packaging requires less material and reduces fuel consumption during transport. However, its production relies on fossil-based feedstocks and chemical additives, and the layers are difficult to separate during recycling. The lighter packaging may therefore reduce transport-related emissions while increasing impacts associated with material production and end-of-life treatment.

A. Identify potential shifts between life cycle stages and environmental impact categories.

B. Discuss possible economic and social implications of the change.

C. Explain what information would be required to assess the overall sustainability implications.

Answer guidance: Consider material and energy requirements, transport distance, product protection, food waste, chemical hazards, production costs, working conditions, collection infrastructure, recyclability, disposal routes, and data uncertainty. A strong response should identify where benefits and burdens occur and avoid drawing conclusions from a single indicator or life cycle stage.

Exercise 4. Debate trade-offs and assumptions

A pilot-scale material shows excellent technical performance and uses less of a critical raw material. The research team therefore presents it as a sustainability improvement. However, scaling up the process may require more solvents, more purification, and a more complex global supply chain. Is it justified to describe the material as more sustainable at this stage?

Answer guidance: There is no single correct answer. The response should explain why laboratory performance alone is not enough; identify possible forms of burden shifting during scale-up; consider the role of uncertainty, assumptions, and missing data; and reflect on how a life cycle perspective could improve early-stage decision-making.

Exercise 5. Identifying hidden consequences within a product system

Choose one everyday product, such as a smartphone, coffee cup, battery, or item of clothing. Identify at least three life cycle stages that are relevant to its sustainability.
For each stage, explain:
A. what kind of impact or burden may occur there;
B. who is affected;
C. why this stage is often overlooked in everyday thinking.

Answer guidance:
There is no single correct answer. A strong response should consider moving beyond the use phase; include upstream and/or end-of-life stages; show that sustainability concerns may be distributed across places, actors, and time.
Optional answer frame:
| Life cycle stage | Possible impact | Who is affected? | Why often overlooked? |

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3/
ENVIRONMENTAL LIFE CYCLE ASSESSMENT

Environmental Life Cycle Assessment (LCA) is the most widely used and standardised method within the life cycle toolbox. It provides an evidence-based framework for quantifying potential environmental impacts of a product, process, or service across its entire life cycle, from raw material extraction and processing, through manufacturing and distribution, to use and end-of-life treatment. Unlike approaches that focus on a single stage, emission type, or geographic location, LCA has the ambition to encompass chains of environmental consequences.

The previous chapter introduced life cycle thinking as a way of framing sustainability challenges, and described the family of life cycle tools as methods for applying that perspective in practice. This chapter focuses specifically on environmental LCA: its methodological structure, the choices that influence its results, and its relevance in research, policy, and innovation contexts. The four phases defined in ISO 14040 and ISO 14044 are outlined, key methodological concepts are explained, and the ground is laid for the more detailed treatment of social and economic dimensions in the chapters that follow.

Are we measuring the right kind of 'better'?

A research team develops a new coating material for photovoltaic panels. In laboratory testing, the coating reduces optical losses and improves energy conversion efficiency by three percentage points. This appears to be a clear environmental benefit, as the same panel can generate more electricity without increasing its size.

However, another perspective raises an important question: what is the coating made of? The production process involves a fluorinated compound that is synthesised through an energy-intensive reaction using several chlorinated precursors, including substances with known toxic effects. Although the coating layer itself is very thin, the total material use becomes relevant at scale.

This example illustrates a common challenge: an improvement in one aspect of a system, such as energy efficiency, may be associated with impacts in another, such as toxicity or resource use. Understanding the overall environmental performance therefore requires a method that accounts for the entire life cycle and multiple types of impacts. Environmental LCA provides this systematic perspective.



WHAT LCA IS AND WHAT IT DOES

Environmental LCA is defined by ISO 14040 as 'the compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle'[1]. This definition encompasses three essential elements. First, LCA is a compilation method: material and energy flows associated with each stage of a product system are recorded as data. Second, it is an evaluation method: these flows are translated into potential environmental impacts using characterisation models. Third, it applies a life cycle scope: the assessment covers stages from raw material extraction to end-of-life[1–4].

The standards that define LCA practice are ISO 14040:2006[1], which establishes the principles and framework, and ISO 14044:2006[5], which provides requirements and guidelines for each phase. These sources establish LCA as a four-phase process: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment, and (4) interpretation. Each phase informs and is informed by the others. The process is explicitly iterative: findings at later stages may necessitate revision of earlier decisions.

LCA offers several distinct strengths compared to other environmental assessment approaches. The scope of environmental impacts covered is broad, including climate change, resource use, water consumption, land use, and human toxicity. Results are expressed relative to a functional unit and impacts are tracked across the full value chain[6]. LCA is also a standardised and internationally recognised methodology.

These strengths notwithstanding, LCA has limitations that must be understood to use it responsibly. The method assesses potential environmental impacts rather than directly measured harms, relying on modelling assumptions and aggregated inventory data that simplify real systems. The results of LCA are shaped by choices regarding system boundaries, functional units, allocation methods, and impact characterisation models. LCA results are therefore model-dependent representations of environmental performance that require careful interpretation[7].

THE FOUR PHASES OF LCA

The ISO framework structures LCA into four interrelated phases that are not strictly sequential; results from later phases regularly inform necessary revisions to earlier decisions. Figure 3.1 illustrates the relationships between phases.

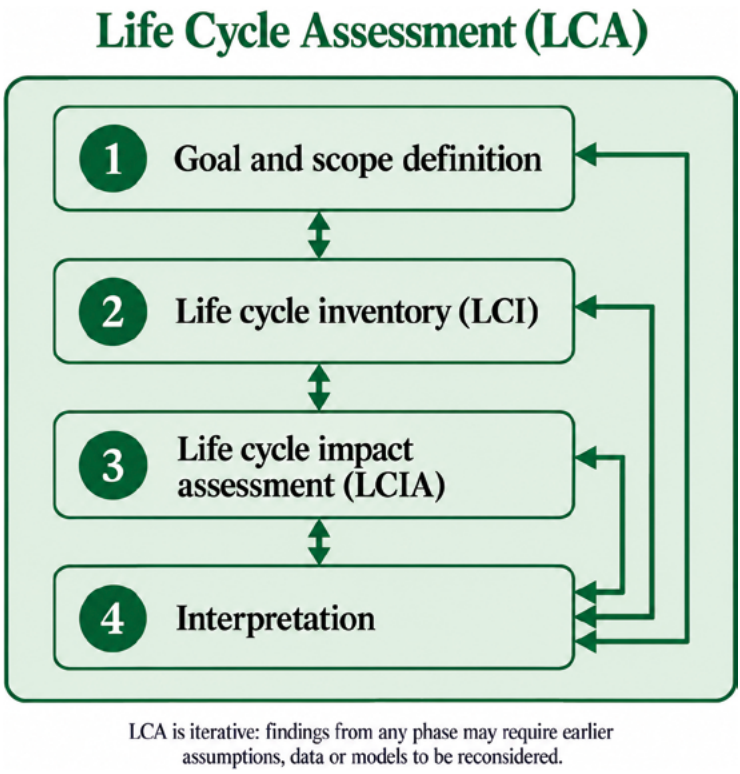

Figure 3.1 The four phases of LCA and interactions among them, based on ISO 14040:2006[1]

Goal and scope definition

The goal and scope definition phase establishes the purpose and boundaries of the study.

The goal of an LCA study should state the intended application, the reasons for carrying out the study, and the intended audience. A study comparing packaging alternatives for a corporate sustainability report, for example, has a different goal from a study informing public procurement policy or supporting a research publication on emerging battery materials.

The scope defines the product system, functional unit, system boundary, impact categories, data quality requirements, assumptions, and limitations. Key terms in the goal and scope definition phase are defined in the following paragraphs.

Functional unit: The quantified description of the function delivered by the product system. This unit serves as the reference basis for all inputs, outputs, and impact results, answering the question: what exactly is being assessed, and in what

quantity? For example, 'production of 1 kg of chemical X' focuses on output mass and may be appropriate for production comparisons, whereas 'delivery of 100 MJ of thermal energy over a service life of 20 years at an efficiency of 85%' defines performance, service life, and context, making it more appropriate for comparisons involving different efficiencies or lifetimes. A poorly chosen functional unit can make the results of a study misleading even if all subsequent data and calculations are correct.

Reference flow: The amount of product or process output actually required to fulfil the functional unit. For example, if the functional unit is defined as serving 1,000 cups of hot beverages, the reference flow for a ceramic mug and for a disposable paper cup will differ substantially.

System boundaries: The processes, stages, and flows included in the study. A *cradle-to-gate* study extends from raw material extraction to the factory gate, whereas a *gate-to-gate* study focuses on a single process or manufacturing stage within the overall product life cycle, assessing environmental impacts occurring between the entry and exit points of a specific facility or operation. A *cradle-to-grave* study adds the use phase and end-of-life management. A *cradle-to-cradle* study extends to cover material recovery and re-entry into circular production cycles. The choice of boundary determines which burdens are captured and which may be missed. For a product where use-phase energy consumption dominates, a cradle-to-gate study would underestimate the most important impacts. A schematic representation of LCA system boundaries is provided in Figure 3.2, illustrating the scope of four different approaches and their influence on the environmental impacts captured during assessment[8].

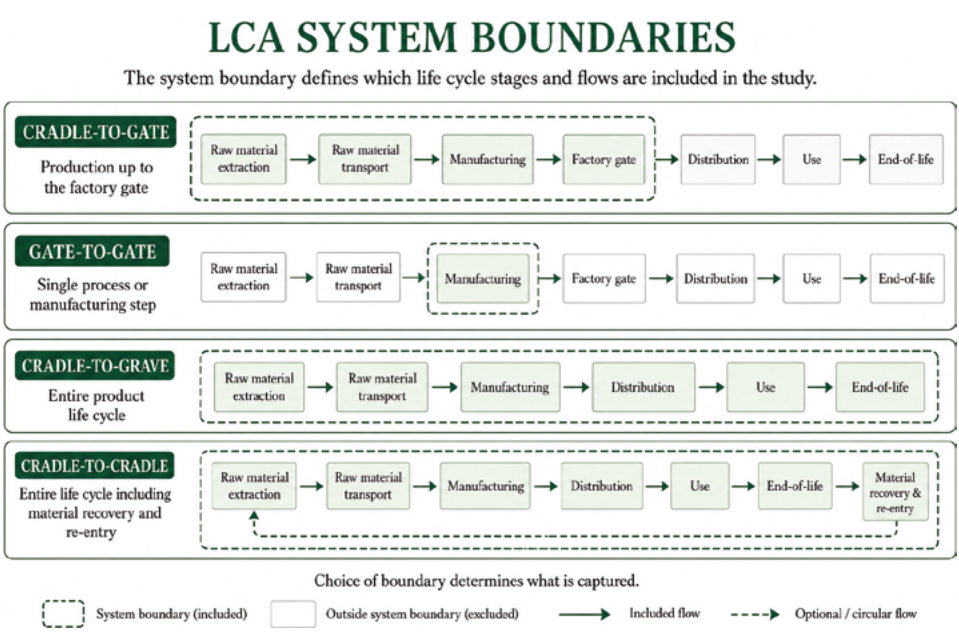

Figure 3.2 LCA system boundary definitions: cradle-to-gate, gate-to-gate, cradle-to-grave, and cradle-to-cradle

Cut-off criteria: The thresholds used to define which flows or processes are excluded based on their expected contribution to the total; processes contributing less than a defined threshold in terms of mass, energy, or environmental relevance are sometimes excluded for practical reasons. Cut-offs must be justified and reported, and their potential influence on results should be assessed, since selective exclusion of upstream or downstream processes can introduce bias.

Life cycle inventory analysis

The life cycle inventory (LCI) analysis phase involves the compilation and quantification of inputs and outputs for all processes within the system boundary: Inputs include energy, materials, and water; outputs include products, co-products, waste, and emissions to air, water, and soil. The result is a detailed accounting of what enters and leaves the product system at each stage.

In practice, LCI data derive from two main sources. Primary data are collected directly from the processes under study, representing the actual conditions of the product system, but also resource-intensive to collect. Secondary data are drawn from life cycle inventory databases, published literature, or engineering estimates

to provide background system data for upstream processes, infrastructure, energy supply, and materials that would be impractical to model from primary sources. Major LCI databases include ecoinvent, the European Life Cycle Database (ELCD), formerly the reference database for EU policy contexts, was discontinued in 2018 and its functions have been taken over by the European Platform on Life Cycle Assessment (EPLCA) maintained by the JRC, the US LCI database, and sector-specific datasets[9].

Data quality is an important consideration in LCI analysis. Relevant criteria include reliability, temporal coverage, geographical and technological representativeness, and completeness. A practical tool for assessing these dimensions is the pedigree matrix, which assigns scores according to defined quality criteria. In ecoinvent, these scores are also translated into uncertainty factors to estimate the additional uncertainty associated with data quality limitations[32]. As data quality affects the reliability of impact assessment results, it should be documented during inventory compilation and reviewed in the interpretation phase[10].

A recurring methodological challenge in LCI analysis is multifunctionality: the situation in which a process delivers more than one useful function or product[11]. For example, a natural gas processing plant produces multiple fuels; a waste incineration plant destroys waste and generates electricity and heat. In such cases, the total environmental burden of the process must be allocated among its multiple outputs[12].

ISO 14044[5] recommends a hierarchy of approaches for addressing multi-functionality starting with avoiding of allocation, if this is feasible. Where allocation cannot be avoided, it should first reflect underlying physical relationships. Other relationships, such as economic value, are used where suitable physical relationships cannot be established.

Subdivision: If the multifunctional process can be disaggregated into separate sub-processes, each with a single function, this approach is preferable.

System expansion: If subdivision is not possible, the system boundary should be extended to include the additional functions that the co-products would otherwise provide; the environmental credit or burden associated with those functions must be accounted for.

Allocation: This approach should be applied only if neither of the above approaches is possible. The total burden is divided among the multiple outputs according to a physical, economic, or other relevant parameter. The choice of allocation approach can substantially affect results, particularly in co-production systems.

Life cycle impact assessment

The life cycle impact assessment (LCIA) phase translates the inventory flows compiled in the LCI phase into potential environmental impacts, linking the quantified input and output flows to their significance for human health, ecosystem quality, and resource availability. LCIA does not measure actual harm; it models the potential contributions of inventory flows to defined impact categories.

LCIA consists of several steps, of which selection of impact categories, classification and characterisation are mandatory under ISO 14044, while normalisation and weighting are optional.

Classification and Characterisation

Classification assigns each inventory flow to one or more impact categories based on its known or expected environmental mechanisms. Carbon dioxide and methane, for example, are classified as contributors to climate change, while sulphur dioxide and nitrogen oxides contribute to acidification, and phosphorus and nitrogen flows contribute to eutrophication. Some flows, such as persistent organic pollutants, may contribute to multiple categories simultaneously.

Characterisation converts classified flows into a common unit within each impact category using factors derived from environmental models. For climate change, characterisation factors are expressed as global warming potential (GWP) relative to carbon dioxide equivalents over a defined time horizon, typically 100 years. For acidification, factors are expressed relative to sulphur dioxide equivalents. Characterisation models are developed and periodically updated by scientific bodies including UNEP, SETAC, and the European Commission Joint Research Centre.

The result of characterisation is a set of impact category indicator results, expressed in category-specific units. Throughout this chapter, the units of the EF 3.1 method are used, as listed in Table 3.1: for example, kg CO_2-equivalent (climate change), mol H^+-equivalent (acidification), CTUh (human toxicity), kBq U-235-equivalent (ionising radiation), and Pt, a dimensionless soil quality index (land use). These results provide a profile of potential environmental impacts across all relevant categories.

Midpoint and Endpoint Approaches

Characterisation models may be developed at different points along the environmental impact pathway.

Midpoint approaches characterise impacts at an intermediate point in the cause-effect chain, closer to the physical emission or extraction. These methods tend to offer generally lower model uncertainty and a closer connection to inventory

flows, but they result in a larger number of distinct impact categories that may be harder to communicate and compare. Examples of midpoint categories include climate change, ozone depletion, acidification, eutrophication, photochemical ozone formation, and human toxicity.

Endpoint approaches, by contrast, characterise impacts at the level of damage to areas of protection: human health, ecosystem quality, and resource availability. These frameworks aggregate midpoint impacts into fewer, more intuitively interpretable results but introduce greater modelling uncertainty and more explicit value choices in the aggregation step[13]. Figure 3.3 illustrates the midpoint-to-endpoint pathway[15, 16].

In practice, many LCIA methodologies are developed at both midpoint and endpoint levels, allowing practitioners to report at the level most appropriate for their goal and intended audience. LCIA methodologies include ReCiPe, CML, TRACI[14] (widely used in North America), EF (the European Commission Environmental Footprint method), and the IMPACT World+ framework. Since it affects both the categories included and the characterisation of inventory flows, the choice of methodology is one of the key decisions in LCIA.

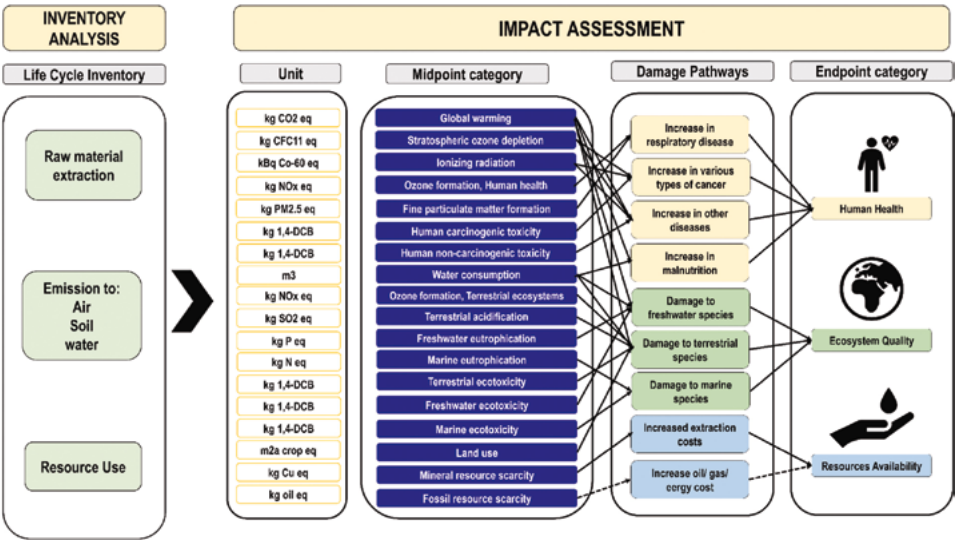

Figure 3.3 Relationship between midpoint and endpoint indicators reproduced from Paul et al. (2024)[16]

Table 3.1 presents a selection of commonly used environmental impact categories in LCA, their unit indicators, and the environmental mechanisms they represent. The list is illustrative, as the full set of categories used in any given study depends on the LCIA methodology chosen and the relevance of categories to the product system under assessment.

Table 3.1 Impact assessment categories, characterization units, and environmental mechanisms used in the Environmental Footprint (EF) Life Cycle Impact Assessment (LCIA).

Impact Category	Unit Indicator	Environmental Mechanism
Climate change	kg CO_2-equivalent	Greenhouse gas emissions and their contribution to global warming via radiative forcing
Ozone depletion	kg CFC-11-equivalent	Emissions of halogenated compounds depleting the stratospheric ozone layer
Photochemical ozone formation	kg NMVOC-equivalent	Emissions of volatile organics and NOx forming ground-level ozone
Acidification	mol H+-equivalent	Emissions of SO_2, NO_x, and ammonia increasing soil and water acidity
Terrestrial eutrophication	mol N-equivalent	Nitrogen deposition increasing nutrient load in terrestrial ecosystems
Freshwater eutrophication	kg P-equivalent	Phosphorus and nitrogen inputs causing algal growth in freshwater systems
Marine eutrophication	kg N-equivalent	Nutrient enrichment causing hypoxia in marine ecosystems
Freshwater ecotoxicity	CTUe	Toxic substance emissions affecting freshwater aquatic organisms
Human toxicity – cancer	CTUh	Intake of carcinogenic substances via multiple exposure pathways
Human toxicity – non-cancer	CTUh	Intake of non-carcinogenic toxic substances via multiple pathways
Land use	Pt (dimensionless)	Land transformation and occupation affecting soil quality and biodiversity
Water use (scarcity-weighted)	m3 depriv.	Freshwater consumption weighted by regional water scarcity
Resource use – fossils	MJ	Depletion of fossil energy carriers (coal, oil, natural gas)

Impact Category	Unit Indicator	Environmental Mechanism
Resource use – minerals/metals	kg Sb-equivalent	Depletion of non-renewable mineral resources
Particulate matter	disease inc.	$PM_{2.5}$ and precursor emissions increase disease incidence.
Ionising radiation	kBq U-235-equivalent	Radioactive releases (e.g., radon-222, carbon-14) increasing human exposure to ionising radiation

Normalisation and Weighting

Normalisation expresses impact category results relative to a reference value, such as the total impact of a reference region (e.g., Europe or the world) over a reference period (e.g., one year). Normalisation allows practitioners to compare the magnitude of contributions across different categories and to assess whether a product system's impacts are large or small relative to broader patterns. However, normalisation also introduces the reference system as an additional layer of methodological choice.

Weighting assigns relative importance to different impact categories through explicit or implicit value judgements. Weighted results can be aggregated into a single score, which simplifies communication and comparison. Nevertheless, ISO 14044 explicitly prohibits the use of weighting for comparative assertions that are publicly disclosed, because weighting inherently reflects value choices that cannot be resolved by science alone. Weighted results must therefore be interpreted with caution and presented alongside the unweighted impact profile.

The distinction between mandatory and optional LCIA steps reflects a broader tension in LCA between completeness of analysis and transparency of assumptions. Every step toward aggregation increases simplicity but reduces transparency regarding the basis for results[17].

Interpretation

The interpretation phase identifies findings from the inventory and impact assessment, evaluates the completeness, sensitivity, and consistency of the study, and formulates conclusions and recommendations in relation to the goal. Interpretation runs iteratively throughout the LCA and may prompt revisions to earlier phases. Key activities in the interpretation phase include identification of significant issues, completeness check, sensitivity analysis, consistency check, and uncertainty analysis.

Identification of significant issues: Determining which inventory flows, processes, life cycle stages, and impact categories make the greatest contributions to results. Hotspot analysis identifies the stages or processes responsible for the largest burdens.

Completeness check: Assessing whether sufficient data are available to support conclusions. Missing data, incomplete processes, or incompletely covered upstream stages may limit the reliability of results. If important gaps are identified, additional data collection or changes to scope may be needed.

Sensitivity analysis: Examining how results change when key assumptions or model parameters are varied. For example, a sensitivity analysis might vary the assumed electricity mix, the allocation method, the lifetime of the product, or the choice of LCIA methodology. Where results are significantly sensitive to plausible alternatives, conclusions must be framed accordingly. A ranking of alternatives that is reversed by a single parameter change should not be presented as definitive.

Consistency check: Verifying that the assumptions, system boundaries, and data quality applied throughout the study are consistent with the goal and scope. For comparative studies, consistency is especially important: all alternatives should be modelled with the same assumptions to ensure that differences in results reflect genuine differences in environmental performance.

Uncertainty analysis: Assessing the combined effect of data variability, model uncertainty, and scenario uncertainty on the reliability of conclusions. The Monte Carlo simulation is a common approach for propagating parameter uncertainty through the model. For studies involving prospective assessment of emerging technologies, uncertainty can be particularly high; results should thus be presented with the explicit acknowledgement of their dependency on assumptions about future conditions.

KEY METHODOLOGICAL CHALLENGES

Several methodological challenges recur across LCA practice and require particular attention in research and innovation contexts.

Attributional and consequential modelling

A fundamental distinction in LCA concerns the choice between attributional and consequential modelling approaches[18]. *Attributional LCA (ALCA)* describes the environmental flows attributable to a product system under specified conditions, which may represent the past, present or future. This approach answers the question: what are the environmental burdens attributable to this product system

under current conditions? *Consequential LCA (CLCA)*, by contrast, models the environmental consequences of a decision by identifying what would change in the broader system as a result of a specified choice. The latter answers the question: what would happen to total system emissions if production of this product were increased or decreased[19,20]?

The two approaches can yield substantially different results. In ALCA, electricity supply is typically represented by the average grid mix; in CLCA, the marginal technology that would be added or displaced by a change in demand is used instead. In ALCA, co-product allocation is handled within the defined system; in CLCA, system expansion is the preferred approach because it captures the expected marginal consequences of the co-product for other systems. The choice between ALCA and CLCA should be driven by the goal of the study: ALCA is more appropriate for accountability and reporting, whereas CLCA is more appropriate for decision support in contexts where change is being modelled.

LCA for emerging and prospective technologies

Applying LCA to technologies that do not yet exist at commercial scale introduces specific challenges[21]. Prospective LCA (see also chapter 7 discussing partly overlapping ex ante or anticipatory LCA) aims to assess the environmental performance of a technology as it is expected to operate in the future, accounting for technological learning, scale-up effects, infrastructure changes, and evolving background systems. This approach is particularly relevant in research and innovation settings, where LCA is used not only to assess current performance but also to guide early-stage design decisions.

One of the main challenges in prospective LCA is data scarcity[22]. At laboratory scale, the full supply chain of a novel material may not yet be established; energy requirements may differ substantially from pilot to full industrial scale; and efficiency may improve with process optimisation. Practitioners must therefore rely on scenarios, analogies with comparable existing technologies, and explicit sensitivity analysis to account for uncertainty. Using present-day inventory data to represent a future industrial technology can significantly overestimate impacts in some categories while underestimating them in others[23,25,26].

Despite these challenges, applying LCA early in the innovation process is valuable because it can identify potential problem areas before design choices become locked in. A hotspot in an early-stage assessment may flag a material or process step that warrants substitution or redesign; conversely, the same finding after industrialisation may be difficult or costly to address.

Data confidentiality

Data confidentiality presents an additional challenge. Companies are often reluctant to share inventory data about their processes (e.g., energy or chemical requirements) to maintain competitive advantage. This creates a transparency problem: organizations may publish LCA results publicly while withholding the underlying data needed to reproduce or verify them.

Allocation in circular systems

Circular economy strategies such as recycling, reuse, remanufacturing, and waste-based feedstocks present specific allocation challenges in LCA[24]. When a material is recycled, the burdens of its original production and the benefits of avoided primary material production must be attributed appropriately. When a product is reused or remanufactured, the residual value of previous production cycles must be accounted for. These situations often do not fit easily into traditional cradle-to-grave system boundaries.

Several approaches have been developed for handling end-of-life allocation, including the cut-off approach, which allocates primary production burdens to first-life use and assigns no upstream burden to recycled material; the closed-loop approximation, under which recycling substitutes for equivalent primary production; and the end-of-life recycling credit approach, which assigns credits for avoided primary production to the system generating recyclable material. Each approach reflects different assumptions about responsibility and market dynamics, and each can yield different results for the same physical system[27].

LCA DATABASES AND SOFTWARE

LCA practice depends on access to life cycle inventory databases, which provide background system data for materials, energy, transport, and industrial processes. These databases contain thousands of unit process datasets that represent the environmental flows associated with specific production activities, enabling practitioners to model upstream supply chains without collecting primary data for every step.

Ecoinvent is the most widely used global LCI database, covering energy, chemicals, metals, agriculture, transport, and waste treatment[28]. It is updated annually and available in both attributional and consequential system model versions. The European Commission's Joint Research Centre provides EF-compliant datasets through the European Platform on Life Cycle Assessment (EPLCA), which has superseded the discontinued European Life Cycle Database (ELCD). The GaBi

database, now maintained by Sphera under the name "Sphera LCA for Experts", provides sector-specific datasets and is particularly used in industrial and automotive applications. The US Life Cycle Inventory (USLCI) Database provides North American process data. Launched in June 2020, the Global LCA Data Access (GLAD) network connects multiple databases and facilitates broader data access across regions and sectors. LCA software platforms support data collection, system modelling, calculation, and reporting. Table 3.2 summarises commonly used software tools[29].

Table 3.2 Selected LCA software tools

Software	Primary Use Case
SimaPro	Research and consulting (premium platform)
openLCA	Open-source platform with growing global user base
Sphera LCA for Experts	Industry and automotive sectors (formerly GaBi)
Brightway2	Python-based framework for advanced or customised modelling

The choice of software affects the modelling environment, database access, transparency of calculation, and the ease of uncertainty and sensitivity analysis.

For research applications involving emerging technologies with limited primary data, hybrid LCA approaches that combine process-based LCA with environmentally extended input-output (EEIO) analysis are increasingly used to extend the system boundary and reduce truncation errors[30]. Prospective LCA tools such as premise allow practitioners to adjust background system datasets to reflect future scenarios, making them relevant for assessing technologies that will be deployed in a future system context[31].

A RESEARCH FRONTIER

One research frontier in environmental LCA for solid-state batteries (SSBs) lies in developing methods for evaluating environmental performance under conditions of high technological uncertainty and limited data availability. Emerging SSB technologies introduce novel materials, including lithium metal anodes and solid-state electrolytes (ceramic, polymer or composite), together with unconventional manufacturing processes for which representative industrial-scale inventory data are scarce or unavailable. As a result, conventional LCA approaches which rely on mature technologies and well-established datasets face significant challenges when applied to batteries at low technology readiness levels (TRLs).

The SOLiD[*3] project addresses these challenges by integrating environmental LCA into the development of next-generation SSB, a technology which is recognised as a promising candidate for future energy storage due to its potential to deliver higher energy density, improved safety, and longer cycle life than conventional lithium-ion batteries. Nevertheless, the environmental performance of solid-state cells remains poorly characterised due to the absence of comprehensive life cycle inventory data for many of the emerging materials and manufacturing processes involved.

A preliminary cradle-to-gate screening LCA conducted within SOLiD at TRLs 3 to 4 identified several key environmental hotspots. The largest contributions to environmental impacts were associated with NMC811 cathode synthesis, lithium metal deposition, atomic layer deposition (ALD) coating processes, and the production of Lithium bis(trifluoromethanesulfonyl)imide (LiTFSI) salt and single-walled carbon nanotubes (SWCNTs). An environmental screening matrix assessed process steps and materials across following indicators: global warming potential, toxicity, resource depletion, and coupled with energy intensity. The highest combined environmental risks were associated with energy-intensive deposition and coating processes, as well as critical raw materials such as lithium, cobalt, nickel, and lanthanum.

Advancing this research frontier requires methodological developments in several interconnected areas. First, primary life cycle inventory data for novel materials and manufacturing processes must be generated where generic datasets are unavailable. Second, inventory modelling approaches must be adapted to account for early-stage technologies through the use of hybrid datasets and engineering assumptions. Third, uncertainty and sensitivity analyses must play a central role in interpreting results, ensuring that conclusions remain robust despite data gaps and rapidly evolving process designs. Finally, environmental assessments should be considered alongside key technical performance indicators, such as energy density, cycle life, and safety, to enable functionally consistent comparisons and reduce the risk of burden shifting between performance and sustainability objectives.

Within the SOLiD project, LCA offers a framework for identifying environmental hotspots, evaluating the relative contributions of novel materials and process steps, and assessing the influence of key assumptions and uncertainties. The results highlight the environmental challenges associated with solid-state battery development and provide guidance as the technology advances to higher readiness levels.

*3 Horizon Europe, Grant No. 101069505

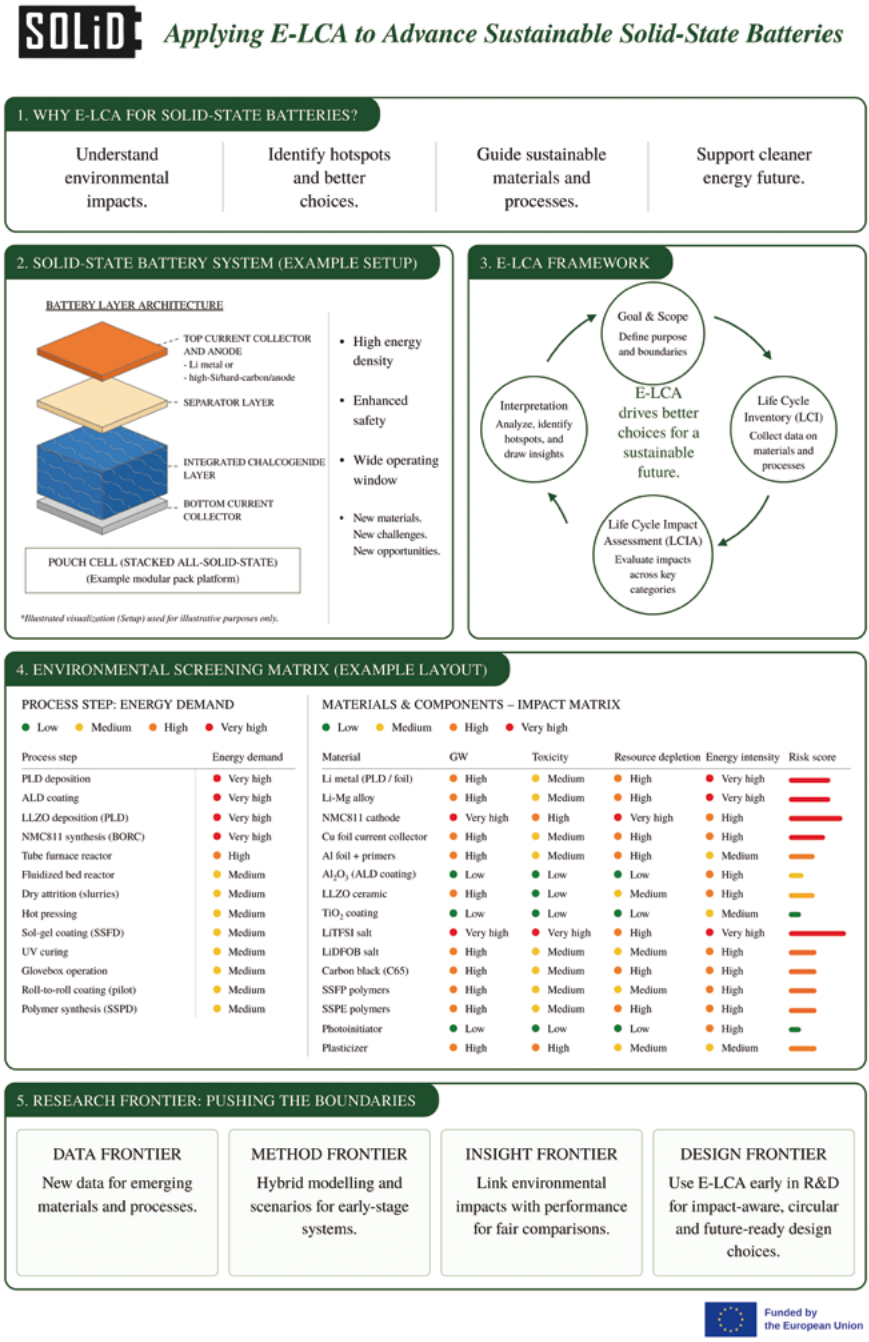

Figure 3.4 Research Frontier Box: Environmental LCA of SOLiD Horizon Europe project.

ENVIRONMENTAL LCA IN RESEARCH AND INNOVATION

This chapter has outlined the methodological structure of environmental LCA and the choices that shape its results. The four ISO phases provide framework for tracing environmental burdens from extraction to end-of-life, while the concepts of functional unit, system boundary, allocation, and impact characterisation define the conditions under which comparisons are performed.

In research and innovation settings, LCA extends beyond compliance or reporting. When applied early in the development process, it can identify:

- Which aspects of a novel technology or material carry the greatest potential environmental burden
- Which design parameters offer the greatest scope for improvement
- Where trade-offs among impact categories may complicate straightforward sustainability claims.

An improvement in climate performance achieved at the cost of substantially increased toxicity or water use is not a simple environmental gain; LCA makes these trade-offs visible and manageable before decisions become locked in.

Nevertheless, applying LCA in early innovation contexts requires acknowledgement of its limitations.

Data limitations: Data for novel materials may be sparse or tentatively estimated.

Prospective uncertainty: Scenarios involve uncertainty about future conditions.

Background system mismatches: Background system data may not reflect future electricity grid mixes or supply chains.

Results should therefore be communicated as decision support, with sensitivity and uncertainty analyses as essential components of credible assessment.

The chapters that follow extend this analytical foundation to the social and economic dimensions of the product system. These chapters address Life Cycle Costing, Social LCA, and the integration of these frameworks into Life Cycle Sustainability Assessment.

RECOMMENDED READINGS

Topic	Recommended reading
Methodological principles and requirements	ISO 14040:2006. *Environmental management—Life cycle assessment—Principles and framework*[1]; ISO 14044:2006. *Environmental management—Life cycle assessment—Requirements and guidelines*[5].
Allocation, recycling and multifunctionality	Heijungs and Guinée (2007). *Allocation and 'what-if' scenarios in life cycle assessment of waste management systems*[11]; Ekvall and Tillman (1997). *Open-loop recycling: Criteria for allocation procedures*[19]; Schrijvers, Loubet and Sonnemann (2016). *Developing a systematic framework for consistent allocation in LCA*[27].
Inventory modelling and data quality	Weidema et al. (2013). *Overview and methodology: Data quality guideline for the ecoinvent database version 3*[10]; Wernet et al. (2016). *The ecoinvent database version 3 (part I): Overview and methodology*[28].
Midpoint and endpoint impact assessment	Huijbregts et al. (2017). *ReCiPe2016: A harmonised life cycle impact assessment method at midpoint and endpoint level*[15].
Weighting environmental impacts	Sala, Cerutti and Pant (2018). *Development of a weighting approach for the Environmental Footprint*[17].
Consequential modelling	Earles and Halog (2011). *Consequential life cycle assessment: A review*[20].
Prospective assessment of emerging technologies	Arvidsson et al. (2018). *Environmental assessment of emerging technologies: Recommendations for prospective LCA*[25]; Cucurachi, van der Giesen and Guinée (2018). *Ex-ante LCA of emerging technologies*[26].
Truncation and aggregation in inventory data	Majeau-Bettez, Strømman and Hertwich (2011). *Evaluation of process- and input-output-based life cycle inventory data with regard to truncation and aggregation issues*[30].

REFLECTION & EXERCISES

Exercise 1. The LCA framework

Environmental LCA consists of four interconnected phases defined by ISO 14040 and ISO 14044. Explain why these phases should not be viewed as a simple linear sequence. How can decisions made during interpretation lead to revisions of earlier phases?

Answer:

The four phases of LCA are iterative rather than strictly sequential. During interpretation, data gaps, inconsistencies, or methodological issues may be identified, requiring revisions to the goal and scope, inventory data, or impact assessment. This iterative process improves the robustness, transparency, and reliability of the final results.

Exercise 2. Multiple choice questions

Q1. A study compares two types of insulation material for a building retrofit. The study reports results up to the factory gate. Which system boundary does this represent?

a) Cradle-to-grave

b) Cradle-to-cradle

c) Cradle-to-gate

d) Gate-to-gate

Q2. A co-production process yields both ethylene and propylene. The practitioner cannot subdivide the process or apply system expansion. Which approach should be used according to ISO 14044?

A. Ignore the co-product entirely

B. Underlying physical relationships or, where these cannot be applied, other relationships such as economic value.

C. Apply endpoint weighting across categories

D. Use cut-off criteria to exclude the co-product

Answer Q1: C

Why: The study excludes the use phase and end-of-life, meaning it ends at the point of manufacture—the factory gate.

Answer Q2: B

Why: ISO 14044 gives priority to avoiding allocation through subdivision or system expansion. If allocation is necessary, it should first reflect underlying physical relationships. Other relationships, such as economic value, may be used where suitable physical relationships cannot be established or applied. Mass-based allocation is appropriate only where mass reflects the relevant physical relationship.

Exercise 3. Functional unit and multifunctionality

A research team is developing a new bio-based polymer to replace a conventional petroleum-based plastic in single-use food packaging. The bio-based polymer is produced from agricultural residues, requires less fossil energy during synthesis, and is certified compostable.

Q1. Define an appropriate functional unit and identify the most suitable system boundary. Justify both choices.

Q2. The agricultural residue feedstock is also sold as animal feed. How should this multifunctionality be handled, and how might the choice affect the results?

Answer Q1:

A suitable functional unit is the packaging needed to contain and preserve 1,000 single-serving food portions for their required shelf life. Using 1 kg of material would be less appropriate, as the two options may differ in thickness, performance, and material intensity per package. The most suitable system boundary is cradle-to-grave, since the main difference between the materials is likely to appear at end-of-life, where composting and conventional disposal can lead to very different outcomes

Answer Q2:

If polymer production diverts residues from animal feed, consequential modelling should include any replacement feed burdens. Where allocation cannot be avoided through subdivision or system expansion, use underlying physical relationships where possible, otherwise economic or other relationships. Test how these choices affect the results through sensitivity analysis.

Exercise 4. Regional electricity and recycling assumptions

A published study claims that electric vehicles have a significantly lower carbon footprint than conventional internal combustion engine vehicles over a 200,000 km service life. The study uses a European average electricity mix for the EV use phase, and it applies the cut-off approach to battery recycling at end of life.

Q1. How would using a national electricity mix instead of the European average affect the results?

Q2. What is the significance of applying the cut-off approach to battery recycling, and how would a closed-loop approximation change the result?

Answer Q1:

The electricity mix can strongly change EV results because the use phase often dominates the footprint. A low-carbon grid would improve the EV's climate performance, while a coal-heavy grid could reduce the advantage or even remove it entirely. Using a European average may obscure this regional variation and make the result less relevant for a specific country or market.

Answer Q2:

The cut-off approach assigns the full primary production burden to the first life of the battery and provides no credit for future material recovery. A closed-loop approximation would instead credit the system for avoided primary production from recovered materials such as lithium, cobalt, nickel, and manganese. Since battery production is material-intensive, this methodological choice could substantially affect the final result.

Exercise 5. Climate change calculation

A manufacturer produces a glass fibre reinforced polymer (GFRP) panel. Production of 1 kg requires the inputs below. At end-of-life, incineration releases 1.15 kg CO_2-eq and recovers 0.80 kWh of electricity, displacing grid electricity at 0.43 kg CO_2-eq/kWh.

Input	*Quantity*	*Emission factor*
Glass fibre	*0.60 kg*	*1.35 kg CO_2-eq/kg*
Epoxy resin	*0.35 kg*	*6.80 kg CO_2-eq/kg*
Electricity	*2.10 kWh*	*0.43 kg CO_2-eq/kWh*
Transport	*1 kg · 200 km*	*0.00011 kg CO_2-eq/kg·km*

Calculate the total cradle-to-grave climate change impact per kg of GFRP, including the end-of-life electricity credit (plus 0.05 kg of additives/losses not shown).

Answer:

Input	Calculation	Result
Glass fibre	0.60 × 1.35	0.81 kg CO_2-eq
Epoxy resin	0.35 × 6.80	2.38 kg CO_2-eq
Electricity	2.10 × 0.43	0.90 kg CO_2-eq
Transport	1 × 200 × 0.00011	0.022 kg CO_2-eq
Production total		4.11 kg CO_2-eq

End-of-life:

- Incineration = 1.150 kg CO_2-eq
- Electricity credit = 0.80 × 0.43 = -0.344 kg CO_2-eq

Net end-of-life impact = 0.806 kg CO_2-eq

Total cradle-to-grave impact = 4.92 kg CO_2-eq per kg of GFRP.

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LIFE CYCLE COSTING

Life Cycle Costing (LCC) operationalises the economic dimension of Life Cycle Thinking. Its relevance is evident across technologies and infrastructure, from buildings to energy storage systems. It extends economic assessment to costs associated with a product, technology, service, or infrastructure system across its life cycle.

LCC results can indicate whether an apparently low-cost alternative transfers costs to later stages, other actors, or future budgets. This method can also reveal whether a more expensive technology may be economically preferable because of longer service life, lower operating costs, reduced maintenance, higher efficiency, or lower replacement needs.

LCC is therefore understood as both a calculation method and a decision-support framework. Applying LCC supports comparison of alternatives on a consistent functional basis, and may help avoid making choices that are economically attractive in the short term but burdensome over the full life cycle.

This chapter provides a general introduction to LCC, with particular emphasis on environmental LCC as the form most compatible with Life Cycle Assessment (LCA) and Life Cycle Sustainability Assessment (LCSA).

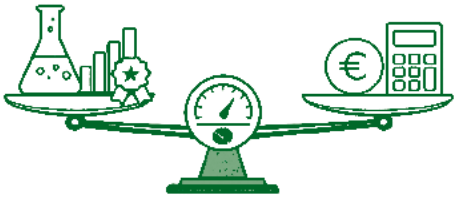
What if the technically best solution is too expensive to survive outside the laboratory?

A new process works well in the laboratory. It improves performance, reduces waste, and looks scientifically convincing. The research team imagines future industrial use.

Then an industry partner looks at the process and asks practical questions: How much do the precursors cost? How much energy does it need? What equipment would be required? How many steps are involved? What happens if the yield drops during scale-up?

The scientific result is still valuable, but another feasibility check needs to be performed. Economic feasibility concerns whether a technology can achieve its intended function at an acceptable cost over its life cycle, considering investment, operation, maintenance, replacement, and end-of-life costs.

Applying LCC can make these cost drivers visible and allows researchers to compare alternatives and identify where future optimisation may be needed.



LCC CONCEPTS AND TERMS

LCC is an economic assessment approach used to estimate the costs associated with a product, technology, service, infrastructure asset, or system over a defined part or the whole of its life cycle[1]. LCC is therefore especially relevant where costs influence the real economic outcome of a decision[1].

Several related terms are used in practice. *Total Cost of Ownership (TCO)* refers to the costs borne by a specific owner or user. TCO overlaps with user-oriented LCC, but is typically confined to a strict user perspective and excludes environmental assessment or external costs[2]. Common in buildings and infrastructure, *Whole-Life Costing (WLC)* often includes costs across planning, construction, operation, maintenance, replacement, and end-of-life. *Through-Life Costing (TLC)* is often used in engineering, fields in which the emphasis is often on cost and performance over the service life.

Although terms such as LCC, TLC, WLC, and TCO are frequently used interchangeably, their precise meanings depend on the application field, analytical perspective, and economic standpoint[3]. In this chapter, LCC serves as the umbrella term, with TCO, WLC, and TLC regarded as related but more context-specific variants.

LCC conceptual framework

The conceptual framework of LCC shows how costs and externalities occur across the product life cycle, from material and component suppliers to product manufacturers, users, and end-of-life actors. Along this chain, LCC distinguishes between internal and external costs. *Internal costs* are those paid directly by actors within the economic system, such as producers, suppliers, users, waste managers, or public authorities. *External costs* refer to monetised environmental or social effects caused by the product system but not directly paid by the actors involved. These externalities lie outside the immediate economic system but within the broader natural and social system.

Not all consequences of a product system are reflected in market prices: some are paid directly by actors in the value chain, while others remain external to the economic transaction and may need consideration through environmental LCC, societal LCC, or broader sustainability assessment. This distinction determines whether LCC is used as a business-oriented cost management tool, an environmental LCC approach aligned with LCA, or societal cost determination method[4].

Standards and guidance for LCC

Unlike environmental LCA, LCC lacks a single universally applied methodological standard. Instead, different standards and guidance documents apply to different sectors and purposes.

For environmental LCC, the work of SETAC (Society of Environmental Toxicology and Chemistry) provides the foundational framework[2]. SETAC's interdisciplinary guidance aligns LCC with the life-cycle logic of ISO. The functional unit quantifies the service or function provided, ensuring that costs are compared on a consistent basis (see discussion below). If environmental impacts are monetised, ISO 14008[7] may also become relevant, although this moves the analysis closer to external-cost valuation and requires attention to avoid double counting.

Important references also include IEC 60300-3-3:2017[8], which presents LCC as a general approach for assessing life-cycle costs across different applications, with particular attention to costs associated with dependability; ISO 15663:2021[9] is used in the petroleum, petrochemical, and natural gas industries, with ISO 15686-5:2017[10] used for buildings and other constructed assets.

In line with IEC 60300-3-3:2017, a *life-cycle cost breakdown* structure provides a three-dimensional way to organise all relevant cost elements across the life cycle of a product, technology, asset, or system (Figure 4.1). Typical cost categories in LCC can be grouped into several expenditure classes.

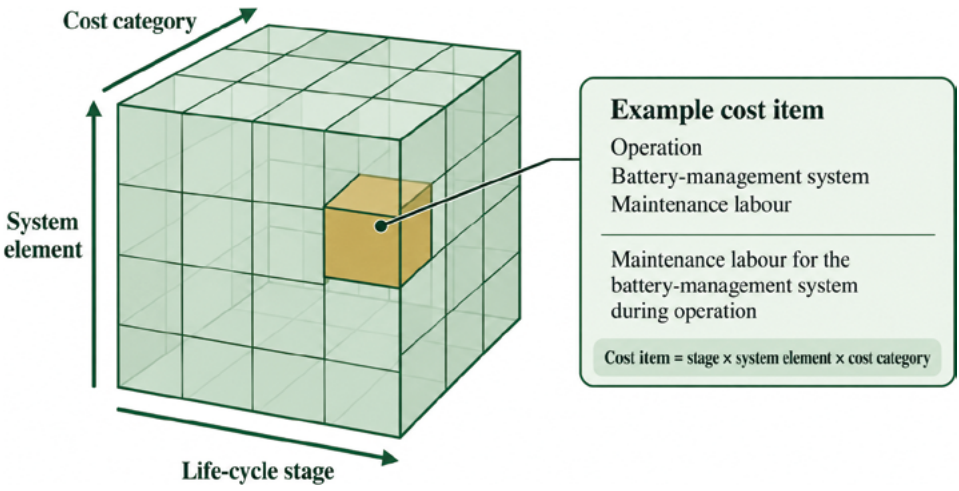


Figure 4.1 Life-cycle cost breakdown[8]

Typical *cost categories* include capital expenditure (CAPEX), operating expenditure (OPEX), maintenance and repair costs, replacement costs, downtime-related costs, and end-of-life expenditure. In some energy, infrastructure, and asset-management sectors, REPEX refers to replacement expenditure, DTEX to costs associated with downtime, and DECEX to decommissioning expenditure.

Purposes and timing of LCC

LCC can be applied for several purposes, including planning, budgeting, public procurement, technology comparison, product development, investment appraisal, hotspot identification, and LCSA. In research and practice, LCC can reveal the long-term cost implications of design and investment choices before they become locked in.

The timing of an LCC study depends on its purpose. *Ex ante LCC* is prospective and is conducted before implementation, relying on assumptions, forecasts, supplier data, engineering estimates, market prices, and scenario modelling; this approach can be applied in early-stage design, procurement, technology selection, or policy planning[12]. *Ex post LCC* is retrospective, using observed data after a product, project, or asset has been implemented; this type of study is useful for performance evaluation, learning, benchmarking, and improving future decisions[11].

Financial concepts and metrics

LCC requires explicit *financial assumptions*, as costs are distributed across different life-cycle stages and time periods. LCC studies must also distinguish between *real* and *nominal* values: real costs exclude general inflation, while nominal costs include expected inflation.

The central concept is the *time value of money* based on financial theory: money available today is worth more than the same nominal amount in the future because it can be invested. Consequently, a cost paid today and a cost paid in the future are not economically equivalent.

The *discount rate* is used to convert future cash flows into present values. This parameter reflects the opportunity cost of capital and, depending on the calculation context, may also embody inflation assumptions, risk, or public-sector guidance[13]. In LCC, the chosen discount rate shapes the outcome: higher rates reduce the weight of future operating savings, replacement costs, and residual value, while lower rates give more importance to long-term consequences. Real costs should be discounted using a real discount rate, while nominal costs should be discounted using a nominal rate that includes expected inflation. The selected rate should also reflect whether the assessment adopts a private, public-sector, or societal perspective.

In corporate finance, *net present value (NPV)* is a metric that compares the present value of future cash flows with the initial cost of the investment. Corporate finance therefore provides a bridge between financial theory and practical managerial decision-making, with NPV as one of its core concepts[14]. For NPV, the standard formula is:

$$NPV = \sum_{t=0}^{n} \frac{CF_t}{(1+r)^t}$$

where:
CF_t = cash flow in year t
r = discount rate
t = time period
n = total number of period

Net present cost (NPC) is calculated using the same discounting logic as NPV but focuses specifically on costs. It represents the present value of all relevant life-cycle costs minus any residual value or other positive cash flows. The application of NPC is appropriate when alternatives provide the same functional service and the analyst wants to identify the least-cost option over a defined time horizon[15].

$$NPC = \sum_{t=0}^{n} \frac{C_t}{(1+r)^t}$$

where:
C_t = cost in year t
r = discount rate
n = time horizon

The *annualised cost* is the present value of life-cycle cash flows converted into an equivalent constant annual amount. In engineering economy, this is expressed as equivalent annual cost, equivalent annual worth, or equivalent uniform annual cost[16]. This metric can support comparisons of alternatives with unequal service lives or replacement intervals, provided they deliver a comparable service and can be repeated or evaluated over a common study period. These assumptions should be stated explicitly to avoid misleading comparisons.

$$AC = NPC \times \frac{r(1+r)^n}{(1+r)^n - 1}$$

The *payback period* is defined as the time required for cumulative savings or benefits to recover the initial investment. Because this metric is simple and intuitive, it is frequently used in practice as a screening indicator. However, both finance and engineering-economy literature treat payback period as limited if used on its own, since doing so would fail to account for costs and benefits occurring after the payback point of time. In other words, in its basic form, payback period does not account properly for the time value of money, thus it is best used as a supplementary metric[13].

The *internal rate of return (IRR)* is the discount rate at which the net present value of an investment equals zero. It can support investment appraisal but may produce misleading results for non-conventional cash flows or mutually exclusive alternatives.

For LCC, cost metrics should match the study goal. Net present cost is suitable when alternatives provide comparable performance within a defined study period, whereas annualised or equivalent annual cost is more useful when lifetimes or replacement cycles differ. The payback period is easy to communicate, but weak if used alone; the internal rate of return can facilitate investment appraisal, but may be misleading with changing cash-flow signs or mutually exclusive options.

Finance literature therefore generally treats NPV as the more robust decision criterion, while engineering economy also uses annual-worth and equivalent-cost methods[15]. In management accounting, LCC is linked to target costing and activity based costing, since many costs are committed during

design even though they are actually incurred later in life cycle.[17].

LCC must be distinguished from *Social Cost-Benefit Analysis (SCBA)*. The question addressed by LCC is: what are the life cycle costs of this product, technology, or asset from a defined perspective? In contrast, a broader welfare question is posed by SCBA: do the total social benefits of an intervention exceed its total social costs? This means environmental and social effects may be monetised under SCBA in cases where LCC would treat them separately or include them only under specific external-cost assumptions[18].

Externalities and monetary valuation

Externalities refer to costs or benefits caused by a product system but not fully reflected in market prices. These may include environmental damages from greenhouse gas emissions, air pollution, water use, land degradation, biodiversity loss, or health impacts.

Monetary valuation is used to express such effects in economic terms, thereby rendering hidden environmental costs. Recent LCA literature shows that monetisation can support communication, comparison, and policy relevance,

but remains methodologically sensitive; guidance for the monetary valuation of environmental impacts and related environmental aspects is provided by ISO 14008:2019[7].

When LCC is integrated into LCSA, monetisation requires avoiding double counting. Reporting an environmental impact in physical units through environmental LCA and its monetary value through LCC does not constitute *double counting* if the results are presented separately and their relationship is transparent. Double counting arises when the same effect is included more than once within an aggregated indicator. The general focus of environmental LCC is therefore on internal costs and external costs expected to become relevant to decision-makers through mechanisms such as taxation. A more comprehensive monetisation of externalities moves the analysis towards societal LCC or cost-benefit analysis[19].

Environmental LCA, LCC, and SCBA therefore have different but complementary roles[20]. Environmental LCA is used to assess environmental impacts in physical or impact-category units, LCC to assess life-cycle costs from a defined economic perspective[21]. SCBA is applied to compare social costs and benefits, often through monetary aggregation.

LCC TYPOLOGY

Three main approaches to LCC can be distinguished according to their scope, perspective, and treatment of external costs: *conventional LCC (cLCC)*, *environmental LCC (eLCC),* and *societal LCC (sLCC)* (Figure 4.2). Each form of LCC assessment addresses a different economic question.

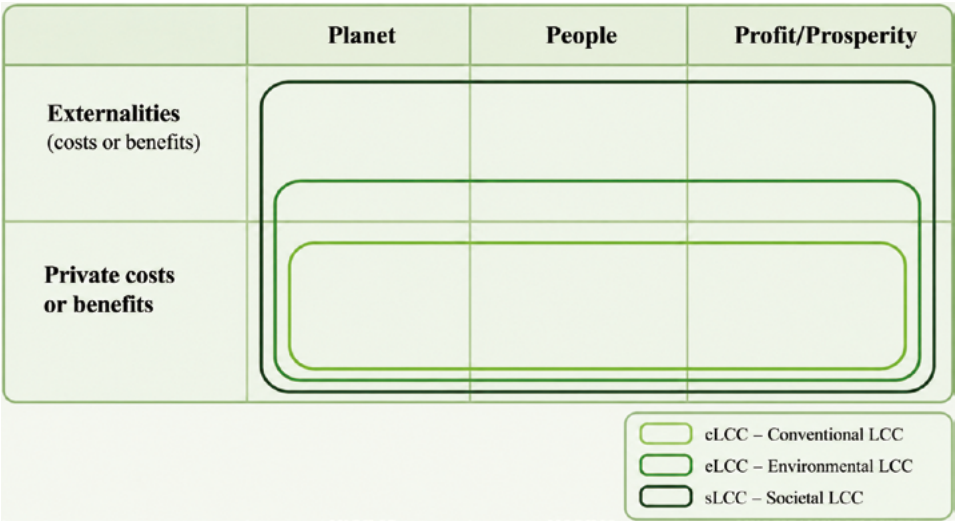


Figure 4.2 Life cycle cost typology. Adapted from UNEP/SETAC Life Cycle Initiative (2011)[22]

The most established and business-oriented form is *Conventional LCC*, which is used to assess costs borne by one main actor, such as a producer, investor, public procurer, owner, or user. The scope of cLCC usually includes direct financial costs such as acquisition, installation, operation, maintenance, repair, replacement, downtime, and end-of-life costs when these expenses are relevant to the chosen actor. cLCC is therefore closely related to TCO or WLC approaches.

Environmental LCC is designed to achieve compatibility with environmental LCA by using a consistent functional unit, system boundaries, and life-cycle stages. In this approach, internal costs borne by relevant actors across the product system are appraised. eLCC may also include selected external costs expected to become internalised through regulation, taxation, carbon pricing, liability, or producer-responsibility schemes[2,23,24].

The use of *Societal LCC* expands the assessment further by attempting to incorporate the wider costs (and benefits) borne by society. This may involve monetising environmental damages, health effects, resource depletion, social impacts, or other externalities not reflected in market prices. However, societal LCC is methodologically complex and less standardised. This approach also creates a higher risk of double counting when combined with LCA or S-LCA indicators[25].

For LCSA, eLCC is usually the most relevant assessment methodology because it can be aligned with the same assumptions used in environmental LCA.

ENVIRONMENTAL LCC

eLCC follows a structured process similar to environmental LCA. After defining the goal and scope, a life cycle cost inventory is developed, cost items are aggregated into indicators, and the results are interpreted (Figure 4.3). This process is iterative, thus assumptions, data quality, system boundaries, and/or cost drivers may need to be revisited as the assessment develops.



Figure 4.3 Phases of environmental LCC

Goal and scope definition in LCC

An eLCC study begins with the *definition of goal and scope*. This process defines the purpose of the study, the decision context, the intended audience, and the way results should be interpreted. The goal and scope definition specifies the stakeholder perspective, functional unit, system boundaries, time horizon, geographical scope, currency, base year, discounting assumptions, data sources, and treatment of uncertainty[25]. This methodological logic follows the life cycle framework of ISO 14040/14044 and has been adapted for eLCC in the SETAC guidance and subsequent methodological literature[2,11,23].

The *stakeholder perspective* determines which costs are included and who bears them. The *cost bearer* is the actor responsible for the cost, whether incurred now or in the future. A manufacturer may focus on research and development, production, warranty, logistics, and producer responsibility obligations. A user or asset owner may focus on acquisition, installation, energy, maintenance, repair, replacement, downtime, and disposal. A public authority, in turn, may consider procurement rules, public budget constraints, and service continuity.

Identifying cost bearers also reveals *cost drivers*, meaning the parameters or life-cycle stages that most strongly influence total cost[2,3].

The *functional unit* provides the reference against which all costs are calculated. In eLCC, this reference should be consistent with the functional unit used in LCA, so that economic and environmental results refer to the same function. For example, comparing two battery systems only by purchase price would be insufficient;

a functional unit such as 'delivery of 1 kWh of electricity from storage under specified operating conditions over a defined service life' allows costs to be related to actual performance.

System boundaries define which life-cycle stages and processes are included: raw material supply, production, transport, installation, use, maintenance, replacement, and end-of-life management may be incorporated. In eLCC, these boundaries should be aligned as far as possible with LCA boundaries, though it must be acknowledged that some cost elements may not correspond directly to physical flows in the LCA environmental inventory.

Cut-off criteria should also be indicated. While small cost items may be excluded if they are unlikely to affect conclusions, such exclusions need to be justified and applied consistently. Unlike cut-offs in environmental LCA, which often relate to mass, energy, or environmental relevance, those for LCC should be based on cost significance and decision relevance.

A process of *allocation* is required when costs are shared between several products, services, actors, or life-cycle stages. Shared production costs, infrastructure costs, maintenance costs, or end-of-life costs must be assigned, using a rule consistent with the goal and scope of the study.

Life-cycle cost inventory analysis

The cost inventory phase translates the product system defined in the goal and scope into monetary data. This stage identifies which cost items occur in each life-cycle stage and assigns them to the functional unit. However, cost inventories differ from environmental inventories, as some relevant costs do not correspond directly to physical flows, with examples including labour, overheads, insurance, downtime, taxes, financing, maintenance contracts, warranty costs, and administrative costs.

Typical cost inventory items include materials, energy, equipment, installation, operation, maintenance, repair, replacement, transport, waste treatment, end-of-life management, residual value as well as possible revenues or avoided costs. *Primary data* may come from sources such as supplier quotations, accounting systems, maintenance records, energy bills, project budgets, or expert estimates, while *secondary data* can include market prices, statistical databases, literature values, public procurement data, and *generic cost* databases.

Each item should be documented with its source, year, currency, geographical context, allocation rule, and uncertainty range. Data availability and confidentiality are recurring challenges in LCC: cost data are often more sensitive than environmental inventory data because they may reveal margins or strategic information. Since confidentiality is a major issue in LCC, market prices are sometimes approximated when direct cost data are unavailable[2].

Aggregation of cost items

After the goal and scope have been defined, cost items need to be organised into a cost structure, usually arranged by life-cycle stages and cost categories. Once this cost structure is established, data are collected from primary sources, supplier information, accounting records, maintenance logs, databases, literature, expert estimates, and market prices. These data are then assigned to the relevant life-cycle stages and allocated to the functional unit.

If costs are incurred over several years, aggregation takes place using appropriate financial indicators. Discounting should only be applied consistently with the study goal, stakeholder perspective, and time horizon[3].

Interpretation

Interpretation in eLCC consists of examinations of the distribution of costs across life cycle stages, alongside the aggregated result. The main cost drivers are also identified, trade-offs between alternatives are explained, and conclusions are tested for stability under different assumptions. When LCC is applied within LCSA, however, automatic conversion of environmental and social dimensions into monetary terms can obscure value choices and create double counting with LCA or S-LCA indicators[2].

Sensitivity analysis is used to examine how results respond to variation in one or more assumptions, most commonly the discount rate, energy price, service life, utilisation rate, maintenance frequency, replacement interval, or residual value. Sensitivity analysis can reveal whether the ranking of alternatives is robust or if it is contingent only on a small number of uncertain parameters. For example, a technology with high acquisition cost but low operating cost may be viewed as preferable only under conditions of high energy prices or a long service life.

Uncertainty analysis reflects the fact that many input values are known only within a range, rather than with precision. Future prices, degradation rates, repair costs, scale-up costs, and end-of-life revenues sometimes may be estimated only within ranges. *Scenario analysis* can be used to represent alternative conditions, while Monte Carlo simulation is applied when parameters are described probabilistically[26]. Simplified parametric models are often suitable for early-stage technologies, in which detailed cost data are unavailable, whereas mature systems can accommodate more elaborate models incorporating reliability assumptions[24].

Uncertainty can be classified into three types: *parameter uncertainty*, concerning uncertain input values such as service life, price, efficiency, or maintenance cost; *scenario uncertainty*, in which future conditions such as market regulation, energy prices, or recycling markets differ; and *model uncertainty*, used when the structure of the cost model itself may simplify reality.

LCC has certain *limitations*: it cannot fully capture environmental, social, cultural, or ethical values. Many sustainability concerns resist adequate expression in monetary terms, including cultural heritage, intergenerational justice, and irreversible ecological damage. LCC therefore complements environmental, social, and ethical evaluation by capturing economic consequences across the life cycle. Monetary valuation should make value choices and avoid double-count impacts already represented by LCA or S-LCA indicators[19,27].

Tools and models for LCC

LCC can be implemented with different levels of methodological complexity, with the selection of tools dependent on the study goal, data availability, required transparency, uncertainty treatment, and reporting needs.

Spreadsheet models are widely used due to their adaptability and suitability for teaching, screening studies, procurement, and early-stage technology assessment. More advanced applications may draw upon public procurement calculators and sectoral LCC tools[28], TCO models, asset-management systems, or LCA/LCSA software add-ons. Sector-specific LCC tools are available to facilitate green public procurement[29,30], while construction-sector applications are used to connect design models with cost databases.

For energy storage use case, the levelised cost of storage (LCOS) is a LCC related indicator that expresses discounted lifetime costs per unit of discounted electricity delivered. LCOS draws on life cycle cost information but does not replace the broader LCC assessment.

Figure 4.4 provides an illustrative example of LCOS modelling for a hybrid energy storage system. In the formulation shown, charging electricity costs include all electricity supplied to the storage system. The result represents the cost of electricity delivered through storage, including its acquisition; an incremental assessment of the storage service would instead account for the electricity consumed through losses while treating the cost of the electricity subsequently delivered separately. The vanadium redox flow battery (VRFB) and supercapacitor serve complementary functions within the hybrid system: the VRFB provides energy delivery over longer periods, while the supercapacitor handles power peaks and rapid cycling. Their illustrative LCOS distributions expresses costs relative to energy throughput, however they do not fully describe the supercapacitor's service, which also depends on power capability, response time and cycling requirements. Monte Carlo simulation illustrates how uncertainty in cost and performance assumptions can influence LCOS distributions.

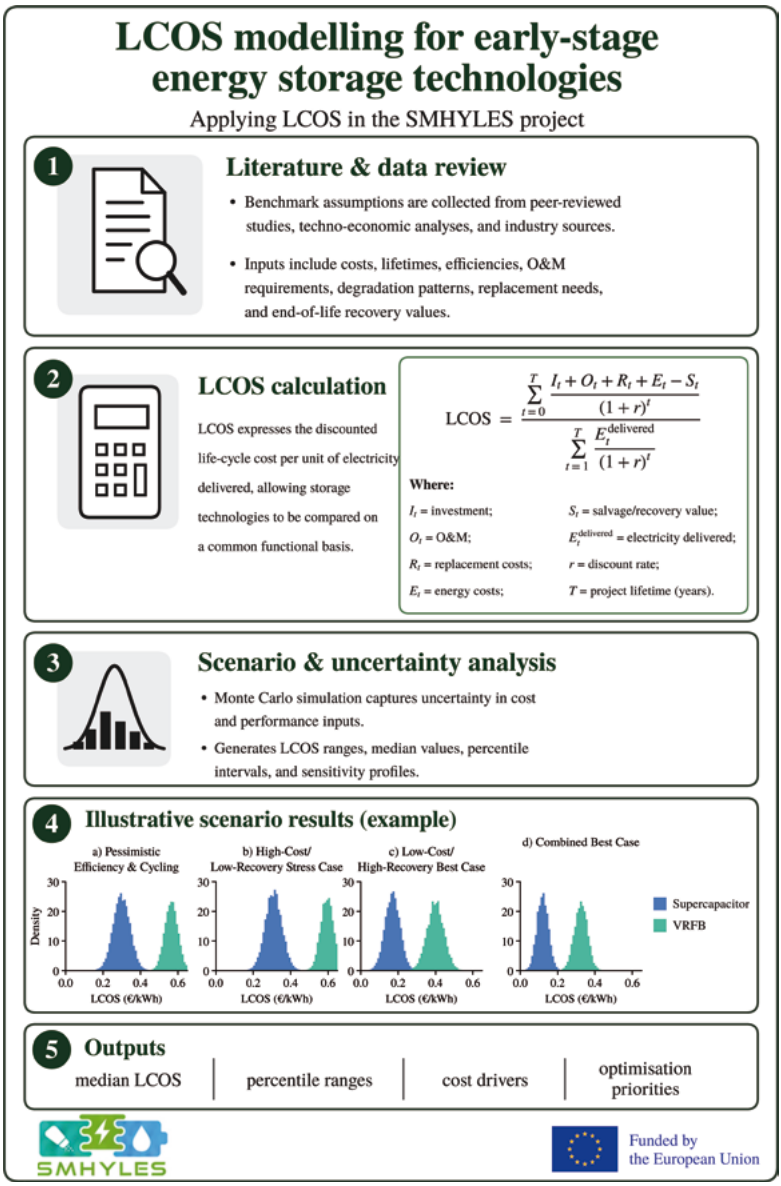


Figure 4.4 Research Frontier Box: Applied Levelized Cost of Energy Storage adapted from the SMHYLES Horizon Europe project (Grant No. 101138029)

LCC IN RESEARCH AND INNOVATION

Life Cycle Costing represents a distinct role in research and innovation by helping connect technical performance with economic feasibility. Many emerging technologies show promising results in the laboratory, but their future application depends on more than efficiency, material properties, or environmental performance. Costs related to raw materials, energy use, equipment, process complexity, and scale-up often determine whether a technology will move from experimental development to industrial deployment.

In early-stage research, LCC summarises cost assumptions, identifies the main cost drivers, compares design routes and tests how results change under uncertain parameters. For innovation projects, LCC is a forward-looking approach for guiding design choices and scale-up strategies.

When combined with LCA and S-LCA, LCC contributes to a more complete LCSA[31,32]. The next chapter introduces S-LCA, an approach used to examine how products and technologies may affect workers, communities, consumers, and other stakeholders across the life cycle.

RECOMMENDED READINGS

Topic	Recommended reading
Environmental life cycle costing	Hunkeler, Lichtenvort and Rebitzer (eds., 2008). *Environmental Life Cycle Costing*[2].
General procedures for life cycle costing	IEC 60300-3-3:2017. *Dependability management—Part 3-3: Application guide—Life cycle costing*[8].
Implementation of environmental LCC	Swarr et al. (2011). *Environmental life-cycle costing: A code of practice*[23]; Rodrigues and da Silva (2024). *Implementation of environmental life cycle costing: Procedures, challenges, and opportunities*[24].
Discounting and economic comparison	Blank and Tarquin (2018). *Engineering Economy*, 8th edition[15]; Fuller and Petersen (1996). *Life-Cycle Costing Manual for the Federal Energy Management Program*[16].
Cost accounting and allocation	Drury (2018). *Management and Cost Accounting*, 10th edition[17].
Alignment of LCC with LCSA	Bachmann et al. (2024). *Life cycle costing as part of a life cycle sustainability assessment of products: Methodology and case studies*[25]; Hoogmartens et al. (2014). *Bridging the gap between LCA, LCC and CBA as sustainability assessment tools*[20].
Monetary valuation of environmental impacts	ISO 14008:2019. *Monetary valuation of environmental impacts and related environmental aspects*[7]; Amadei, De Laurentiis and Sala (2021). *A review of monetary valuation in life cycle assessment: State of the art and future needs*[27].
Uncertainty in cost assessment	Barahmand and Eikeland (2022). *Techno-economic and life cycle cost analysis through the lens of uncertainty: A scoping review*[26].

REFLECTION & EXERCISES

Exercise 1. Conceptual foundations of LCC

Which statement best distinguishes conventional LCC from societal LCC?

A. Conventional LCC includes all externalities, while societal LCC excludes them.

B. Conventional LCC focuses on costs borne by the decision-maker, while societal LCC may also consider costs borne by society more broadly.

C. Conventional LCC is used only in public policy, while societal LCC is used only in business.

D. Conventional LCC always includes environmental impacts in physical units, while societal LCC does not.

E. Conventional LCC is a type of LCA, while societal LCC is unrelated to life cycle approaches.

Answer: B

Conventional LCC usually reflects the private or organizational cost perspective of the actor making the decision. Societal LCC broadens the perspective to include wider costs borne beyond the immediate decision-maker.

Exercise 2. Comparing two technologies

Two laboratory technologies are compared over 8 years using a simple undiscounted LCC.

Technology A: acquisition €20,000; annual operation €3,000; annual maintenance €1,000

Technology B: acquisition €28,000; annual operation €1,800; annual maintenance €700

Which option has the lower total undiscounted life-cycle cost?

A. Technology A, because it has the lower acquisition cost.

B. Technology A, because maintenance is less important than purchase price.

C. Technology B, because lower annual costs outweigh the higher purchase price.

D. Both technologies have the same total LCC.

E. In this scenario, life-cycle cost cannot be compared without discounting.

Answer: C

Technology A = €20,000 + 8 × (€3,000 + €1,000) = €52,000

Technology B = €28,000 + 8 × (€1,800 + €700) = €48,000

Exercise 3. Cost categorisation

Choose one product or technology, such as a battery system, laboratory device, washing machine, electric vehicle, or photovoltaic installation. Classify the following cost items into an LCC structure: acquisition and installation, operation and energy use, maintenance and repair, replacement of parts, downtime or loss of service, training or labour, decommissioning, waste treatment or disposal, residual or salvage value. Then explain which cost is usually easiest to estimate, which is most uncertain in early-stage assessments, and which is most likely to be underestimated if the analysis is done too narrowly.

Model answer: Using a laboratory device as an example, acquisition and installation form part of initial costs; operation and energy use, together with routine labour, fall under operating costs; maintenance and repair and replacement of parts constitute maintenance costs; downtime or loss of service represents an indirect or performance-related cost; decommissioning and waste treatment are classified under end-of-life costs; and residual or salvage value represents an end-of-life benefit. The easiest costs to estimate are usually acquisition, installation, and sometimes routine energy use, as these expenditures are often known at the time of purchase. The most uncertain costs in early-stage assessments are replacement needs, downtime, decommissioning, waste treatment, residual value, and future labour costs. If the analysis is too narrow, maintenance, downtime, replacement, labour, and end-of-life costs are the factors most likely to be underestimated.

Exercise 4. Decision-making beyond the lowest LCC

A public authority is using LCC to compare two infrastructure options. Option A has the lower total life-cycle cost, but higher environmental impacts during operation. Option B has higher life-cycle costs, but lower emissions, better repairability, and more favourable end-of-life recovery.
Discuss whether the decision-maker should automatically select Option A on the basis of lower LCC alone. What additional information from LCA, S-LCA, stakeholder consultation, or policy priorities would be needed before reaching a final decision?

Answer guidance: The answer should show that the option with the lowest LCC is not automatically the best overall choice. The possibility that lower economic costs may be associated with higher environmental or social burdens elsewhere should be considered, including possible externalities. The discussion should address trade-offs between short-term affordability and longer-term sustainability performance, considering emissions, reparability, circularity, public values, and strategic policy goals. The response would also identify what further evidence would be needed, such as environmental hotspot data, social risks, stakeholder preferences, regulatory requirements, resilience considerations, or alignment with climate and circular economy objectives.

Exercise 5. Externalities and the limits of LCC

A company is comparing two production technologies. One option has lower direct life-cycle costs, but relies on fossil energy and creates higher air pollution. The other has higher direct costs, but produces lower emissions and fewer health risks for surrounding communities.

A. What can standard LCC reveal in this case?

B. What can it not reveal on its own?

C. How may externalities complicate the interpretation of the result?

D. Under what circumstances might societal LCC be more appropriate than conventional LCC?

E. Why is it useful to combine LCC with LCA or sustainability assessment in such a case?

Answer guidance: While there is no single correct answer, the response should distinguish private costs from wider social and environmental costs, explain that externalities may remain invisible in conventional LCC, and demonstrate why broader decision support is needed when the choices have consequences beyond the direct decision-maker.

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5/
SOCIAL LIFE CYCLE ASSESSMENT

Life cycle thinking frames assessment objects as outcomes of connected activities across extraction, production, transport, use and end-of-life. While environmental LCA aids in tracing environmental exchanges across this chain, Life Cycle Costing tracks economic consequences.

Many important effects, however, are social: these concern workers' rights, community well-being, consumer safety, supplier relations, equity and access to benefits. Such aspects are often less visible because they are embedded in organisational practices, local institutions and distant supply chains. A product may therefore perform well environmentally while serious questions remain regarding labour or rights.

Social Life Cycle Assessment (S-LCA) examines socially relevant conditions and potential effects associated with a product system. Applied to a smartphone, for example, S-LCA reveals the labour conditions, institutions, rights, risks, responsibilities, and unequal relationships embedded throughout the global value chain.

Illustrative case: The people behind the materials

A clean energy technology is being developed in a modern laboratory. The project is planned to create scientific knowledge, and contribute to future decarbonisation. Within the research environment, the work is regarded as clearly positive.

Developing the technology also depends on raw-material extraction and manufacturing beyond the laboratory. These activities may create employment, but can also expose workers and nearby communities to risks that technical reports overlook.

S-LCA brings all actors involved into the picture. The central question is how workers, communities, consumers and society may be affected across the life cycle. Although in early-stage research, the answers are often uncertain, posing these questions early may help researchers avoid blind spots and pursue innovation more responsibly.



S-LCA CONCEPTS AND TERMS

S-LCA emerged from the attempt to extend life cycle thinking beyond environmental exchanges and cost flows into the social conditions embedded in product systems. Early work showed that social impacts are not usually generated by physical emissions in the same direct manner as environmental impacts[1–3]. Consequently, S-LCA follows the general logic of LCA, but requires its own concepts. The main guidance documents, the principles of S-LCA, stakeholder categories, and the key distinctions between social hotspots, footprints, handprints, risks, performance and impacts are introduced in the following sections.

Standards and guidance for S-LCA

The methodological foundations were consolidated by the first UNEP/SETAC Guidelines for Social Life Cycle Assessment of Products[4], in which life-cycle-based social assessment was introduced as a distinct field. Later methodological work clarified specific elements of the approach: the importance of baselines[5]; different types of outcomes[6]; the characterisation of labour-rights-related impacts[2]; and how S-LCA results can create effects in decision processes[7].

The field has since moved from exploratory methodology toward more formalised practice. According to the 2020 UNEP Guidelines for Social Life Cycle Assessment of Products and Organizations, S-LCA may be used for screening, reference-scale assessment, impact-pathway modelling, product comparison, organisational learning, due diligence and improvement[8].

ISO 14075:2024 establishes an international standard framework on this methodological family and defines principles, framework, and other requirements[9]. S-LCA is defined in this document as the "compilation and assessment of the socially relevant inputs and outputs and the potential *social impacts* of a *product system* throughout its *life cycle*" (Clause 3.2; emphasis in original).

The principles of S-LCA

The principles shown in Figure 5.1 guide S-LCA from scoping to reporting. The assessment should identify who may be affected, examine relevant social conditions across the product life cycle and relate the analysis to the function defined in the study. Where alternatives are compared, the functional unit provides a common basis, although the results may still require interpretation for specific stakeholder groups[10,11].

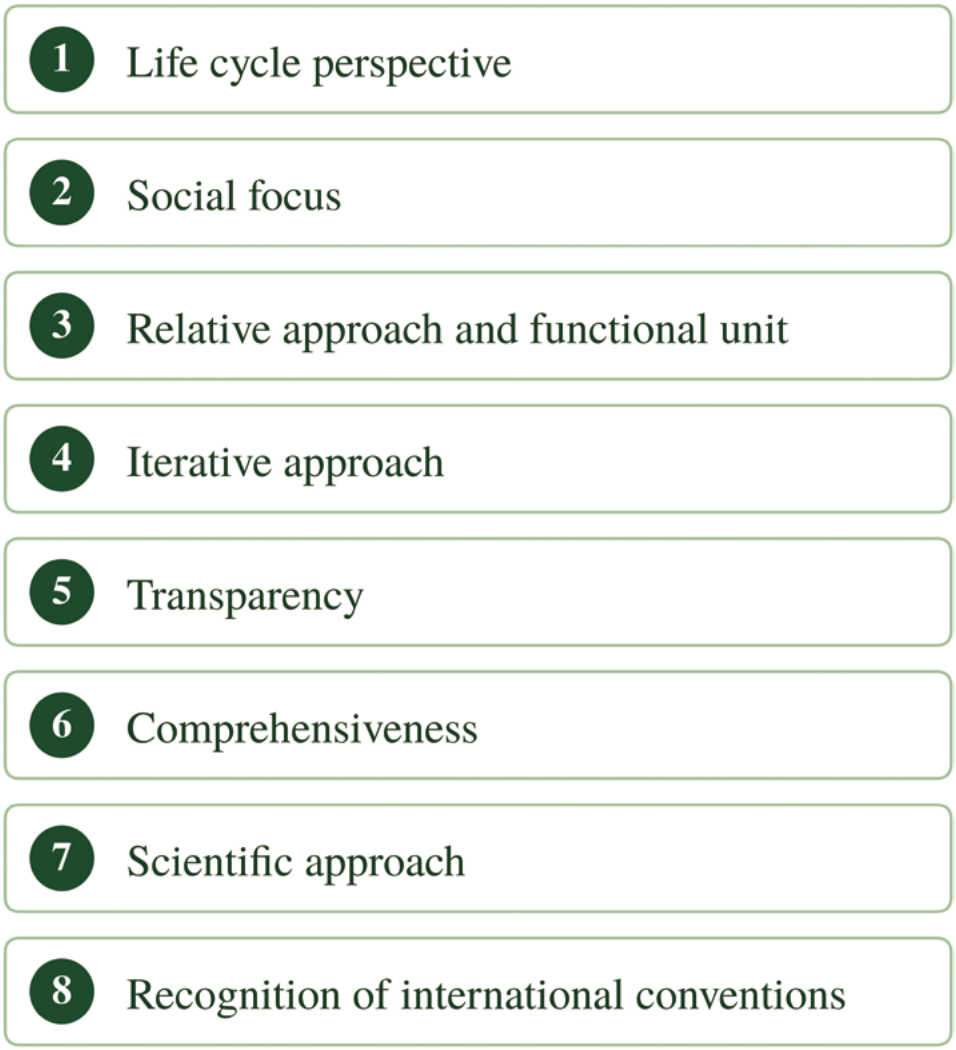

Figure 5.1 S-LCA Principles

Life cycle perspective. Social issues should be examined across the full product system, not only at the level of the final manufacturer or brand owner. Social risks and benefits may arise during raw material extraction, processing, transport, assembly, use, maintenance, recycling and waste management[12,13].

Social focus. The social focus of S-LCA concerns who is affected and how. Workers, local communities, consumers, value-chain actors, society and children may experience different types of harm or benefit[14,15].

Relative approach and functional unit. S-LCA assesses a product system in relation to the function it provides. The functional unit connects social information to a comparable product function, especially when alternatives are assessed. However, social results may also require stakeholder-specific interpretation beyond simple numerical comparison.

Iterative approach. Social data, stakeholder relevance and interpretation usually necessitate refinement during the study. Initial screening can reveal missing actors, important regions or relevant subcategories.

Transparency. S-LCA often combines mixed data sources with context-dependent value choices. System boundaries, data sources, stakeholder categories, indicators, reference points, limitations and uncertainty should be clearly reported. Transparent reporting prevents overclaiming and supports credible interpretation[16].

Comprehensiveness. All relevant life cycle stages and stakeholder groups should be considered, with the scope set by materiality and data availability.Any exclusions or differences in assessment depth should be justified.

Scientific approach. S-LCA should be systematic and evidence-based. Where qualitative judgement is needed, it should be documented and supported by credible evidence[6].

Recognition of international conventions. S-LCA uses international conventions and standards as normative reference points for evaluating social performance. These may include human rights principles, ILO labour standards and social responsibility guidance.

Stakeholder categories

In the main S-LCA guidance documents and related standards, the assessment is structured around several stakeholder groups: workers, local communities, consumers, value-chain actors, society and, in some cases, children as a separate or cross-cutting group (Figure 5.2)[4,9]. Variation in scope, depth and comparability across S-LCA studies largely derives from the way indicators and subcategories are selected[17].



Figure 5.2 Stakeholder Categories and Impact Subcategories based on the UNEP Guidelines for Social Life Cycle Assessment of Products and Organizations 2020[8]

Workers are often assessed stakeholder category. Relevant subcategories typically include freedom of association and collective bargaining, child labour, fair salary, working hours, forced labour, occupational health and safety, social benefits among others. The labour-rights perspective has been particularly important in methodological discussions of social impact characterisation[18].

Local communities may be affected by extraction, industrial facilities, infrastructure, land use, waste treatment or changes in access to resources. Common subcategories include access to material and immaterial resources, safe and healthy living conditions, cultural heritage, indigenous rights, community engagement, secure living conditions and local employment.

Value-chain actors include suppliers, smallholders, subcontractors, distributors and business partners, with attention to fair competition, responsible sourcing and fair-trading relationships.

Consumers are usually considered through themes such as product safety, transparency, privacy, responsible communication, access to essential products and feedback mechanisms.

At the level of *society*, S-LCA may consider corruption, economic development, public sustainability commitments, technology development, armed conflict and ethical conduct.

Children may require separate attention because they can be affected as workers, consumers, community members and future persons.

Materiality assessment helps determine which stakeholders and social issues warrant inclusion in the study. Selection should be informed by engagement with affected stakeholders, with exclusions justified in relation to the goal and scope. ISO 26000 may provide general guidance on stakeholder engagement and social responsibility[19].

Subcategories should be selected according to the goal and scope, product system, sector, geography, stakeholder relevance, data availability, and decision context. Studies in the construction and biodiesel sectors provide examples of contextual adaptation instead of applying a universal checklist[20,21].

Social risk, impact and performance

A key interpretive distinction in S-LCA is the difference between *social risk*, *social performance* and *social impact*. While these terms are sometimes used interchangeably, they in fact refer to different types of information.

Social risk usually refers to the potential occurrence of a social issue in relation to a country, sector, process, stakeholder group or supply-chain activity. It is common in database-assisted hotspot screening, where the tools use country-sector information, indicators and risk-assessment schemes to identify social hotspots[22,23].

Social impact refers to a change in stakeholder well-being, rights, health, livelihood or social conditions that can be linked to activities within a product system. In S-LCA, social impact assessment goes beyond risk or performance scoring: life-cycle activities are examined for their potential positive or negative effects on people and organisations[24].

Positive impacts have been treated unevenly in S-LCA, as reviews of the field show that the literature has historically focused more on negative risks than on positive contributions. This is in part because many social concerns relate to undesirable factors such as rights violations, unsafe work, child labour, discrimination, corruption, or community conflict[25]. Nevertheless, product systems may also generate social benefits, including what experts call "decent work", skills development, improved access to essential services, safer products, local value creation, and poverty reduction[15].

Social performance describes an observed or reported condition of an organisation or supplier compared with a defined reference point. In reference-scale approaches, this reference point may be a an international convention or a sector benchmark[26].



Figure 5.3 Key S-LCA terms[6,9,24,25]

Social hotspot, footprint and handprint

Early-stage S-LCA can identify potential social concerns, before technologies become embedded in large-scale supply chains[27]. These concepts can inform design and sourcing decisions before commercial deployment[28].

A *social hotspot* refers to a specific activity, process, life cycle stage, or geographical location within a product system where a social issue or social risk is likely to arise. It is a social concern in the supply chain that makes a significant contribution to the overall social profile of the product system.

In database-based S-LCA screening, a social hotspot denotes an activity, sector, region, or supply-chain segment associated with elevated potential social risk. This represents a preliminary screening result. Under ISO 14075, hotspots are identified through the assessment of study results; database signals should therefore be described as potential hotspots for further analysis[22,29].

Social footprint and social handprint are application-specific concepts. A *social footprint* can be understood as the modelled negative social burden or risk profile associated with a product, organisation, or value chain. In many applications, this burden is summarised through indicators such as risk-weighted worker hours or comparable social-risk metrics. The *social handprint* belongs to a separate complementary concept and concerns positive change relative to a defined baseline[30,31].

S-LCA FRAMEWORK

ISO 14075 formalises S-LCA through four interconnected phases: *goal and scope definition*, *social life cycle inventory analysis, social life cycle impact assessment*, and *interpretation*[32]. It also sets requirements for conducting and transparently reporting an assessment.

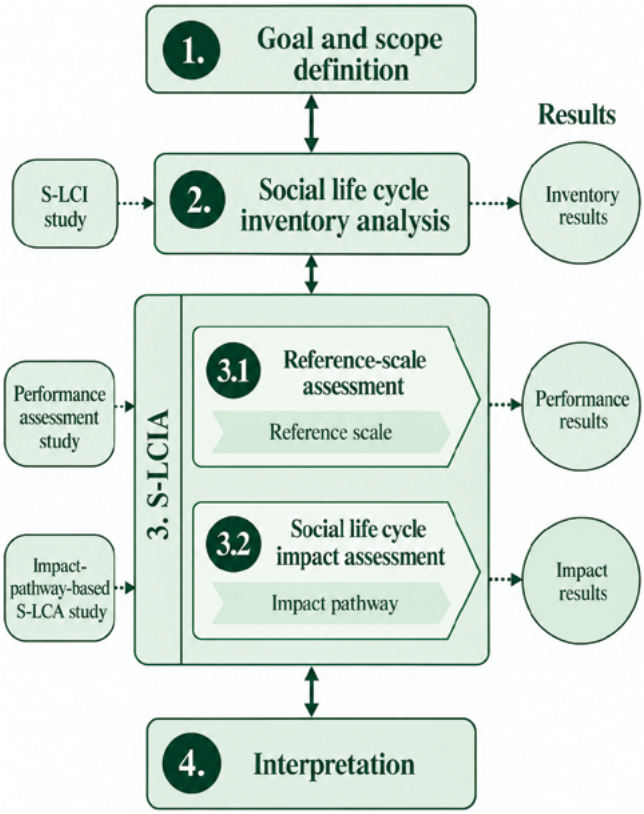

Figure 5.4 Methodological framework of ISO 14075[32]

Goal and scope definition

The initial g*oal definition* determines what an S-LCA can credibly claim. The *goal* specifies why the study is being conducted, who will use the results, what decision context it supports, and what the intended application is. A supply-chain screening study, for example, requires different evidence from a comparative product assessment or a study intended for public reporting. These purposes require different levels of data quality, system detail, and stakeholder coverage[9].

The *scope* identifies the product system, functional unit, life-cycle stages, stakeholder groups, social topics and assessment method. It should also specify the geographical and sectoral resolution, data sources and rules for excluding processes or topics.

S-LCA boundaries may extend beyond physical production processes to employment relations, contracts, governance arrangements and supplier

responsibilities. A process-based model alone may therefore omit actors or institutional relationships that are important to the social assessment[33].

The *functional unit* connects the social inventory to the function delivered by the product (Figure 5.5). For example, database-assisted approaches may link country-sector social risk information to the amount of production or labour required to fulfil a given functional unit, often through activity variables such as worker hours[23].



Figure 5.5 Product functions & functional unit (S-LCA)

Goal and scope should also clarify the type of study being conducted: hotspot screening, S-LCI, S-LCA (reference-scale or impact-pathway), product social impact assessment, or value-chain social assessment[34]. *S-LCI* and *S-LCA studies* answer different but closely connected questions.

An *S-LCI study* investigates what social information is associated with the product system. It documents data on labour conditions, community issues, consumer concerns, value-chain relations, social risks, management practices, or stakeholder evidence. An *S-LCA study* goes one step further and investigates what this information indicates for stakeholders. The same inventory data may lead to different conclusions depending on the baseline, reference scale, impact category, stakeholder group, or causal pathway used for assessment[5,6,35].

Social life cycle inventory

The purpose of the *Social Life Cycle Inventory* is to collect information needed to describe social conditions associated with the product system and its value chain. Unlike environmental inventory, which usually records physical inputs and outputs, S-LCI combines quantitative data, semi-quantitative ratings, and qualitative evidence (Figure 5.6).

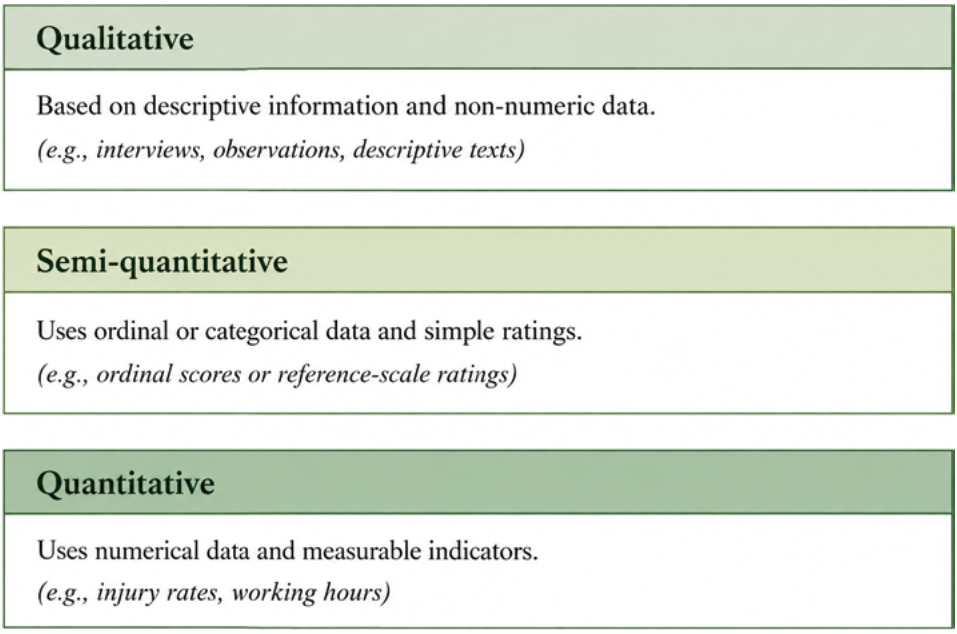

Figure 5.6 S-LCA data input types

Typical *S-LCI data* cover employment conditions, occupational health and safety, labour rights, community relations, governance, consumer protection, and human-rights risks, drawing on indicators such as wages, working hours, and accident rates.

These data can derive from *primary sources*, such as companies, suppliers, workers, communities, or NGOs, via audits, surveys, interviews, and site visits, or from *secondary sources*, including statistics, international organisations, academic literature, sustainability reports, sector studies, and S-LCA databases. Data availability remains a central challenge for S-LCA[36–38].

Database-assisted S-LCI often relies on activity variables that link social information to the product system. For example, worker hours connect country-sector

social risk information to the labour embedded in production. This logic is adopted in two major databases: the Product Social Impact Life Cycle Assessment (PSILCA) and the Social Hotspots Database. PSILCA documentation and later methodological work show how database structure, social indicators, worker-hour modelling, and raw-value approaches influence interpretation[23]. Comparable support is provided by work on the Social Hotspots Database, which links input-output modelling, labour intensity, and social risk characterisation across product supply chains[39].

However, worker hours are not equally suitable for all stakeholder groups. They are relevant for worker-related risks, but less direct for community well-being, consumer safety, children's rights, or society-level issues. Each indicator's link to the product system should therefore be explained in the S-LCI phase, and data quality documented. *Data triangulation* is often necessary because single-source social data may be incomplete, biased, outdated, or insufficiently context-specific.

Social performance and impact assessment

The *Social Life Cycle Impact Assessment* phase is that during which meaning is assigned to the information collected in the Social Life Cycle Inventory. It concerns how inventory data should be evaluated in relation to stakeholder groups and social topics. This phase is positioned within the four-phase life-cycle structure of goal and scope definition, inventory analysis, assessment and interpretation.

However, S-LCIA differs from environmental LCIA because many social issues cannot be modelled through physical cause-effect chains with the same level of precision. Social effects are often context-dependent, shaped by legal systems, labour relations, governance quality, and institutional practices. This is reflected in two main modelling approaches: *reference scale approach* and the *impact pathway approach*[32]. ISO 14075 uses related but not identical terminology: under Social Life Cycle Performance Assessment (S-LCPA), outcomes are evaluated against defined reference points, while under Social Life Cycle Impact Assessment (S-LCIA), potential social impacts are assessed through causal pathways.

Accordingly, the *reference scale approach* corresponds broadly to Type I assessment in the UNEP guidance. Under this approach, inventory information is evaluated against defined *performance reference points*. These reference points may be based on legal requirements, international conventions, ILO standards, human-rights expectations, sector benchmarks, living-wage estimates, expert judgement, stakeholder expectations or best available practice. Results are usually expressed as ordinal performance levels, classes, or colour codes, ranging, for example, from unacceptable to best practice. In contrast, categories ranging from very high to low risk are typically used in database-assisted social risk screening and should not be interpreted as verified benchmarks of performance. This approach

is used because it is practical and applicable when causal models are not available. Nonetheless, results depend strongly on the construction of the scale, the choice of reference points and the interpretation of thresholds[26,29].

The impact pathway approach corresponds broadly to Type II assessment. With this method, causal chains between product-system activities and changes in stakeholder conditions are modelled. For example, low wages may be linked to household deprivation, unsafe work to health damage, child labour to loss of education, or land displacement to livelihood disruption. This approach is conceptually closer to environmental LCIA because it uses characterisation models and, when possible, characterisation factors to translate inventory data into indicator results.

Some proposed indicators use health- or well-being-related metrics, including quality-adjusted life years (QALYs). Although impact-pathway assessment is acknowledged in ISO 14075, consistent application of this approach across social topics remains limited by weak causal evidence and data constraints[35].

ISO 14075 specifies the selection of impact categories and indicators, characterisation models or reference scales, and the classification of S-LCI results as *mandatory elements* of S-LCIA, whereby inventory results should be assigned to relevant impact categories through classification. If an impact pathway approach is applied, characterisation factors are used to convert S-LCI results; otherwise, a reference scale is applied to determine the corresponding level. Weighting and aggregation remain *optional elements*.

S-LCIA methods do not all produce the same type of outcome. Some generate *performance scores*, others provide *risk profiles*, *hotspot signals*, or *impact estimates*. Results should therefore not be compared or aggregated without understanding the underlying assessment model[6]. Aggregation may facilitate communication, but it can conceal non-compensable issues such as forced labour, child labour, or violations of indigenous rights.

Interpretation

Interpretation is the phase during which significant issues are identified, data quality is evaluated, consistency checked, uncertainty explained, and findings summarised. In line with ISO 14075[9] and the UNEP Guidelines[8], interpretation should always be linked back to the study's goal and scope and to the assessment model used.

Social risk indicates the likelihood of adverse conditions, social performance describes results against defined benchmarks, and social impact refers to changes in stakeholder well-being attributable to the product system. Accordingly, a high-risk country-sector score in PSILCA or the Social Hotspots Database signals a need for further investigation, but does not necessarily demonstrate verified harm

at a specific supplier or site. Similarly, reference-scale results describe performance against a norm or benchmark, while impact-pathway results characterise possible causal relationships between life-cycle activities and social outcomes[16].

Uncertainty in S-LCA can arise from system boundaries, stakeholder and subcategory selection, data sources, activity variables, geographic resolution, scoring rules, and aggregation choices. Methodological diversity remains substantial, conclusions should therefore reflect the quality and strength of the available evidence[40,41].

Critical review is important when results are used externally, comparatively or for public reporting. This should establish whether assumptions, data sources, reference scales, impact pathways and conclusions are transparent and justified. Stakeholder validation can further improve credibility by testing whether findings are plausible and whether important issues have been missed. *Communication* should remain cautious: S-LCA provides evidence on risks, performance, potential impacts and improvement priorities, but it does not prove that a product is socially sustainable in absolute terms.

Tools and models for S-LCA

Database-assisted S-LCA illustrates the boundary between social risk screening and impact assessment particularly well. Databases such as the Social Hotspots Database[39,42], PSILCA[23,43] and, where available, the SOCA (social add-on to ecoinvent) database provide information on country-sector risks, social indicators, stakeholder topics, and activity variables across global supply chains. These are useful for early hotspot screening and for identifying issues that require more detailed investigation.

The Social Hotspots Database combines input-output modelling, labour intensity, social topics, risk categories and worker-hour-related modelling to identify potential social hotspots across product supply chains and product categories. PSILCA follows a comparable logic, using country-sector data, social indicators, risk-assessed elementary flows and, in newer versions, raw-value information to support hotspot interpretation[44]. SOCA has also been used as a social database for product systems.

Software environments such as openLCA, SimaPro and Quantis Suite can operationalise databases and model product systems. Related frameworks, such as SA8000, EcoVadis, GRI reporting and OECD due-diligence guidance, may further inform indicators.

Other relevant assessment approaches include Product Social Impact Assessment[14], the Social Value Initiative Handbook[15] and social footprint/handprint approaches, which focus more directly on product- and company-level performance.

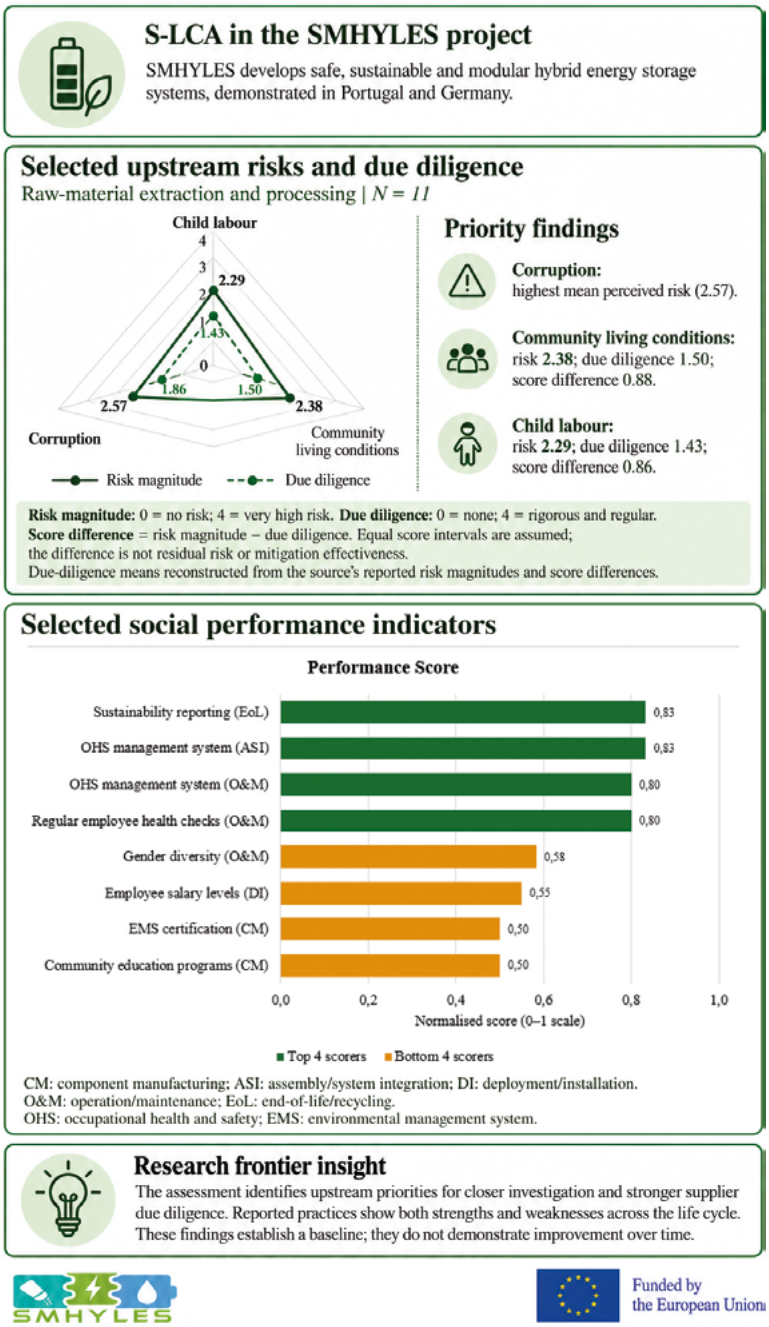

Figure 5.7 Research frontier box: example of SMHYLES project S-LCA

S-LCA IN RESEARCH AND INNOVATION

Decisions made during research and development can affect working conditions and many other social conditions associated with an emerging technology. Examining these aspects early may reveal concerns that are not visible in an environmental inventory. S-LCA follows the general LCA logic, but it cannot simply replicate environmental LCA.

While environmental LCA mainly traces physical flows and environmental mechanisms, S-LCA is concerned with social relations. These aspects are often qualitative and depend on governance and local conditions.

New materials or products can create benefits, such as safer products or new jobs. At the same time, they may reproduce social risks. S-LCA supports the identification of these issues before technologies become locked into large-scale deployment.

Early-stage S-LCA usually relies on incomplete and partly generic evidence because suppliers or production may not yet be established. Even with this limitation, the assessment can help researchers identify affected social topics. In the following chapter, S-LCA is integrated with environmental LCA and LCC within the broader framework of Life Cycle Sustainability Assessment.

RECOMMENDED READINGS

Topic	Recommended reading
Principles and methodological guidance	ISO 14075:2024. *Environmental management—Principles and framework for social life cycle assessment*[9]; Benoît Norris et al. (2020). *Guidelines for Social Life Cycle Assessment of Products and Organizations 2020*[8].
Selection of social indicators	Kühnen and Hahn (2017). *Indicators in social life cycle assessment: A review of frameworks, theories, and empirical experience*[17]; Sureau et al. (2018). *Social life-cycle assessment frameworks: A review of criteria and indicators proposed to assess social and socioeconomic impacts*[24].
System boundaries	Dubois-Iorgulescu et al. (2018). *How to define the system in social life cycle assessments? A critical review of the state of the art and identification of needed developments*[33].
Baselines and reference conditions	Jørgensen et al. (2010). *Defining the baseline in social life cycle assessment*[5].
Database screening of social risks	Benoît Norris, Norris and Aulisio (2014). *Efficient assessment of social hotspots in the supply chains of 100 product categories using the Social Hotspots Database*[22]; Ciroth and Eisfeldt (2016). *PSILCA—A Product Social Impact Life Cycle Assessment Database*[23].
Social impact assessment approaches	Parent, Cucuzzella and Revéret (2010). *Impact assessment in SLCA: Sorting the sLCIA methods according to their outcomes*[6]; Sureau, Neugebauer and Achten (2020). *Different paths in social life cycle impact assessment (S-LCIA)—A classification of type II impact pathway approaches*[35].
Positive social impacts	Di Cesare et al. (2018). *Positive impacts in social life cycle assessment: State of the art and the way forward*[25].
Social footprint and handprint approaches	Weidema (2018). *The social footprint—A practical approach to comprehensive and consistent social LCA*[30]; Husgafvel (2021). *Exploring social sustainability handprint—Part 1: Handprint and life cycle thinking and approaches*[31].

REFLECTION & EXERCISES

Exercise 1. Social score result

Which statement best explains why S-LCA often cannot rely on a single numerical result alone?

A. Because social impacts can never be described using indicators.

B. Because S-LCA is relevant only for qualitative case studies, not for product systems.

C. Because social impacts often involve rights, dignity, participation, discrimination, and community well-being, factors which may be partly measurable but also require contextual and qualitative interpretation.

D. Because S-LCA focuses only on consumer satisfaction and therefore does not require structured data.

E. Because environmental indicators are always more important than social indicators.

Answer: C

Why: Social impacts can sometimes be supported by indicators, scores, or risk levels, although many social issues also depend on context, values, power relations, and stakeholder perspectives. For this reason, S-LCA often combines quantitative evidence with qualitative interpretation.

Exercise 2. Social impact mapping

Social impacts may involve child labour, occupational safety, community displacement, gender discrimination, or consumer privacy. Although some aspects can be represented through indicators, scores, or risk levels, others require contextual interpretation. Select one of the above issues and answer the following questions:

A. What aspects of this issue may be measured?

B. What aspects would remain difficult to quantify?

C. Why might qualitative evidence remain necessary even when indicators are available?

Answer guidance: Recognize that, while social impacts are partly measurable, they are also shaped by context, perception, power relations, and rights-based concerns. Regarding child labour, quantitative indicators may include the number or proportion of underage workers, their ages, and working hours. However, these indicators may not capture coercion, hazardous conditions, household dependency, informal employment, or the child's own experience. Interviews, site observations, school records, and consultation with local organisations can provide the contextual evidence needed to interpret these indicators and assess possible rights violations.

Exercise 3. Positive and negative social impacts

Select one product you use daily, such as a smartphone, laptop, coffee, clothing item, bicycle, or battery-powered device.
Identify at least:
A. one possible positive social impact
B. one possible negative social impact
C. the stakeholder group or groups affected
Self-check question: Does a positive benefit for one stakeholder group automatically compensate for harm experienced by another group?

Answer guidance: Recognise that social impacts may be distributed unevenly across stakeholder groups and life cycle stages, and that benefits in one part of the product system do not automatically compensate for harm elsewhere. **Example structure:**

Product	**Possible positive social impact**	**Possible negative social impact**	**Affected stakeholder**
Example: Smartphone	Access to communication and services	Labour risks in mineral extraction	Consumers, workers, local communities

Exercise 4. Social hotspots and stakeholder categories

Explain the difference between a social hotspot and a stakeholder category in S-LCA. Then give one example of each from a product system of your choice.

Model answer: In database screening, a potential hotspot is a stage, process, location or supply-chain segment associated with elevated social risk and therefore requiring further investigation. Under ISO 14075, a hotspot is identified from the study results. A stakeholder category is the group potentially affected, such as workers, local communities, consumers, society or value-chain actors.

Exercise 5. S-LCA mixed evidence

S-LCA frequently combines quantitative indicators, qualitative information, expert judgement, and stakeholder input.
Briefly explain why this type of mixed approach is frequently necessary. Then identify one advantage and one limitation of each of the following:
A. quantitative risk indicators
B. expert judgement
C. stakeholder consultation

Answer guidance: Quantitative indicators enable systematic comparison, but may conceal contextual differences. Expert judgement may be flexible and useful in cases when data are limited, but such assessments are by their very nature subjective. Stakeholder consultation provides context-rich evidence, but is resource-intensive and may be affected by unequal representation and power. The response should explain how combining these approaches could improve robustness.

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6/
LIFE CYCLE SUSTAINABILITY ASSESSMENT

Life Cycle Sustainability Assessment (LCSA) is an integrative framework for evaluating products, technologies and systems across environmental, economic and social dimensions. Building on Life Cycle Thinking, LCSA extends environmental Life Cycle Assessment (LCA) by connecting it with Life Cycle Costing (LCC) and Social Life Cycle Assessment (S-LCA).

Sustainability assessment requires attention to multiple indicators, life cycle stages and stakeholder perspectives, since a technology may deliver climate benefits while increasing costs, generating social risks or shifting burdens to other parts of the value chain.

The chapter first sets out the main concepts and terminology of LCSA and key principles. The methodological sections follow the life cycle assessment structure: goal and scope definition, inventory analysis, impact assessment and interpretation. Particular attention is given to system boundaries, functional unit, uncertainty and integration approaches.

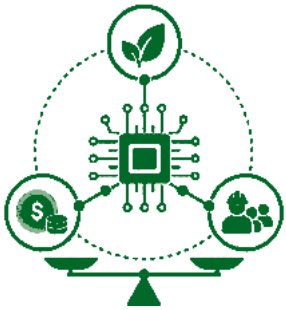
Visualisation and decision-support approaches are also addressed, including dashboards, sustainability triangles, weighting, monetisation, multi-criteria decision analysis, and hotspot mapping. LCSA is presented as a framework for exposing trade-offs and informing research and innovation.

Sustainability is not a single number

A project team compares two technological routes. The environmental assessment favours the first option, while the cost analysis favours the second. The social assessment does not offer a simple answer either, since each option carries different risks in different parts of the supply chain.

The team expected the assessment to identify a preferred option, but the three assessments point in different directions. No single result captures the full sustainability profile of either option.

The results show what is gained and lost and which assumptions drive the conclusion, giving the team a basis for discussing the decision. LCSA brings these three kinds of evidence together so that trade-offs can be discussed.



LCSA CONCEPTS AND TERMS

With Life Cycle Thinking, the assessment is expanded to the full life cycle of a product system, including raw material extraction, production, use and end-of-life[1]. The development of LCSA reflects the need to complement environmental LCA with evidence on economic viability and social conditions when addressing sustainability conditions[2,3]. LCSA therefore extends the life cycle perspective to the three dimensions of sustainability: environmental, economic and social[4,5].

Sustainability challenges rarely occur within a single dimension, as a product or technology may reduce environmental impacts while increasing costs, creating new social risks, or shifting burdens to another life-cycle stage or region. For this reason, single-dimension assessments, although valuable, may overlook important trade-offs and burden-shifting effects. LCSA can be understood as an umbrella framework that connects environmental, economic and social assessment methods while preserving the life cycle logic of LCA[6].

The integrated perspective has become more important as decision-makers increasingly expect evidence that goes beyond narrow eco-efficiency claims.

LCSA is concerned with how a product or organisation performs across sustainability dimensions[7,8].

LCSA can be defined as the combination of Environmental LCA, LCC and S-LCA (Figure 6.1)[2,4]. The formula captures the idea that the environmental, economic, and social aspects of sustainability must be evaluated together to represent a conceptual integration rather than a mathematical summation of individual assessments. The three components should be aligned through a common goal, functional comparability, compatible system boundaries and transparent assumptions.



Figure 6.1 UNEP/SETAC LCSA Equation based on Klöpffer (2008)[2] and UNEP/SETAC Life Cycle Initiative (2011)[4]

The practical implementation of LCSA depends on the purpose of the study, the decision context, the maturity of the technology and the availability of data. Different LCSA studies may vary in their level of integration, ranging from parallel presentation of three assessment results to more formalised approaches.

Guidance for LCSA

Guidance for LCSA refers to the methodological principles, procedures and reporting practices that support the application of LCSA. Figure 6.2 presents the main references that have shaped methodological guidance for LCSA, arranged chronologically from early conceptual formulations to recent handbook-level resources, illustrating how LCSA evolved towards a complex framework.

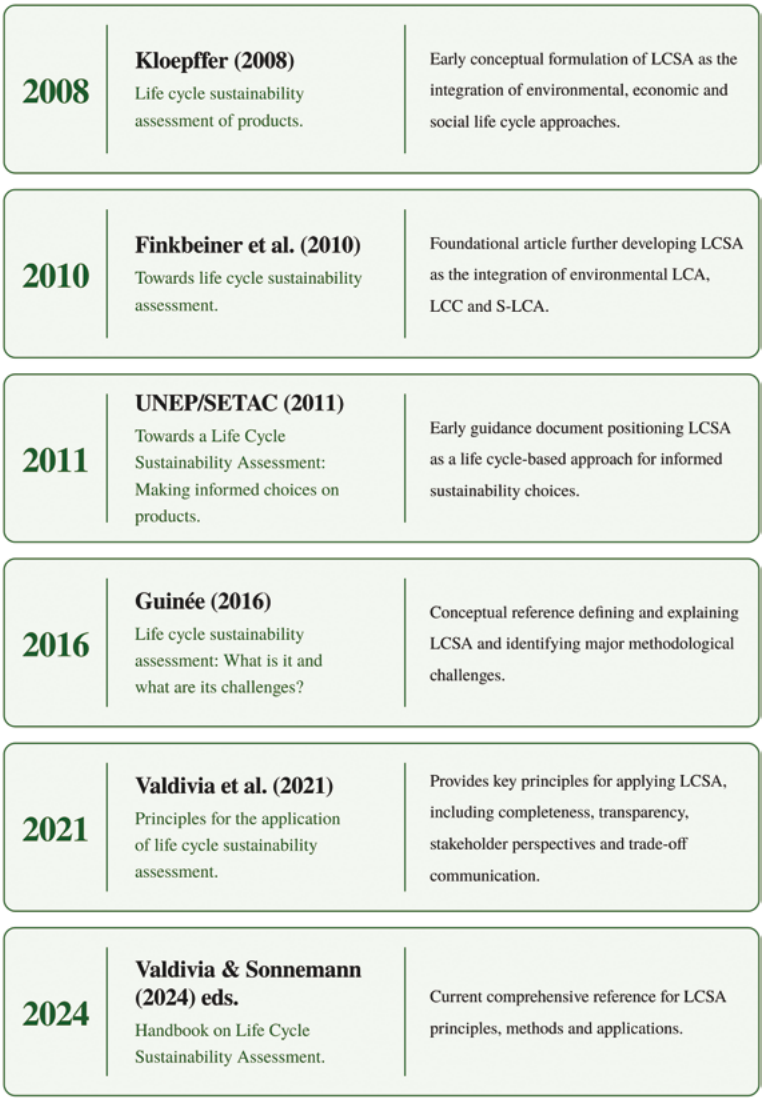


Figure 6.2 Key LCSA references

Ten LCSA Principles

Alongside the development of the LCSA framework, principles for its application have gradually evolved, showing how LCSA should be applied so that it constitutes more than a loose combination of indicators. Figure 6.3 summarizes the work by Valdivia et al.[9] and later by Valdivia and Sonnemann[10].



Figure 6.3 Ten LCSA principles based on Valdivia et al. (2021)[9]

Understanding the Areas of Protection: LCSA should begin by clarifying what the assessment seeks to protect or improve. While environmental LCA traditionally is concerned with Areas of Protection such as human health, ecosystem quality and resource availability, LCSA broadens this logic to include economic and social areas[9,11].

Alignment with ISO 14040: LCSA commonly follows the procedural logic of ISO 14040[12] and ISO 14044[13], particularly the iterative relationship between the four phases (goal and scope definition, life cycle inventory analysis, life cycle impact assessment and interpretation), using this established life cycle structure as an organising framework while extending the assessment to economic and social dimensions. However, ISO 14040 and ISO 14044 apply specifically to environmental LCA; adopting their structure does not make a complete LCSA study ISO-compliant.

Completeness: LCSA should consider environmental, economic and social aspects across all life cycle stages or the entire value chain[10]. Completeness does not mean including every possible indicator, but rather that relevant sustainability issues, whatever their nature or origin, should not be omitted from the assessment without justification.

Stakeholders' Perspective Consideration: Sustainability relevance depends on who is affected by the product system. Relevant stakeholder groups and affected groups should be identified and, where material and feasible, represented in the assessment process[9].

Product Utility Consideration: Product utility facilitates the identification of core product functions and core characteristics, while also acknowledging co-benefits[9]. Accordingly, alternatives should be compared on the basis of the same function or service. Product utility is therefore closely linked to the functional unit.

Materiality of System Boundaries: System boundaries should include all life cycle stages that materially influence sustainability conclusions, whether through environmental burdens, costs or social risks[8,9].

Consistency: Assumptions, boundaries, scenarios, reference units, and data treatment should be internally consistent across the assessment components[10].

Transparency: Data sources, methods, limitations, uncertainties, weighting choices, and stakeholder inputs should be documented clearly[14].

Explicit Trade-offs Communication: LCSA should expose trade-offs, such as lower climate impacts combined with higher costs or social risks[3]. The interpretation of trade-offs should take account of local values and ethical concerns[10].

Caution When Compensating Impacts: Aggregation and weighting of positive and negative impacts between the three pillars and within them should be applied carefully, since good performance in one dimension should not automatically compensate for serious harm in another[15].

Identifying hotspots and trade-offs

In LCSA, a *hotspot* is a life cycle stage, process, actor or indicator that contributes disproportionately to environmental, economic or social burdens[3]. The results of hotspot analysis indicate where improvement efforts are most relevant.

A *trade-off* occurs when improvement in one sustainability dimension leads to deterioration in another, such as lower greenhouse gas emissions but higher life cycle costs, or improved technical performance but increased social risk. In manufacturing systems, hotspots may arise from material inputs occupational conditions or cost-intensive quality-control procedures[16].

THE LCSA FRAMEWORK

The LCSA framework follows the life cycle logic of goal and scope definition, inventory analysis, impact assessment and interpretation, while extending it three-dimensionally. Compared with environmental LCA alone, the framework requires more attention to diverse data types and to trade-offs between dimensions.

Goal and scope definition in LCSA

In LCSA, *goal and scope definition* is more complex than in environmental LCA alone, because the environmental, economic and social assessments rely on different indicators and data structures. The *intended application and decision context* define the purpose of the assessment and guide the choice of methods and indicators, following the general structure of ISO 14040[12] and ISO 14044[13].

The *targeted audience* determines the level of detail, terminology and communication format. Researchers, companies, policymakers, consumers and affected communities all interpret environmental, economic and social results from different perspectives, and communication should therefore be adapted to each recipient group.

The *functional unit* provides the common basis for comparing alternatives by defining the function or service delivered by the product system, while the *reference flow* specifies the amount of product or system output required to fulfil that function. In LCSA, functional comparability should be ensured across the dimensions, any differences in reference units or data structures should be explained and reconciled.

System boundaries in LCSA define which life cycle stages and processes are included in the assessment and therefore strongly influence the validity of sustainability conclusions. While environmental LCA commonly structures system boundaries around physical flows such as raw materials, energy use, emissions and waste, financial flows and social risk exposure across the product system must also be considered (Figure 6.4).

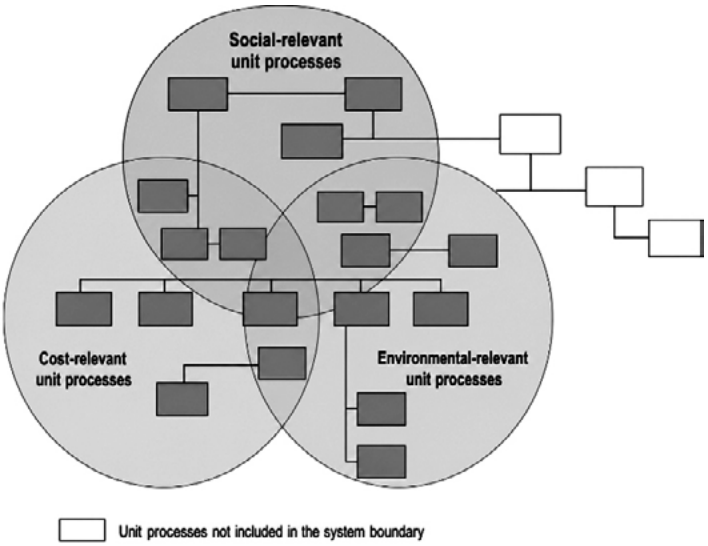


Figure 6.4 System boundaries in LCSA based on UNEP/SETAC Life Cycle Initiative[4]

For example, upstream raw material extraction may be environmentally significant, economically volatile and socially sensitive, even if it is geographically distant from the foreground manufacturing process. A *materiality* perspective is useful here: the boundary should include life cycle stages and actors that can materially affect the interpretation of hotspots across sustainability dimensions[14]. System boundaries in LCSA should be aligned as far as possible across environmental LCA, LCC and S-LCA, although complete alignment is often difficult in practice[8].

Life cycle inventory analysis in LCSA

The inventory phase in LCSA requires the collection of environmental, economic and social data describing the relevant processes, organisations and supply-chain activities within the defined system boundary. One of the central difficulties of LCSA is that these data differ in units, quality, scale, uncertainty and interpretive logic[3].

As an example, the Figure 6.5 illustrates how inventory modelling in LCSA can be organised around a single unit process within an organisation. The central unit process is described by three types of information corresponding to the three sustainability dimensions. Environmental LCA data include material and energy inputs and environmental outputs, such as water consumption and emissions of CO_2 or N_2O; LCC data include monetary flows, such as costs entering the process and revenues associated with the product output; S-LCA data include activity-related

or labour-related information, such as working hours, linked to social indicators and stakeholder categories.

In emerging-technology contexts, inventory modelling is particularly important because sustainability performance depends on early choices of materials and processes. Technology-manufacturing-oriented LCSA therefore requires data on product composition, process routes, production conditions and organisational practices[16]. Moreover, laboratory-scale or pilot-line data may not yet represent future industrial-scale production.

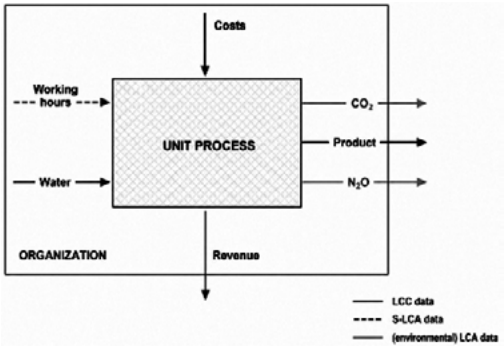


Figure 6.5 Example of LCSA inventory data for unit process and organisation levels based on UNEP/SETAC Life Cycle Initiative[4]

Life cycle impact assessment in LCSA

In the *impact assessment* phase of LCSA, each sustainability dimension follows a specific analytical logic. In environmental LCA, inventory flows are translated into potential environmental impacts through characterisation models, which link emissions and resource uses to impact categories such as climate change[17,18]. In LCC, economic flows are expressed through monetary indicators such as whole life cycle cost, net present cost, or annualised cost[19,20]. In S-LCA, social issues are assessed through stakeholder categories, subcategories, performance reference points, or impact pathway approaches[21,22].

The LCSA framework substantially increases LCIA complexity, since even environmental LCA alone produces multiple indicators at midpoint level or at the level of Areas of Protection, such as human health, ecosystems and abiotic resources. *Normalisation* expresses indicator results relative to selected reference information, such as regional or per-capita impacts, supporting interpretation without making indicators automatically comparable. Relative importance is assigned to impact categories or decision criteria through *weighting*, which may lead to aggregated results or a score[15]. In environmental LCA, *weighting and aggregation* are optional

under ISO 14044[13] and further addressed in ISO/TS 14074[23]. In LCSA, weighting across environmental, economic, and social dimensions falls within the broader interpretation or MCDA step and should be reported as an explicit value-based choice[15].

Monetary valuation, or *monetisation,* expresses selected impacts in monetary terms and can be used as one form of weighting. ISO 14008[24] provides guidance for the monetary valuation of environmental impacts and related environmental aspects, while monetisation of social impacts remains an emerging and method-dependent practice. In LCSA, monetisation is mainly relevant in terms of environmental and social indicators, since cost-based results are already reported in LCC[10].

Nevertheless, the economic dimension may also include resource-related indicators, such as surplus costs, economic rent, or supply-risk approaches[25,26]. Surplus-cost indicators are used within environmental resource-impact assessment, whereas supply risk may be treated as an economic or strategic indicator. If environmental and social impacts are fully monetised, societal LCC may resemble a monetisation-based form of LCSA, and monetised S-LCA values have also been proposed[27]. Double counting may occur when environmental or social effects have already been partly internalised in market prices, and are therefore also already reflected in LCC results.

The integration of LCC with environmental LCA has long been discussed as a way to connect environmental performance with economic consequences across the same product system. While such integration can support a more complete assessment, it requires consistent system boundaries and assumptions[28].

Interpretation in LCSA

Interpretation in LCSA should connect the results back to the original goal and scope. The purpose is not to declare a product 'sustainable' or 'unsustainable', but to explain under which assumptions, for which indicators, and from whose perspective one option performs better or worse[14]. The interpretation should identify dominant life cycle stages, relevant indicators, data limitations, methodological assumptions, uncertainty and possible trade-offs among environmental, economic and social dimensions.

Uncertainty, data quality, and sensitivity

Uncertainty in LCSA refers to limited confidence in assessment results caused by incomplete data, methodological choices, scenario assumptions, geographical variability, temporal change and/or value-based weighting decisions[29].

Economic uncertainty may result from price volatility, discount rates, future maintenance and replacement needs, and end-of-life cost assumptions. Social

uncertainty often arises when generic country-sector data are used to represent site-specific working conditions, supplier practices or community impacts. For emerging manufacturing technologies, uncertainty is further amplified by the gap between laboratory-scale data and expected industrial-scale performance. Scale-up assumptions influence environmental impacts, costs and social conditions simultaneously, since future production volumes, automation levels, energy demand and labour requirements may differ substantially from pilot-line conditions[16].

Data quality describes the reliability, representativeness, completeness and consistency of the information used across E-LCA, LCC and S-LCA. In LCSA, data quality is particularly challenging.

In *sensitivity analysis*, changes in key parameters or assumptions which may affect LCSA results are examined. Influential variables are identified and robustness checks are performed to determine whether the conclusions hold under alternative scenarios.

INTEGRATION AND DECISION-SUPPORT APPROACHES

Integration combines results from environmental LCA, LCC, and S-LCA. Results may be presented side by side or integrated through methods such as *Multi-Criteria Decision Analysis (MCDA)*. These approaches help compare alternatives and clarify trade-offs.

MCDA facilitates comparison when environmental, economic and social indicators point in different directions. Even environmental LCA produces several impact category results, and LCSA further expands this set by incorporating economic and social indicators. MCDA can organise heterogeneous results into a decision matrix without converting them to a single physical or monetary unit. Criteria may be weighted according to stakeholder, policy or strategic priorities, and sensitivity analysis can be used to establish whether conclusions remain robust. However, MCDA parameters such as criteria selection, scoring, weighting and stakeholder preferences reflect value choices that must be documented[30,31].

Other decision-support approaches may complement LCSA. *Social Cost-benefit analysis (SCBA)* can provide a broader monetary appraisal, while risk assessment can be used to examine specific hazards and their probability and consequences; neither constitutes a core component of the conventional LCSA framework. Cost-benefit analysis is an economic method that compares costs and benefits in monetary terms. While LCA is useful for the identification of environmental hotspots and the avoidance of burden shifting across life cycle stages, SCBA is applied to decisions requiring options to be assessed through net benefits or monetary valuation of externalities[32]. *Risk assessment* is concerned with a different focus, namely

the probability of specific hazards, often for a defined location, population or scenario, and can therefore provide insight into exposure pathways, and site-specific hazards[33,34]. In LCSA, risk assessment can strengthen the interpretation of uncertain or hazardous processes, however its spatial, temporal and probabilistic logic must be integrated given that it differs from the comparative and functional-unit-based structure of LCA.

Visualisation approaches

LCSA results are often multidimensional and disaggregated, which renders visualisation important for interpretation and communication[35]. Visual tools such as *contribution trees, radar charts, sunburst graphs, hotspot tables* and *geographical displays* can help interpreting results, but should be accompanied by a clear account of the underlying assumptions[36].

Side-by-side presentation: The simplest approach presents environmental, economic and social results separately and interprets them collectively, thus preserving the visibility of trade-offs and avoiding artificial aggregation. This method is suitable when the objective is to understand hotspots and differences between alternatives. *Hotspot and trade-off* mapping is used to identify areas in which environmental, economic and social concerns overlap across life cycle stages. This approach avoids aggregation and instead illustrates where sustainability concerns are concentrated. It is especially useful for emerging technologies, where uncertainty is high and the assessment mainly informs design improvement.

The *dashboard, triangle, crown* and *wheel* represent four specific examples of visualisation (Figure 6.6).

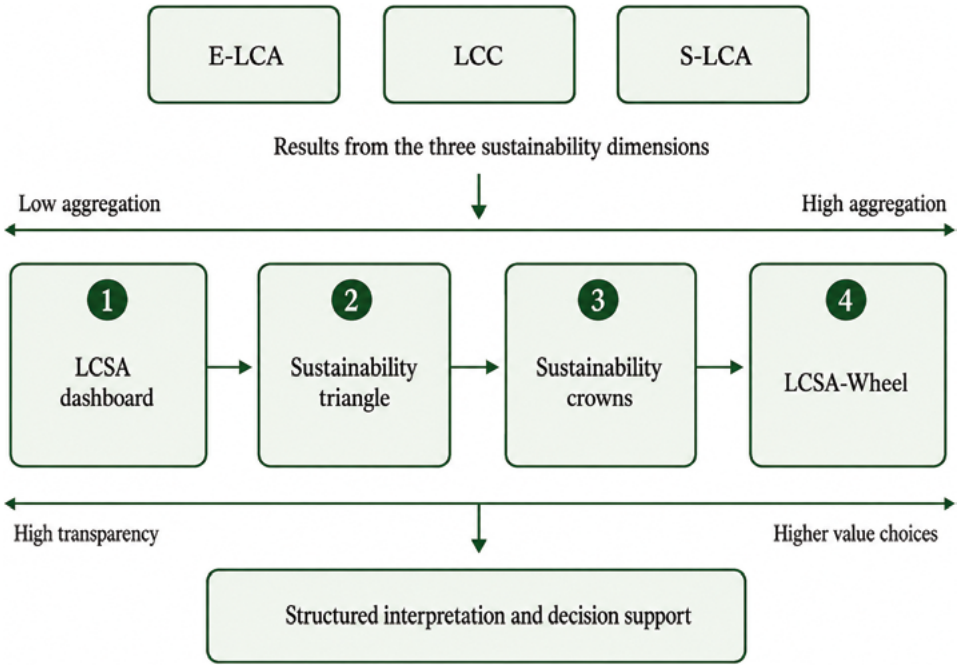


Figure 6.6 Visualisation approaches

A *Life Cycle Sustainability Dashboard* presents environmental, economic and social indicators in a common visual structure, using tables, colour coding, symbols or performance bands, thereby conveying complex results to decision-makers while avoiding premature reduction into a single score[37]. However, thresholds for colours, scores or performance categories require justification and documentation. The *Life Cycle Sustainability Triangle* offers a more conceptual visualisation of the balance between the sustainability dimensions, and can be used when alternatives perform unevenly across the three dimensions, for example when an emerging battery technology performs well environmentally but less well economically because of high pilot-scale production costs.

Other visualisation approaches include *Sustainability Crowns* and the *LCSA-Wheel*. Sustainability Crowns[38] display selected indicators in a circular format and are used to compare alternatives, thereby illustrating whether poor performance is concentrated in a few indicators or distributed across several sustainability dimensions[38]. The LCSA-Wheel, a more recently proposed visualisation approach, similarly employs a circular structure to enhance the readability of LCSA results for both expert and non-expert audiences[38].

Figure 6.7 provides an example of LCSA applied to the European project SOLiD. Global Reporting Initiative (GRI) Standards, the Sustainable Development Goals (SDGs), and UNEP guidance on LCSA are combined to support sustainability assessment in battery research. Once relevant impact categories, indicators, and stakeholder groups have been defined, environmental LCA, LCC, and S-LCA are conducted through aligned phases encompassing goal and scope, inventories, impact or cost assessment, and interpretation. This process identifies the relevant battery life cycle stages and links the indicators to the GRI Standards and the SDGs. The framework supports priorities such as safer batteries with higher energy density, longer cycle life, sustainable manufacturing, circularity, and resource efficiency.

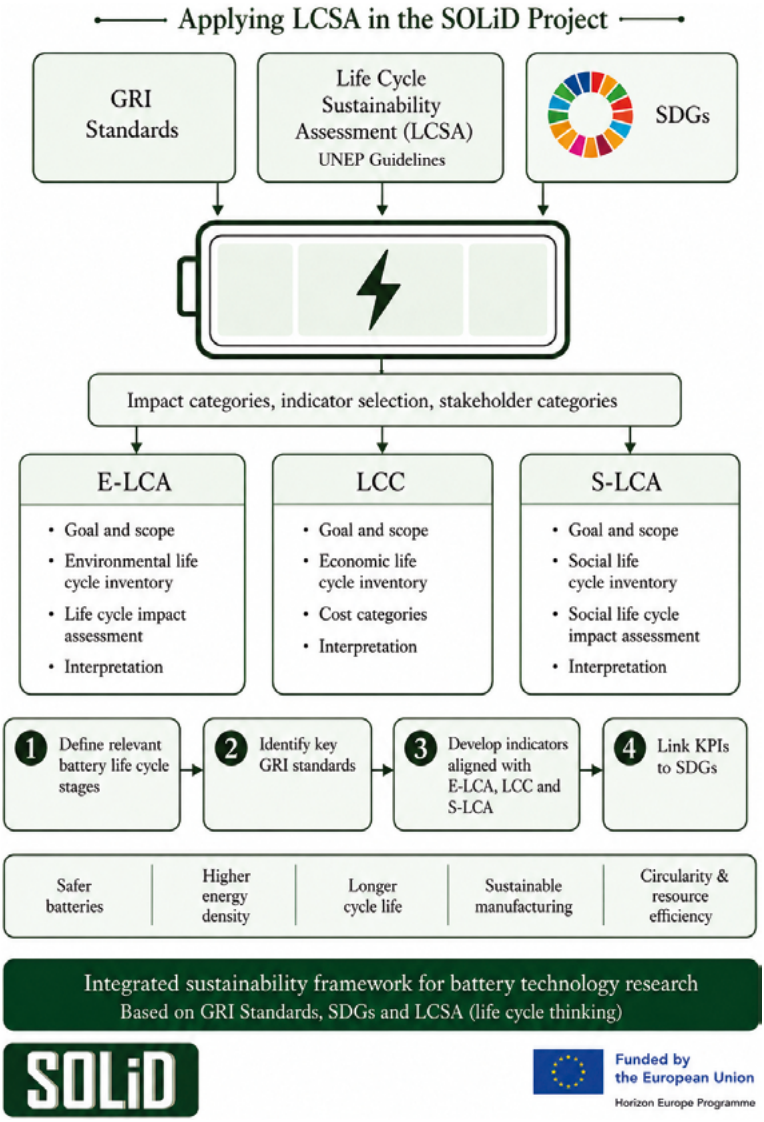


Figure 6.7 Research frontier box: SOLiD Horizon Europe project LCSA approach

LCSA IN RESEARCH AND INNOVATION

LCSA connects technological development with environmental, economic, and social responsibility. It helps identify trade-offs across a technology's life cycle. In research, it links assessment results to material selection and scale-up assumptions. For innovation projects, LCSA allows environmental, economic and social performance to be examined together at the design stage.

This is particularly relevant for emerging technologies such as advanced batteries, where early design choices determine future costs and supply-chain risks. Across the innovation process, LCSA functions as a framework for learning and reflection, from early concept development to later stages of technology demonstration and implementation.

The next chapter builds on this role by examining emerging trends that are reshaping sustainability assessment, including digitalisation, policy frameworks, Safe and Sustainable by Design, circularity, and absolute sustainability.

RECOMMENDED READINGS

Topic	Recommended reading
Comprehensive methodological guidance	Valdivia and Sonnemann (eds., 2024). *Handbook on Life Cycle Sustainability Assessment*[10].
Integration of environmental, economic and social assessment	Valdivia et al. (2011). *Towards a Life Cycle Sustainability Assessment: Making Informed Choices on Products*[4]; Klöpffer (2008). *Life cycle sustainability assessment of products*[2].
Principles for applying LCSA	Valdivia et al. (2021). *Principles for the application of life cycle sustainability assessment*[9].
Conceptual and methodological challenges	Guinée (2016). Life cycle sustainability assessment: What is it and what are its challenges?[8]
Weighting sustainability dimensions	Tarne, Lehmann and Finkbeiner (2019). Introducing weights to life cycle sustainability assessment—How do decision-makers weight sustainability dimensions?*[15]
Multicriteria assessment and trade-offs	Cinelli, Coles and Kirwan (2014). *Analysis of the potentials of multi-criteria decision analysis methods to conduct sustainability assessment*[31]; Munda (2004). *Social multi-criteria evaluation: Methodological foundations and operational consequences*[30].
Uncertainty and variability in assessment results	Michiels and Geeraerd (2020). *How to decide and visualize whether uncertainty or variability is dominating in life cycle assessment results: A systematic review*[36].
Visualisation and interpretation	Backes et al. (2023). *Visualization and interpretation of life cycle sustainability assessment—Existing tools and future development*[38]; Traverso et al. (2012). *Life cycle sustainability dashboard*[37].

REFLECTION & EXERCISES

Exercise 1. LCSA description

Which statement best explains why LCSA is useful when environmental LCA, LCC, and S-LCA indicate different preferred options?

A. LCSA automatically converts all environmental, economic, and social results into one objective final score.

B. LCSA eliminates the need for interpretation by using only quantitative indicators.

C. LCSA provides a framework for considering environmental, economic, and social results together, making trade-offs and tensions more visible.

D. LCSA considers only the sustainability dimension prioritised by the decision-maker.

E. LCSA is another term for LCA with additional environmental indicators.

Answer: C

Explanation: LCSA brings together environmental, economic, and social evidence within the sustainability assessment framework. It does not automatically resolve trade-offs or eliminate value judgements. Instead, it renders conflicting results more transparent.

Exercise 2. Matching methods

A retailer is comparing single-use plastic, paper, reusable plastic, and cotton shopping bags. Their performance depends on production impacts, reuse rates, costs, supply-chain conditions, consumer behaviour, and stakeholder priorities.

Match each decision question with the most appropriate method:

1. *Which option has the lowest life-cycle energy use and greenhouse gas emissions?*
2. *Which option is most economical when used a specified number of times?*
3. *Which method assesses social performance and potential social risks across the product life cycle?*
4. *Which option provides the best overall balance across environmental, economic, and social dimensions under different reuse scenarios?*
5. *Which option is preferred when retailer costs, consumer convenience, environmental impacts, and stakeholder priorities are evaluated using explicit criteria?*

Methods:

a) Multi-Criteria Decision Analysis (MCDA)

b) Social Life Cycle Assessment (S-LCA)

c) Life Cycle Costing (LCC)

d) Environmental Life Cycle Assessment (environmental LCA)

e) Life Cycle Sustainability Assessment (LCSA)

Model answer:

1. d), 2. c), 3. b), 4. e), 5. a)

Exercise 3. Weighting in an LCSA study

A simplified LCSA screening with environmental LCA, LCC, and S-LCA has been conducted for two technology options. For an initial decision screening, the results are scaled into performance scores ranging from 1 = very poor performance to 5 = very good performance (illustrative scores).

Dimension	*Weight*	*Option A*	*Option B*
Environmental	*0.40*	*4*	*2*
Economic	*0.30*	*2*	*4*
Social	*0.30*	*3*	*4*

A. Calculate the weighted performance score for each option.

B. Repeat the calculation using environmentally prioritised weights: environmental = 0.60, economic = 0.20, and social = 0.20.

C. Explain why the preferred option changes.

D. Apply a minimum-performance rule requiring a score of at least 3 in every dimension.

E. Discuss the limitations of weighting and aggregating LCSA results.

Model answer:

Initial weights:

Option A: (4 × 0.40) + (2 × 0.30) + (3 × 0.30) = 3.10

Option B: (2 × 0.40) + (4 × 0.30) + (4 × 0.30) = 3.20

Option B performs slightly better.

Environmental priority:

Option A: (4 × 0.60) + (2 × 0.20) + (3 × 0.20) = 3.40

Option B: (2 × 0.60) + (4 × 0.20) + (4 × 0.20) = 2.80

Option A performs better, demonstrating that the result depends on value-based weighting.

Under the minimum-performance rule, neither option qualifies: Option A performs poorly economically, while Option B performs poorly environmentally.

The exercise shows that aggregation can support comparison while concealing poor performance, uncertainty, distributional effects, and trade-offs. The weighted result represents an MCDA-based interpretation of LCSA evidence.

Exercise 4. Interpreting conflicting results in LCSA

A comparison of two insulation materials uses the following assessment settings:
Environmental LCA: impacts per square metre of insulation providing a specified thermal resistance over 50 years.
LCC: costs per installed square metre over 30 years.
S-LCA: social risks per kilogram of material from raw-material extraction to factory gate.
A. Identify the inconsistencies between the three assessments.
B. Explain why their results cannot yet be directly integrated.
C. Propose a common functional unit, reference period, and system boundary.
D. Identify any assumptions needed to make the comparison consistent.

Answer guidance: The assessments differ in functional unit, time horizon, and system boundaries. A harmonised study could assess the insulation required to provide a specified thermal resistance for one square metre of building envelope over 50 years. All three components should cover comparable life-cycle stages, including production, installation, maintenance, replacement, and end-of-life. Differences in durability, replacement rates, data quality, and geographical coverage should be explicitly addressed.

Exercise 5. Understanding the ten principles of LCSA

An LCSA compares reusable and single-use food containers. The environmental assessment covers the full life cycle, but the cost assessment ends at the factory gate and the social assessment considers only final assembly. Informal waste collectors are excluded because data are unavailable. Results are combined into one score without disclosing the weights. The study concludes that employment created during recycling compensates for unsafe working conditions.
A. Identify at least five LCSA principles that have been insufficiently applied.
B. Explain how each principle has been violated.
C. Recommend one improvement for each identified weakness.
D. Assess whether the study can support a claim that one container is "more sustainable".

Answer guidance: Relevant principles include completeness, stakeholder perspectives, materiality of system boundaries, consistency, transparency, explicit communication of trade-offs, and caution when compensating impacts. The study should harmonise boundaries, include relevant stakeholders and life-cycle stages, report data gaps and weighting choices, and present positive and negative social impacts separately. The current results do not support a robust comparative sustainability claim.

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7/
LCSA CHALLENGES AND EMERGING TRENDS

Life Cycle Sustainability Assessment (LCSA) can examine sustainability performance under conditions of change and uncertainty. The methodological challenges and emerging trends that will shape its future application are elaborated in this chapter.

Key challenges include the continuing development of S-LCA, inconsistencies in methodology and also the risk of premature sustainability claims. Prospective, ex-ante, and anticipatory approaches that allow sustainability considerations to inform research are then introduced.

Connections between LCSA and Safe and Sustainable by Design, circular economy, criticality assessment, absolute sustainability, digital product information, and artificial intelligence (AI) are also explored. These developments extend LCSA from retrospective impact assessment towards a more reflective and policy-relevant framework.

How can sustainability assessment keep up with fast-moving research and innovation?

A research project is preparing for its review meeting. The technical work packages report progress: new materials have been tested, prototypes are under development, and pilot activities are planned. The sustainability team is then asked to present evidence on sustainability indicators. The difficulty is that many answers depend on the future.

Industrial-scale production is not yet running. Recycling routes are not yet mature. Suppliers may change. Electricity mixes will evolve. Regulations are developing. Digital product passports, safe and sustainable by design, due diligence and ESG expectations are becoming part of the discussion, but their practical meaning is still taking shape.

This is the challenge for future LCSA, which must be used to support decisions before everything is known by working with changing expectations. Above all, LCSA must help researchers make choices while innovation is still open.



CHALLENGES FOR FUTURE LCSA

LCSA challenges include the conceptual, methodological, data-related and interpretive difficulties that emerge when environmental LCA, life cycle costing (LCC) and S-LCA are combined within one assessment framework.

Table 7.1 links the ten LCSA principles proposed by Valdivia et al.[1,2] to the main challenges of current assessment practice. Read this way, the principles also function as a diagnostic framework for locating where LCSA remains methodologically and practically difficult.

Table 7.1 LCSA principles[1,2] and challenges

LCSA principles	*Challenge*
Understanding the Areas of Protection	Immaturity of Social LCA[3]
Alignment with ISO 14040	Lack of harmonised methodology[4]; Limited comparability across studies[5,6]
Completeness	Institutional and practical capacity constraints[5,7]
Stakeholders' perspectives	Perspective dependence in LCC[8]; Weak connection to real decision processes[7]
Product utility	Functional unit complexity[6,9]
Materiality of system boundaries	Inconsistent system boundaries[4];
Consistency	Temporal mismatch between impacts[10]; Overlapping indicators and double counting[11]
Transparency	Data asymmetry and confidentiality[7,8]; Uncertainty and scenario dependence[12,13]
Explicit communication of trade-offs	Trade-offs between sustainability dimensions[4,7,10]; Aggregation, weighting and value choices[10]
Caution when compensating impacts	Overcompensation across sustainability dimensions / risk of misleading single-score sustainability claims[14]

The first challenge concerns the conceptual basis of LCSA. As an example, S-LCA remains less mature than environmental LCA[3], especially in defining impact pathways, *Areas of Protection* and causal links between inventory data and social outcomes[15].

A second group of challenges concerns *methodological alignment* and *completeness*. Although LCSA is expected to follow the ISO 14040 logic, no fully harmonised procedure currently exists for integrating environmental LCA, LCC and S-LCA[4]. This contributes to limited comparability across studies[5,6]. Complete LCSA also

requires substantial expertise, the lack of which sometimes leads to partial or simplified applications[5,7].

Further challenges concern perspective and system boundaries. LCC results depend on whose costs are considered, for example the producer's or society's[8], while product utility may include functional unit complexity[6,9], which extends beyond technical performance to encompass parameters such as durability. Inconsistent boundaries across the three dimensions can further distort interpretation[4].

Temporal mismatches, data asymmetry, confidentiality[7,8], scenario dependence[12,13], uncertainty and possible double counting[11] need to be reported *consistently* and *transparently*[10,12,13]. These issues are particularly relevant when environmental LCA, LCC and S-LCA rely on different modelling assumptions.

LCSA often exposes *trade-offs* between sustainability dimensions which may prevent consistent ranking of alternatives[4,7,10]. Aggregation and weighting may support interpretation, but they can also hide value choices and create a misleading impression of precision[7,10]. Caution is therefore needed to avoid *overcompensation* across dimensions and premature sustainability claims, especially for emerging technologies[14,16].

These challenges reflect current limitations of LCSA and provide the rationale for developments in prospective modelling, absolute sustainability, circularity, criticality, digitalisation, and policy-oriented applications.

PROSPECTIVE, EX-ANTE AND ANTICIPATORY LCSA

Prospective, ex-ante and *anticipatory LCSA* refer to the application of life cycle-based sustainability assessment to technologies, whose future performance remains uncertain. These variants of LCSA are relevant for emerging technologies that are not yet fully commercialised, such as advanced batteries, or bio-based materials. Their purpose is to support decisions during innovation, when design choices are still open, even though the three approaches overlap conceptually. The terminology was developed mainly in environmental LCA.

Prospective LCSA can be used as the main term for future-oriented assessment[13,17,18]. It is concerned with modelling how a product system may perform at a future point in time, using future background systems, projected electricity mixes, and learning effects. For example, prospective sustainability screening has been applied to sodium-ion battery cathode materials, illustrating how emerging material options can be compared at an early-stage assessment before technology pathways are fixed[19]. *Ex-ante LCSA*[12,20] is closely related, but is distinguished by timing: it is

conducted before commercial implementation or large-scale deployment. *Anticipatory LCSA*[20–22] combines future-oriented modelling with responsible-innovation principles, encompassing also possible societal implications.

SAFE AND SUSTAINABLE BY DESIGN

Safe and Sustainable by Design (SSbD) is an innovation approach that integrates safety, sustainability, and socio-economic considerations into the design from the earliest stages of development. In the EU context, SSbD has been developed primarily for chemicals and materials, although its logic can inform wider technology and product development. SSbD is concerned with whether potential risks and sustainability burdens can be anticipated, reduced or avoided while design options are still open. SSbD is structured as an iterative process (Figure 7.1) that includes scoping, definition of the SSbD scenario, safety and sustainability assessment, evaluation, and documentation[16,23].

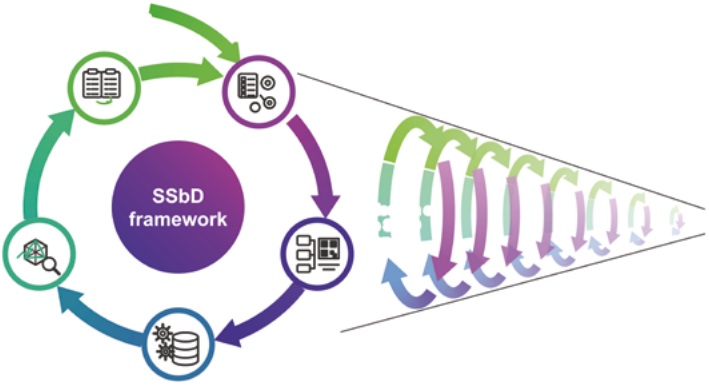

Figure 7.1 Safe and Sustainable by Design framework[16]

Many life cycle impacts are determined before a product reaches commercial scale[18]. LCSA strengthens SSbD by providing a life cycle perspective and facilitating the avoidance of burden shifting. For example, replacing a hazardous substance may improve safety, but the substitute may require scarce materials, energy-intensive processing, higher costs or problematic end-of-life treatment.

The main challenge is proportionality. At low technology readiness levels, complete data are rarely available, and full LCSA may be too demanding or uncertain. Screening approaches, scenario analysis and prospective LC(S)A may therefore be more appropriate than detailed comparative claims[18,24].

CIRCULAR ECONOMY AND LCSA

The concept of the *circular economy* provides an important context for the application of LCSA. This refers to an economic system in which the traditional end-of-life concept is replaced by strategies for reducing, reusing, recycling and recovering materials, that is, keeping products, components and materials in use and preserving value through the life cycle[25].

Circular economy approaches can operate at micro, meso and macro levels and are intended to support sustainable development for current and future generations[26]. Nevertheless, the circular economy is often interpreted narrowly through reduce–reuse–recycle activities, while its links to social equity and future generations are less consistently addressed[27].

Moreover, circularity should not automatically be interpreted as sustainability. A product system may close material loops while still generating high environmental impacts, excessive costs, or poor labour conditions. In this context, LCSA is used to assess whether circular strategies actually improve environmental, economic and social performance across the life cycle[28,29].

Circular LCSA extends this perspective by connecting circularity indicators with life cycle sustainability indicators. Circularity indicators are therefore treated as part of a broader assessment of life cycle performance (Figure 7.2)[10].

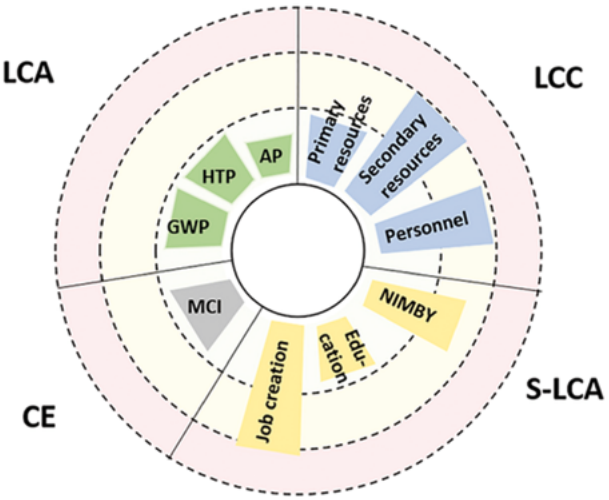

Figure 7.2 Possible visualisation of circular life cycle sustainability assessment[10]

The integration of LCSA and the circular economy is relevant for material-intensive technologies such as electronics, vehicles and energy infrastructure. Circular strategies may reduce primary raw material demand and end-of-life burdens, but they may also require new business models[6].

CRITICALITY ASSESSMENT

Criticality assessment is used to evaluate whether the supply of a material is vulnerable to disruption and how important that material is for a given system. For instance, at the product level, criticality assessment complements environmental LCA by examining whether required materials are vulnerable to supply chain disruption, geopolitical concentration, limited substitutability or other constraints[30].

Criticality assessment methods differ in their purpose, scale and compatibility with life cycle thinking (Table 7.2). Some approaches, such as the *NRC criticality matrix*[31] and the *European Commission critical raw materials method*[32], were developed mainly for policy and strategic resource governance, with a focus on supply risk, economic importance and the potential consequences of supply disruption.

Other assessment tools, such as *Geopolitical Supply Risk* (*GeoPolRisk*), *Economic Scarcity Potential (ESP)* and *ESSENZ*, are more directly compatible with product-level LCA because they can be linked to material flows in product systems:

- *GeoPolRisk*[33,34] is concerned mainly with geopolitical supply risk and its implications for product systems.
- *ESP*[35] evaluates the potential economic consequences of scarcity.
- *ESSENZ*[36] integrates a wider set of resource-related aspects, including availability, socioeconomic constraints and environmental considerations.

However, integrating criticality assessment into LCSA is methodologically challenging because criticality may be interpreted through the three sustainability dimensions. Criticality indicators also differ from conventional life cycle inventory flows and are not always compatible with existing characterisation models. In addition, the term "critical" carries a normative element, since it depends on the perspective from which it is judged[37].

Within LCSA, criticality represents an additional interpretive layer by adding a resource-security and supply-chain resilience perspective. This is the rationale behind the proposed framework *LC^{3}SA*, which extends Life Cycle Sustainability Assessment by integrating resource circularity and criticality alongside environmental, economic and social sustainability assessment[38]. The framework was created to address a key limitation of conventional LCSA: the fact that resource

availability, supply vulnerability and circularity performance are not always captured adequately by standard environmental, social or cost indicators.

Table 7.2 Criticality assessment methods and approaches[37]

Method / approach	Main purpose	Main criticality logic	Level of assessment	Main limitations
NRC criticality matrix	General raw material criticality assessment	Combines supply risk and impact of supply restriction	Economy / sector	Not directly product-level; limited LCA integration
EU Criticality Assessment/CRM method	Identification of critical raw materials for the EU	Combines economic importance and supply risk	EU economy / strategic value chains	Not directly for product-level LCSA
GeoPolRisk - Geopolitical Supply Risk	Product-level geopolitical supply risk assessment	Linked to raw material extraction and trade concentration	Product / technology	Focuses mainly on geopolitical supply risk
ESP - Economic Scarcity Potential	Economic consequences of raw material scarcity	Scarcity-related economic implications of resource use	Product / life cycle	Methodology difficult to communicate to non-specialists
ESSENZ	Integrated assessment of resource efficiency and criticality	Extends ESP by broader resource-related categories	Product / life cycle	Complexity and overlap with other LCSA
LCSA-criticality assessment	Integration of criticality into LCSA	Connects criticality indicators with LCSA assessment	Product / technology / value chain	Methodologically immature

Low-carbon and digital technologies often depend on materials characterised by concentrated supply, limited substitutability, or constrained recycling. Permanent magnets and photovoltaics rely on materials whose assessment requires environmental, economic, social, and supply-security evidence. Lithium, cobalt, nickel, and graphite, for example, present different concerns related to mining and refining concentration, price volatility, trade dependence, and social risks[6].

In the EU methodology, critical raw materials are identified mainly through the combination of economic importance and supply risk, with supply risk reflecting factors such as global and EU supply concentration, governance conditions, recycling, substitution potential and import dependency[32] (Figure 7.3).

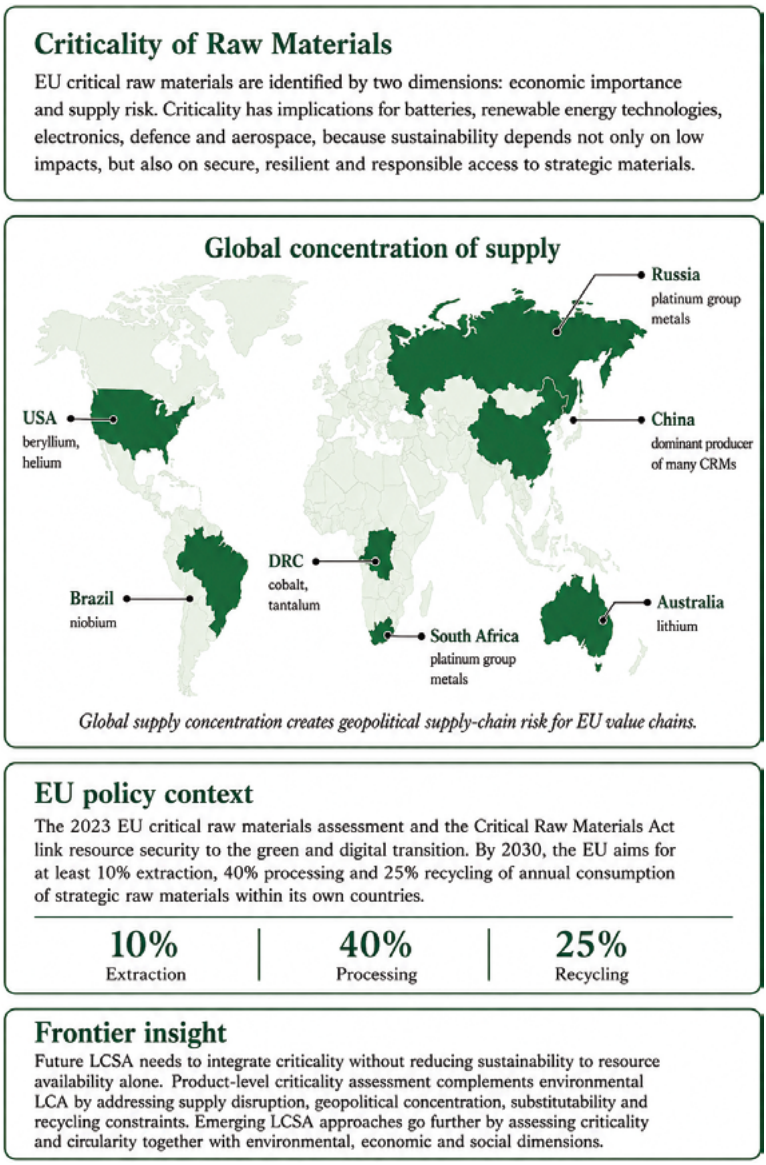

Figure 7.3 Countries accounting for largest share of global supply of CRMs[32]

ABSOLUTE SUSTAINABILITY

Conventional life cycle studies usually compare alternatives per functional unit to identify relative differences and potential burden shifting. However, relative improvement does not establish absolute sustainability: an option may outperform its reference system while still exceeding the ecological limits.

Under an assessment of *absolute sustainability*, whether a product, technology, organisation or sector operates within an assigned share of a safe operating space is evaluated. This space may be defined through planetary boundaries, carrying capacities or regional environmental limits. In an LCSA context, the absolute perspective shifts the question from "Which option performs better?" to "Is this option compatible with defined sustainability limits?"[39,40].

In environmental LCA, this shift has been advanced through carrying-capacity-based normalisation, absolute environmental sustainability assessment, and planetary-boundary-based LCIA. Carrying-capacity-based normalisation develops reference values at midpoint level[39], while planetary-boundary-based LCIA links product-system impacts to assigned shares of the safe operating space[41] (Figure 7.4). Operational methods for absolute social and economic sustainability remain much less developed.

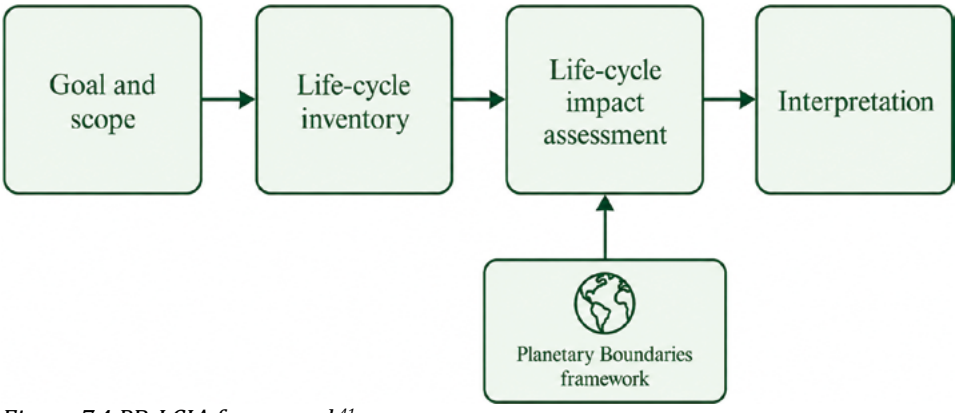

Figure 7.4 PB-LCIA framework[41]

Assessing absolute sustainability involves normative choices about how planetary boundaries are translated and allocated to products, organisations or individuals. These choices shape the results because planetary boundaries do not map directly onto product-level LCA indicators[42].

POLICY-RELEVANT AND DATA-DRIVEN LCSA

LCSA can inform evidence for sustainability governance and accountability. This evidence can be used to demonstrate whether products and organisations meet applicable sustainability requirements[43].

In the EU context, it is visible in product policy instruments such as the Ecodesign for Sustainable Products Regulation and Digital Product Passports, which have created the demand for product-level information on durability, recycled content, and environmental performance[44].

The Ecodesign for Sustainable Products Regulation establishes a general framework for digital product passports as part of broader ecodesign requirements, while battery passports are specifically regulated under Regulation (EU) 2023/1542 on batteries and waste batteries[45]. These passports could, in LCSA terms, improve access to information on composition, performance, repairability, recycled content, environmental impacts, circularity and compliance, underlining the need to translate LCA-related information into verifiable data requirements for digital battery passport platforms[46].

The policy relevance of LCSA is also visible in strategic resource governance. The Critical Raw Materials Act, for example, links clean technology deployment to circular material supply chains, including 2030 benchmarks for extraction, processing and recycling capacities[47].

At the corporate level, the CSRD and ESRS maintain the role of value-chain sustainability information in reporting, while the Green Claims initiative aims to require environmental claims to be substantiated through science-based and verifiable methods[48]. Beyond product-level policy, life-cycle approaches are also relevant for energy-transition planning, as in policy-oriented comparison of future energy scenarios[49].

Part of the infrastructure needed to respond to these policy and reporting demands is provided by *digitalisation*, which has been reshaping LCSA by improving the availability and processing of life cycle data.

One persistent barrier to LCSA is data fragmentation, as environmental inventory data, cost data, circularity data and social data are often collected by different actors, stored in different formats and reported at different levels of detail. Data fragmentation limits comparability, making it difficult to integrate environmental LCA, LCC and S-LCA into one coherent framework[1,7]. Digital tools can partly address this problem by enabling structured data exchange across supply chains and automated inventory development.

Several software environments can support LCSA-related workflows, although most are primarily designed for environmental LCA. Tools such as *SimaPro*, *openLCA*, *Sphera* LCA for Experts and *Brightway* are widely used for life cycle inventory modelling, impact assessment, scenario analysis and uncertainty-related calculations. *Umberto* supports material-flow and process-oriented modelling, whereas *One Click LCA* is suitable for building and construction-related assessments[50].

These software tools are often combined with external databases, including *ecoinvent* for environmental inventory data, *SHDB* and *PSILCA* for social risk and Social LCA data, and *EXIOBASE* for environmentally extended input–output analysis. The software and database landscape are rapidly evolving, envisioning automated data exchange and AI involvement.

Artificial intelligence is relevant for LCSA and LCA data workflows, with machine learning used to support life cycle inventory development, life cycle impact prediction, data gap filling, and uncertainty analysis. Recent reviews highlight the potential of AI tools to improve computational efficiency and identify patterns in complex life cycle datasets[51,52].

Further applications include data cleaning, inventory-flow classification, literature-based data extraction, hotspot screening, and scenario generation; AI-generated data nevertheless require verification, since models may reproduce database biases, provide poorly documented estimates, or create false precision.

While digitalisation can strengthen LCSA by improving data processing, its application requires methodological judgement and critical evaluation to prevent oversimplified sustainability labels or unsupported single-score claims.

THE FUTURE OF LCSA IN RESEARCH AND INNOVATION

LCSA's future role is bound by its capacity to support research and innovation before sustainability problems become locked into products, technologies and infrastructures. Since key decisions about research are often made at early development stages, LCSA can function as a forward-looking framework for responsible innovation.

Future LCSA applications will need to connect comparative assessment with explorative questions of absolute sustainability, circularity, criticality and long-term transition pathways. Consequently, the question is not only which option performs better, but whether a technology is compatible with environmental limits, economic feasibility and social responsibility. However, sustainability must not be reduced to a simplified label.

Digitalisation, product passports, AI, and traceability systems will all improve the availability and processing of life cycle data. Digital and AI-assisted tools may reduce the effort required to assemble data, but LCSA practitioners remain responsible for the results.

RECOMMENDED READINGS

Topic	Recommended reading
Methodological challenges and implementation experience	Costa, Quinteiro and Dias (2019). *A systematic review of life cycle sustainability assessment: Current state, methodological challenges, and implementation issues*[6]; Alejandrino, Mercante and Bovea (2021). *Life cycle sustainability assessment: Lessons learned from case studies*[13].
Prospective assessment of emerging technologies	Thonemann, Schulte and Maga (2020). *How to conduct prospective life cycle assessment for emerging technologies? A systematic review and methodological guidance*[12]; Arvidsson et al. (2024). *Terminology for future-oriented life cycle assessment: Review and recommendations*[17].
Anticipatory assessment and responsible innovation	Wender et al. (2014). *Anticipatory life-cycle assessment for responsible research and innovation*[20].
Safe and Sustainable by Design	Garmendia Aguirre et al. (2025). *Safe and Sustainable by Design Chemicals and Materials: Revised Framework*[16]; Caldeira et al. (2022). *Safe and Sustainable by Design Chemicals and Materials: Framework for the Definition of Criteria and Evaluation Procedure for Chemicals and Materials*[23].
Circularity and sustainability assessment	Luthin, Traverso and Crawford (2024). *Circular life cycle sustainability assessment: An integrated framework*[10]; Corona et al. (2019). *Towards sustainable development through the circular economy—A review and critical assessment on current circularity metrics*[28].
Raw material criticality and its integration into LCSA	Cimprich et al. (2019). *Raw material criticality assessment as a complement to environmental life cycle assessment: Examining methods for product-level supply risk assessment*[30]; Hackenhaar et al. (2024). *A comprehensive framework covering life cycle sustainability assessment, resource circularity and criticality*[38].
Absolute environmental sustainability	Bjørn et al. (2020). *Review of life-cycle-based methods for absolute environmental sustainability assessment and their applications*[40]; Paulillo and Sanyé-Mengual (2024). *Approaches to incorporate planetary boundaries in life cycle assessment: A critical review*[42].

Topic	Recommended reading
Digital product passports	Jensen et al. (2023). *Digital product passports for a circular economy: Data needs for product life cycle decision-making*[44]; Haupt, Cerdas and Herrmann (2024). *Derivation of requirements for life cycle assessment-related information to be integrated in digital battery passports*[46].
Machine learning in life cycle assessment	Romeiko et al. (2024). *A review of machine learning applications in life cycle assessment studies*[51]; Neupane et al. (2025). *Machine learning algorithms for supporting life cycle assessment studies: An analytical review*[52].
Temporal dynamics	Dynamic LCA: temporal aspects such as when emissions occur and how their impacts develop Levasseur et al. (2010)[53], Beloin-Saint-Pierre et al. (2020)[54], Müller et al (2025)[55].

REFLECTION & EXERCISES

Exercise 1. Assessment approach

A research team is assessing a novel technology that is still at the pilot scale. The assessment combines scenario modelling with consideration of future recycling systems, stakeholder concerns, and potential policy implications.
Which term best describes this assessment approach?
A. Conventional ex-post LCA
B. Attributional LCA
C. Anticipatory LCSA
D. Gate-to-gate LCA
E. Environmental hotspot screening.

Answer: C
The approach is best described as anticipatory LCSA because it examines an emerging technology through future scenarios and uncertainty while considering wider sustainability and societal implications. Attributional modelling is not inherently retrospective; modelling approach and temporal positioning are separate methodological choices. However, attributional LCA alone does not capture the broader anticipatory scope described here.

Exercise 2. Safe and Sustainable by Design

A manufacturer is developing a novel process and must select one of two process routes before proceeding to pilot-scale production:
Option A uses a solvent with lower toxicity concerns but requires higher processing temperatures and greater energy input.
Option B uses a more hazardous solvent but requires less energy, involves fewer processing steps, and enables better recycling of the coated product.
Apply the SSbD framework to compare the options:
A. Identify the relevant steps of the SSbD framework and explain how they should be applied to the two process routes.
B. Explain why the safer option is not necessarily more sustainable and why the more resource-efficient option is not necessarily safer.
C. Recommend which additional data and assessment methods are needed before selecting one option for pilot-scale development.

Answer guidance: The iterative SSbD sequence should be applied: scoping analysis, selection of an appropriate screening scenario, safety assessment, environmental and socio-economic sustainability assessment, evaluation, and documentation. Solvent hazards and exposure risks should be compared with energy demand, emissions, material efficiency, costs, performance, and recyclability across the life cycle.
Option A may reduce toxicity risks but increase energy-related impacts, while Option B may be more resource-efficient yet present unacceptable risks to workers or the environment. Further evidence on hazards, exposure, process emissions, energy sources, yields, costs, product performance, and end-of-life scenarios is therefore required before either option can be recommended.

Exercise 3. Circularity and sustainability

A company claims that its new product is "more sustainable" because it contains 30% recycled material and is designed for easier disassembly.
Critically evaluate this claim by comparing circularity metrics with LCSA. In your answer:
A. Identify the product characteristics that circularity metrics would primarily capture.
B. Explain which additional environmental, economic, and social questions would be examined through LCSA.

Answer guidance: Circularity metrics primarily capture material-related features, including recycled content, material efficiency, durability, repairability, disassembly, reuse, and recyclability. LCSA would additionally examine environmental impacts, life-cycle costs, and social effects across the product's full life cycle.
For example, processing recycled material may require more energy or generate higher emissions than using primary material. Easier disassembly may also increase production costs or involve hazardous and poorly controlled work during recovery. Greater circularity can therefore support sustainability, but it is not sufficient evidence of improved overall sustainability.

Exercise 4. Criticality in LCSA

Select one critical raw material used in an energy, mobility, or digital technology, such as lithium, cobalt, nickel, graphite, rare earth elements, or iridium.
A. Explain why the material may be considered critical.
B. Identify which related environmental and social concerns would need to be assessed through LCA and S-LCA.

Answer guidance: Criticality should be distinguished from environmental, economic, and social performance. Supply concentration, import dependence, substitutability, recycling constraints, price volatility, and vulnerability to disruption should be considered alongside environmental impacts, life cycle costs, labour conditions, human rights, and effects on local communities. Explain that criticality assessment complements LCA, LCC, and S-LCA by adding a resource-security perspective.

Exercise 5. AI-supported LCSA

Artificial intelligence (AI) is increasingly used to support the collection, processing, and interpretation of data for life cycle-based sustainability assessments.

A. Select and explain three ways in which AI could support an LCSA study.

B. For each application, identify one potential benefit and one methodological risk.

C. Explain why AI-generated data, assumptions, and interpretations require thorough source verification, and expert review.

Answer guidance: Each AI application should be connected to a specific stage or challenge of LCSA. For example, AI may accelerate literature-based data extraction, estimate missing inventory values, identify patterns across environmental, economic, and social results, or generate alternative technology scenarios. Relevant risks include fabricated or outdated information, biased training data, inappropriate proxies, concealed assumptions, weak traceability, false precision, and limited reproducibility. AI should therefore be treated as a supporting tool rather than an autonomous decision-maker, with its outputs validated against reliable sources, documented transparently, and reviewed by relevant methodological and domain experts.

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CONCLUSION

With this work we introduce the concepts of sustainability and Life Cycle Thinking, with the core of the book devoted to Life Cycle Sustainability Assessment and its three dimensions: environmental LCA, Life Cycle Costing, and Social LCA. Emerging trends and challenges are covered in the final section, while the concepts and methods are explained throughout in an integrated and accessible way.

However, the book also provides a broader reflection on the value of adopting a life cycle perspective. Although numerous definitions, methods, approaches, and detailed procedures are already available, the ability to step back and maintain perspective remains equally important. We should not become lost in an overwhelming volume of numbers, scenarios, and simulations, but remain focused on broader sustainability goals and the specific decisions the data support.

What, then, is the central message of this book? It is an invitation to consider research and innovation within a broader context and from a life cycle perspective. If we are to build a more sustainable future, these considerations must enter the conversation not as an afterthought, but from the very first design decision.

LIST OF FIGURES

Chapter 1

Fig.	Figure title	Source/licence
1.1	From triple bottom line to the 3Ps	Compiled by the author, informed by Elkington (1997, 2018).
1.2	Global shortfalls and overshoots across doughnut boundaries	Reproduced from Fanning and Raworth (2025) under CC BY 4.0.
1.3	SDG wedding cake	Reproduced from Azote for Stockholm Resilience Centre, Stockholm University, under CC BY-ND 3.0.
1.4	Research frontier: steering emerging technologies under uncertainty	Compiled by the author, based on the TwinVECTOR project deliverable Guidelines for Sustainability Assessment (2025). AI-assisted.

Chapter 2

Fig.	Figure title	Source/licence
2.1	Life cycle stages	Adapted by the author from the Life Cycle Initiative (2026).
2.2	Life cycle-based concepts	Compiled by the author, based on Valdivia and Sonnemann (2024).
2.3	Levels of LCT application	Compiled by the author.
2.4	Sustainability assessment principles	Adapted by the author from the TwinVECTOR project deliverable Guidelines for Sustainability Assessment (2025). AI-assisted.

Chapter 3

Fig.	Figure title	Source/licence
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3.2	LCA system-boundary definitions	Compiled by the authors.
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4.3	Phases of environmental LCC	Compiled by the author.
4.4	Research frontier: applied levelised cost of energy storage	Compiled by the author, informed by the work undertaken in the SMHYLES Horizon Europe project. AI-assisted.

Chapter 5

Fig.	Figure title	Source/licence
5.1	S-LCA principles	Compiled by the authors, informed by UNEP guidance and Valdivia et al. (2021).
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5.3	Key S-LCA terms	Compiled by the author, informed by Parent et al. (2010), ISO 14075:2024, Sureau et al. (2018), and Di Cesare et al. (2018).
5.4	Methodological framework of ISO 14075	Author's conceptualisation informed by ISO 14075:2024.
5.5	Product functions and functional unit in S-LCA	Compiled by the author.
5.6	S-LCA data input types	Compiled by the author.
5.7	Research frontier: S-LCA in the SMHYLES project	Compiled by the author for the SMHYLES Horizon Europe project. AI-assisted.

Chapter 6

Fig.	Figure title	Source/licence
6.1	UNEP/SETAC LCSA equation	Compiled by the author, informed by Kloepffer (2008) and UNEP/SETAC Life Cycle Initiative (2011).
6.2	Key LCSA references	Compiled by the author, informed by the cited LCSA literature.
6.3	Ten LCSA principles	Adapted by the authors from Valdivia et al. (2021) under CC BY 4.0.
6.4	System boundaries in LCSA	Adapted by the authors from UNEP/SETAC Life Cycle Initiative (2011).
6.5	LCSA inventory data at unit-process and organisation levels	Adapted by the authors from UNEP/SETAC Life Cycle Initiative (2011).
6.6	Visualisation approaches for LCSA results	Compiled by the author, informed by the common LCSA visualisation approaches.
6.7	Research frontier: LCSA approach in the SOLiD project	Compiled by the authors for the SOLiD Horizon Europe project.

Chapter 7

Fig.	Figure title	Source/licence
7.1	Safe and Sustainable by Design framework	Reproduced from Garmendia Aguirre et al. (2025), © European Union, 2025.
7.2	Possible visualisation of circular LCSA results	Reproduced from Luthin, Traverso and Crawford (2024) under CC BY-NC-ND 4.0.
7.3	Countries accounting for the largest share of global CRM supply	Map adapted by the author from European Commission (2023), © European Union, 2023.
7.4	PB-LCIA framework	Created by the author, informed by Ryberg et al. (2018).

SUMMARY

This compendium provides a concise, research-oriented guide to Life Cycle Sustainability Assessment. It introduces the conceptual foundations of Life Cycle Thinking and explains how environmental LCA, life cycle costing, and social LCA can be combined to assess sustainability across the life cycle.

The book connects Life Cycle Sustainability Assessment with current developments relevant to sustainability research and innovation, including the European Green Deal, Digital Product Passport, Safe and Sustainable by Design approaches, circularity, critical raw materials, and emerging technologies.

Structured exercises, visual templates, and "Research frontier" boxes support learning and engagement of readership. The book is intended for researchers, doctoral students, innovators, and practitioners who need a straight-forward introduction to Life Cycle Sustainability Assessment as a method for sustainability-oriented analysis.

METHODOLOGY

This research-oriented monograph adopts an interdisciplinary methodology to explain Life Cycle Sustainability Assessment (LCSA) and its application in sustainability-oriented research and innovation. It combines conceptual synthesis with comparison of methods.

The book is based primarily on a structured review of scientific literature, internationally recognised standards, methodological guidelines, and relevant European policy documents. Sources were chosen for their scientific quality and their relevance to contemporary research and innovation. Particular attention was devoted to guidance developed by ISO, the European Commission, UNEP, SETAC, and the Life Cycle Initiative. This book does not present a systematic literature review and therefore does not aim to provide an exhaustive analysis of the field.

A predominantly deductive approach was used, shifting from established concepts of sustainability and Life Cycle Thinking, through the individual assessment methods, to their integration within LCSA. This structure is complemented by critical comparison and synthesis to identify methodological limitations and emerging research challenges. It connects environmental assessment with economics, social sciences, policy, and innovation studies.

The chapters follow a step-by-step structure that moves from conceptual foundations to individual methods, integrated assessment, and emerging applications. Technology-related examples illustrate methodological choices and challenges. Exercises and Research Frontier boxes help readers apply LCSA concepts in practice.

BOOK CONTRIBUTION

Life Cycle Sustainability Assessment (LCSA) sits at the intersection of established methodology and open research questions. This book is intended for readers working at that intersection. The book's novel contribution lies in bringing the established LCSA methods together in an accessible guide for research and innovation. It connects methodological choices with examples from emerging technologies. The book also provides LCSA links toward circularity, critical raw materials, emerging technologies, and Safe and Sustainable by Design.

What distinguishes this book from much of the existing LCSA literature is the integration of diverse methods. The book further connects LCSA with current European sustainability policies and innovation frameworks. Exercises, reflection questions, and Research Frontier boxes were designed to encourage next generation of students and researchers to move beyond applying established methods and toward the identification of sustainability-oriented research questions.

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Finally, to the students and early-career researchers who will carry life cycle thinking further than this book does: may these pages be a starting point, not a limit.

AUTHORSHIP

Viera Pechancová 90% (Book concept, Chapters 1–2, 4–7)
Debashri Paul 10% (Chapter 3)

DECLARATION OF AI ASSISTANCE

During the preparation of this book, the authors used ChatGPT (OpenAI) to assist with refining selected passages related to language editing, reference discovery, and the creation and revision of selected illustrations. The author reviewed and revised the AI-assisted material and takes full responsibility for the accuracy, integrity, and originality of the published content.

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REVIEWERS

REVIEWER 1

"An accessible and well-structured introduction to LCSA, offering readers a clear pathway into its concepts, methods, and applications. The recommended readings and reflection exercises further support learning by deepening key concepts and connecting them with practical applications."

Dr. Yolanda Lechón. Research Professor at CIEMAT

REVIEWER 2

"A clearly structured and accessible introduction to life cycle sustainability assessment, connecting LCA, LCC and S-LCA with emerging technologies and current European policy. A good starting point for students and researchers in the field of sustainability assessment."

Dr. Manuel Baumann, principal investigator at KIT-ITAS

BACK BOOK COVER (OF PAPERBACK BOOK)

This book provides a concise, research-oriented guide to Life Cycle Sustainability Assessment (LCSA). It introduces the foundations of sustainability and Life Cycle Thinking, explains environmental life cycle assessment, life cycle costing, and social Life Cycle Assessment, and discusses their integration.

Adopting a research and innovation perspective, the book connects LCSA with current developments in sustainability policy, circularity, critical raw materials, and emerging technologies. Exercises, reflection prompts, and research frontier boxes encourage active learning.

The book will be of interest to students, researchers, and innovators seeking a straightforward introduction to LCSA as a framework for sustainability-oriented analysis and decision support.

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