LIFE CYCLE ASSESSMENT (LCA) AND THE CIRCULAR ECONOMY

Aspects that require special attention
NICER Programme Insight Report

Irene Josa[1,2], Xiaocheng Hu[3], Benoit Chachuat[4], Andrew Abbott[5], Phil Purnell[6], Aiduan Borrion[1]

CE-HUB
UKRI National Interdisciplinary Circular Economy Research

NICER PROGRAMME

University of Exeter

UK Research and Innovation

Contents

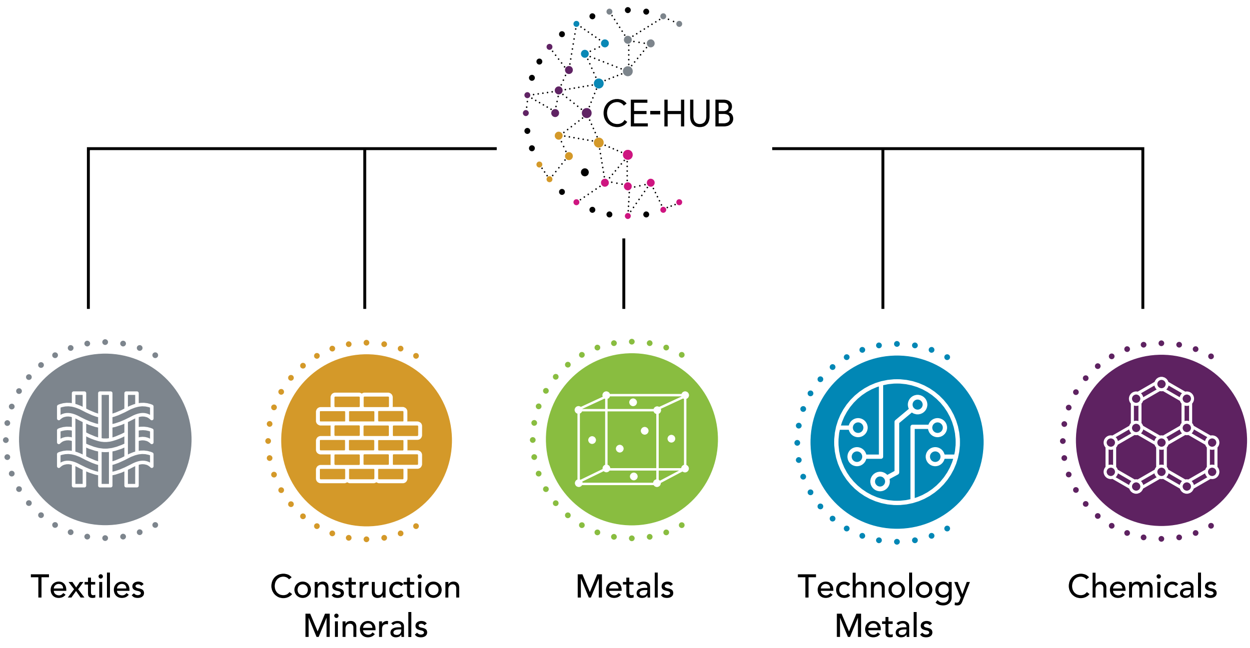
1 Department of Civil, Environmental & Geomatic Engineering, University College London; **2** (now) The Bartlett School of Sustainable Construction, University College London. **3** Green Future Solutions & Engineering Department, Faculty of Environment, Science and Economy, University of Exeter. **4** The Sargent Centre for Process Systems Engineering, Imperial College London. **5** School of Chemistry, University of Leicester. **6** School of Civil Engineering, University of Leeds.

About the National Interdisciplinary Circular Economy Research Programme

The National Interdisciplinary Circular Economy Research (NICER) programme is a £30 million four-year investment from UKRI and the Department for Environment, Food & Rural Affairs (DEFRA) to deliver the research, innovation and evidence base needed to move the UK towards a circular economy. Launched in January 2021 and comprising initially of 34 universities and over 150 industrial partners, NICER is made up of five Circular Economy Research Centres each focused on a specialty material flow, and the coordinating CE-Hub:

- The National Interdisciplinary Circular Economy Research Hub (CE-Hub), led by the University of Exeter
- The Textiles Circularity Centre (TCC), led by the Royal College of Art
- The Interdisciplinary Circular Economy Centre for Mineral-based Construction Materials (ICEC-MCM), led by University College London
- The National Interdisciplinary Centre for the Circular Chemical Economy (CircularChem), led by Surrey University
- The Interdisciplinary Circular Economy Centre for Technology Metals (Met4Tech), led by the University of Exeter
- The Interdisciplinary Centre for Circular Metals (CircularMetal), led by Brunel University London

NICER is the largest and most comprehensive research investment in the UK Circular Economy to date. It has been delivered in partnership with industrial organisations from across sectors and DEFRA to ensure research outcomes contribute to the delivery of industrial implementation and government policy. A core aim of the programme is growing the Circular Economy community through a significant programme of outreach and collaboration.

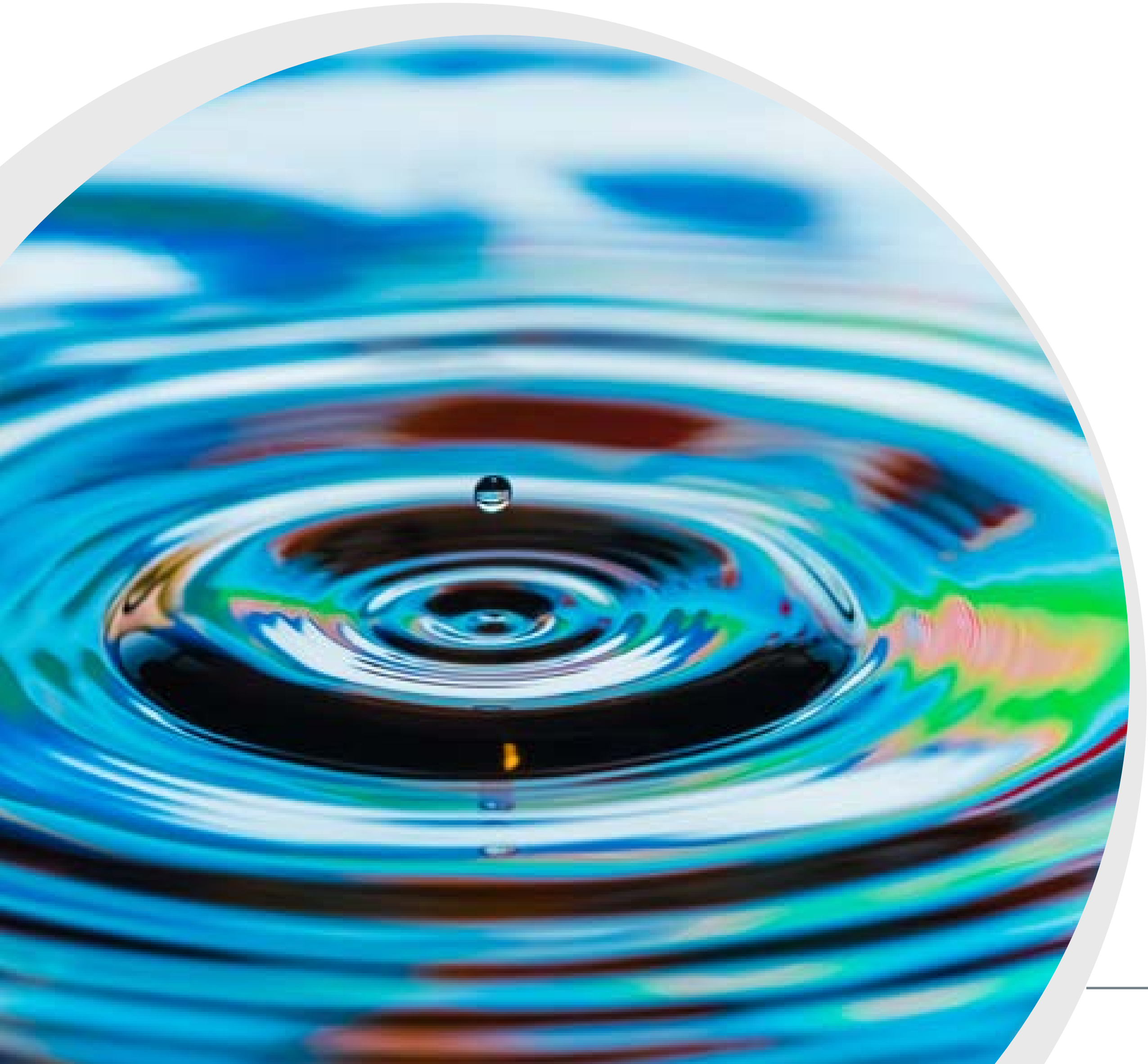


About the NICER Insight Reports series

The objectives of the NICER programme are to:

1. Accelerate understanding and solutions to enable circularity of specific resource flows,
2. Provide national leadership, coordinate and drive knowledge exchange across the programme as a whole and with policy, consumer, third sector and business stakeholders,
3. Ensure research is embedded with stakeholders by involving businesses, policymakers, consumers and society, the third sector, and other affected groups and communities at every part of the programme.

The transition towards a UK circular economy requires a whole system approach. This means that, in addition to accelerating knowledge at the resource and sector level, there are a number of agnostic system level enablers or drivers that can be applied to accelerate adoption at scale. The purpose of the NICER Insight Report Series is therefore to highlight learning from across the NICER Programme in relation to these system wide enablers. Small and Medium Enterprises and the Circular



Introduction

Life cycle assessment (LCA) is a powerful tool for evaluating the impacts of a product or service throughout its entire lifespan (International Organization for Standardization [ISO] 2006a; ISO 2006b). A product life cycle can include everything from the extraction of raw materials, through manufacturing and use, to the management of a product at end-of-use (Figure 1). LCA most commonly examines environmental impacts, including resource use, and emissions to impacts on the biosphere, based on the energy materials and other inputs over the life cycle. It may also include assessment of economic and social impacts, such as life cycle costs, labour practices and community well-being. LCA enables identification of impact hotspots within the life cycle, helping businesses and organisations make informed decisions about design, production, and end-of-use strategies.

The Circular Economy presents a compelling alternative to the traditional linear "take-make-dispose" model. It offers a vision of sustainable resource use, whereby products, components and materials are maintained at their highest utility and value at all times and scales, with continual interlinked cycling of man-made materials, and cascading cycling of biological materials to ultimately nourish the earth. Its goals are greater economic stability, with more equitable sharing of resources, and maintenance of consumption and environmental impacts within planetary boundaries (Stegemann, 2017). This approach aligns well with the holistic perspective of LCA. LCA can be a valuable tool in implementing a Circular Economy, as it can be used to assess the benefits of various circular strategies, such as product design for disassembly, and component or material reuse or recycling.

After receiving information from all the NICER centres that carried out an LCA, a list of 10 key insights has been collated. The insights have been divided into four areas (Figure 1):

- Scoping
- Methodology
- Data
- Communication

Examples for each of the insights are given in boxes, with colour coding for outcomes from each NICER centre as follows:

Textiles Circularity Centre (TCC)

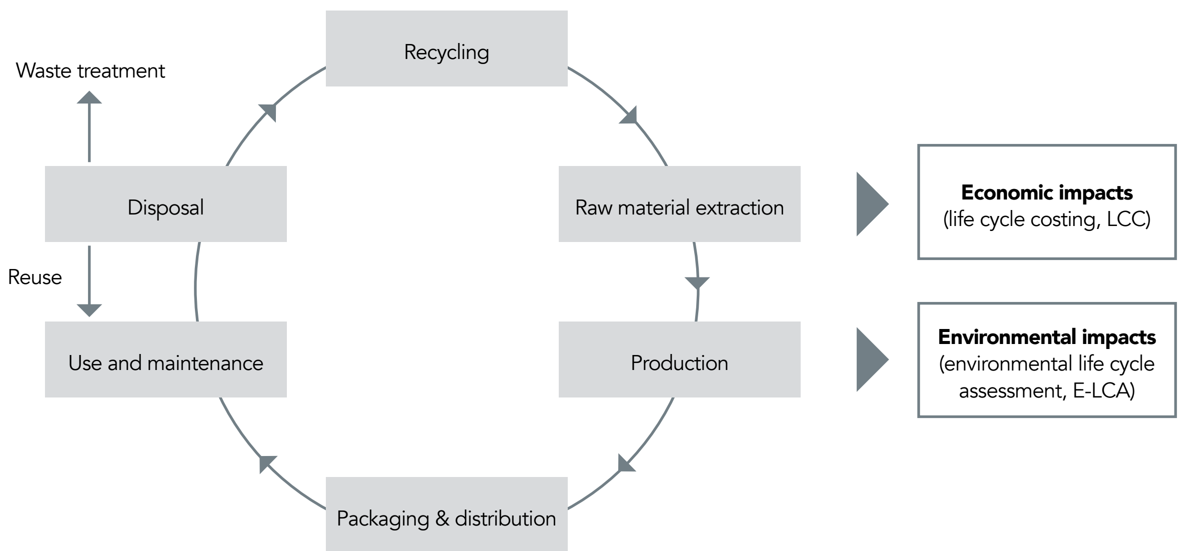
Interdisciplinary Circular Economy Centre for Mineral-Based Construction Materials (ICEC-MCM)

Circular Metal

Met4Tech

Circular Chem

Figure 1. Generic representation of LCA



Summary of insights

Scoping

1. Adopt a life cycle perspective for holistic evaluation
2. Define system boundaries and functional units for consistent and transparent analysis
3. Pay attention to supporting processes
4. Consider social behaviour to prevent unintended consequences

Methodology

5. Appropriately expand the system and/or allocate impacts
6. Understand material flows for reliable analysis

Data

7. Manage uncertainties, especially in scaling early-stage technologies
8. Consider geography

Communication

9. Communicate assumptions, scope, and generalizability
10. Be aware of the limitations of LCA

Insight One

Adopt a life cycle perspective for holistic evaluation

Circular Economy practices must often be implemented in complex, interconnected systems with intentional design of products to extend their lifespan and facilitate reuse or recycling. Widespread implementation of a Circular Economy entails overcoming multifaceted challenges in such systems, which impede progress in closing material, component, and product loops.

Systems thinking is key in comprehending resource recovery systems to drive profound transformative change (Iacovidou et al., 2021). Beyond merely closing loops, transformational change must foster sustainability throughout resource exploitation, usage, and management.

Embracing a system-of-systems perspective enables a thorough examination of internal and external subsystem elements and their interrelationships, considering cultural, temporal, and spatial dynamics. Systems thinking underpins various theories, ontologies, and tools aimed at overcoming obstacles and facilitating the transition to a circular, sustainable future. By amalgamating such approaches, disciplinary barriers can be overcome, to enable a transdisciplinary understanding of the political, environmental, economic, social, and technical dimensions of resource production, usage, and management.

A life cycle perspective enables a holistic understanding of the impacts across all stages of a system, preventing unintended consequences and promoting the sustainable design of products and processes. In the life cycle perspective, all relevant stages and impact categories need to be considered to avoid burden shifting (in which impacts are transferred to a different part of the system rather than removed).

Degradation of materials across cycles

Mechanical recycling often results in a loss of quality, as seen with plastic bags. Typically, there is a limit to the number of times a material can undergo mechanical recycling due to the degradation of its properties. In molecular recycling, materials are broken down to their basic molecular components and reconstituted, effectively restoring them to their original quality. Yet molecular recycling uses more energy and produces more emissions.

Consistent, transparent and unbiased examination of the whole life cycles of these alternatives (e.g., degradation of materials across cycles) within comparable system boundaries is crucial to enable decision-making.

Impact assessment at different supply chain levels

In a study by Josa & Borrion (under review), an LCA was conducted at different levels of the concrete supply chain, from the production of 1 tonne of cement, to 1 m^3 of concrete, to the construction of 1 m^2 of a building.

This approach enabled conclusions regarding the impacts associated with products considering different system boundaries. The results showed that the scenarios analysed could reduce greenhouse gas emissions of cement, concrete, and a reinforced concrete building by up to 35%, 37%, and 29%, respectively.

Thus, different system boundaries were used to identify downstream impacts.

Insight Two

Define system boundaries and functional units for consistent and transparent analysis

System boundaries delineate the flows and processes that are included or excluded from the LCA, to enable capture of the entirety of relevant processes and interactions by the analysis.

Functional units quantify the product or service that is the subject of an LCA, providing a reference to which the inputs and outputs can be related. They provide a consistent measure for comparing impacts of alternative products or services (e.g., use of paper cups or china cups to deliver the service of a beverage) within the same system boundary.

Circular Economy models aim to reduce primary resource use and waste by closing resource loops. Defining appropriate system boundaries and functional units for LCA is crucial for capturing the environmental impacts of interest in relation to implementation of circular practices, including all relevant upstream processes (e.g., material extraction) and downstream processes (e.g., recycling and disposal). Iteration of the LCA, including and excluding different parts of the system, can help to identify the processes with most impact, and define an appropriate system boundary (Insight Five).

Clear system boundaries and functional units help to enable stakeholders in making transparent and informed decisions that contribute to the advancement of a sustainable Circular Economy.

Appropriate system boundary and functional unit in battery production

Battery production typically includes unrecorded elements, such as the crucial hexafluorophosphate (PF6) component. It is therefore important to delineate appropriate system boundaries for LCA, which enable assessment of the potential repercussions of overlooking such critical components in the production process.

Different LCA studies of batteries might also use different functional units as well as different system boundaries. For example, one study might use 1 kg of battery as the functional unit for the production phase, while another might use 1 kWh of battery capacity as the functional unit for the use and end-of-life phases. This inconsistency in functional selection can make it difficult to conduct comprehensive literature reviews, perform comparative analyses, or incorporate data from the existing literature for further studies.

A targeted system boundary for olefin production

In most studies conducted by CircularChem, the scope was not "cradle to grave" (from raw material extraction to end-of-life disposal). For example, in fuel-related studies, the focus was often up to the point of the fuel reaching the tank, excluding the use phase. This limitation of the system boundary is consistent with the focus of CircularChem research on production of olefins. In this case, a more targeted approach helps to better understand the life cycle impacts of production of specific chemical components.

Insight Three

Pay attention to supporting processes

Circular practices often rely on processes that support primary activities, like transportation and electricity. Therefore, giving special attention to these processes in LCA enables a more accurate assessment of the environmental impact associated with the product or service under study.

Impact of energy sources

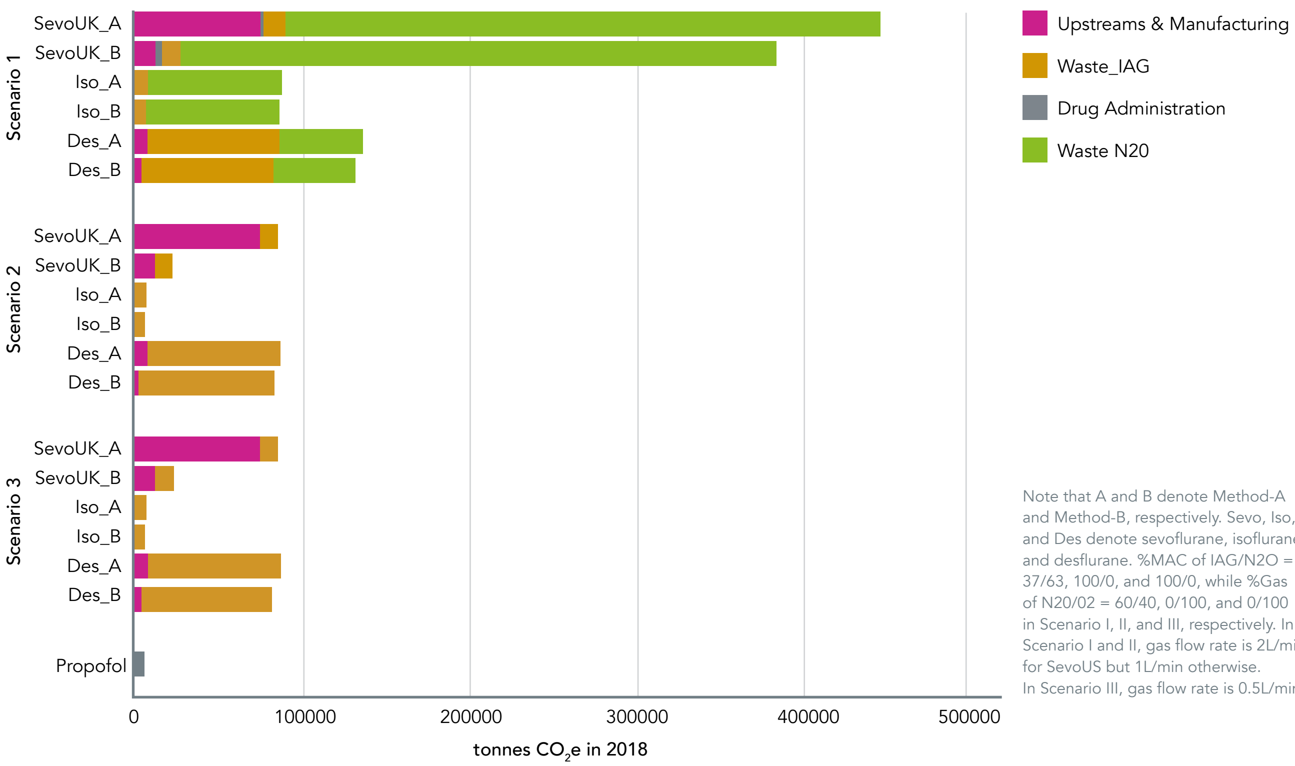
Leonzio et al. (2023) performed an economic and global warming potential assessment for ethylene production by carbon dioxide electro-reduction and methanol-to-olefin processes, with methanol obtained in several ways. In this study, four different sources of electricity were considered, namely solar, wind, nuclear energy from a small modular reactor, and nuclear energy with a large-scale plan. Significant differences were found when considering different electricity sources.

Inclusion of supporting processes may be challenging as data is often missing, often, e.g., due to commercial sensitivities, regarding the electricity usage of conveyor belts, vacuum conditions, power for shredding, or yields; or limitations in information about supply chains or databases regarding electricity mixes. Assumptions are often made regarding supporting processes, which magnifies the potential uncertainties; e.g., results for a study of the same system, but with average electricity mixes from different years may differ significantly.

Impacts from upstream manufacturing processes

Hu et al. (2021) shed light on the disproportionate contribution of upstream manufacturing processes to the carbon footprint of a UK anaesthetic (Fig. 2). This perspective underscores the need for assessments that encompass all facets of a product's life cycle.

Figure 2. Carbon Footprints of anaesthetics used in the UK, 2018 (Hu et al., 2021)



Note that A and B denote Method-A and Method-B, respectively. Sevo, Iso, and Des denote sevoflurane, isoflurane, and desflurane. %MAC of IAG/N2O = 37/63, 100/0, and 100/0, while %Gas of N20/02 = 60/40, 0/100, and 0/100 in Scenario I, II, and III, respectively. In Scenario I and II, gas flow rate is 2L/min for SevoUS but 1L/min otherwise. In Scenario III, gas flow rate is 0.5L/min.

Insight Four

Consider social behaviour to prevent unintended consequences

In supporting Circular Economy transitions, understanding social behaviour is essential to prevent unintended consequences that may arise from consumer behaviour, work practices, and societal norms, which may be ingrained and hard to change, or highly dynamic. Incorporating social considerations into LCA enables consideration of pertinent effects, reducing the risk of rebound or backfire effects stemming from complex social dynamics. As Iacovidou et al. (2021) underscore, "despite the numerous benefits associated with Circular Economy, substantial challenges persist, deeply entrenched within prevailing systems."

One approach to addressing social considerations in LCA is to use consistent inventories of energy and material inputs across assessment of economic, environmental, and social impacts. This approach ensures that social indicators, such as job creation, are integrated seamlessly into the analysis, providing a holistic understanding of the impacts of Circular Economy initiatives. For instance, in the field of carbon capture, researchers have applied this methodology to assess some of the social implications of implementing such technologies (Maselli et al., 2024).

However, challenges persist in understanding and addressing social behaviour within LCA frameworks. For instance, in the case of end-of-life management of batteries, consumer behaviour leads to logistical constraints that pose a significant barrier to battery recovery. The logistics of collecting. transporting, sorting, and processing small volumes of batteries are complex and costly, often rendering such endeavours economically infeasible. These challenges can be captured to some extent in the material flow analysis that underpins LCA (Insight Six), but are difficult to mitigate. Extended producer responsibility schemes aim to address these challenges by holding producers accountable for the end-of-life management of their products, but consumer participation remains a key issue.

Moreover, LCA studies can only provide static assessments of social behaviour impacts, overlooking the dynamic interplay between social behaviour and other aspects, including environmental outcomes. Understanding the dynamic nature of social behaviour and its interaction with environmental impacts is crucial for developing effective Circular Economy strategies.

Social factors in the recycling of critical metals and materials in low-carbon technologies

Zante et al. (2024) critically reviewed a set of chemical and physical tools for improved recovery of metals from various waste streams, with a strong focus on the renewable energy sector (wind turbines, solar cells) as well as lithium-ion batteries and catalysts for hydrogen production.

They emphasised that, in some instances, the enabling innovation facilitating new circular approaches outlined in their paper may be social and not technical in nature.

Insight Five

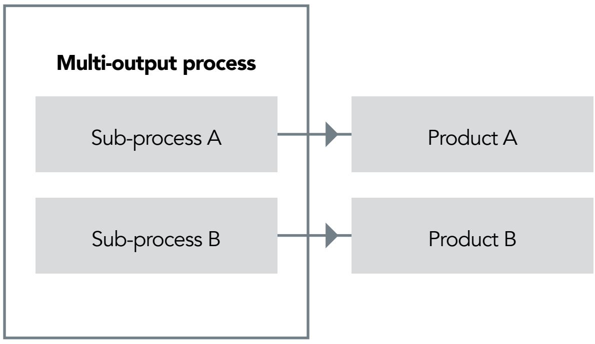
Appropriately expand the system and/or allocate impacts

The multifaceted nature of circular practices often involves multiple products or services sharing common resources. This means that there are often scenarios where multiple functions are performed by a single process or product (see Fig. 3).

In this context, system expansion is recommended to include the LCA modelling of the further fate of the by- products and wastes and the resulting changes (substitutions) in the product system. For example, in the case of waste incineration, where the process serves multiple purposes such as generating electricity and treating waste, practitioners aim to expand the system boundaries as much as possible to capture all relevant impacts.

Where expansion is not feasible, allocation provides a mechanism for the equitable distribution of environmental burdens and benefits among different stages of the life cycle. Allocation methods distribute environmental impacts among the different functions based on physical or economic criteria (e.g., mass, energy, exergy, carbon content, or monetary value). However, there is no one-size-fits all basis for allocation, as argued by Newman and Styring (2023). Thus, transparent reporting of allocation methods and assumptions is essential for ensuring the credibility and reproducibility of LCA results.

Figure 3. Representation of multi-output processes



Price or mass-based allocation for rare earth elements?

Rare earth elements (REEs) are used in various products such as magnets, motors, and vehicles. The environmental impact of mining REEs can vary depending on the difficulty of separating each element during processing. Additionally, market volatility can cause the prices of REEs to fluctuate. Thus, allocation of environmental impacts based on REE prices is not necessarily fair. A less expensive REE might actually have a higher environmental footprint than a more expensive one. Furthermore, price does not necessarily reflect the scarcity of a REE; rare and environmentally impactful REE might have lower prices due to limited demand. In this context, analysts often resort to mass allocation, which may not adequately capture the environmental impacts of REEs due to their low proportion in the final product.

Allocation approaches for chemical production

In the studies conducted by CircularChem, different allocation approaches for chemical co-products were used, i.e., allocation of environmental impacts on the basis of the masses of different products (Leonzio et al., 2023), or allocation of economic impacts based on the contributions of different products to their overall revenue (Nyhus et al., 2024), or based on the estimated cost of CO_2 capture for each point-source (Rodríguez-Vallejo et al., 2021).

Insight Six

Understand material flows for reliable analysis

Circular Economy models emphasise the efficient use and reuse of materials. Material flow analysis (MFA) – quantification of material flows through, and stocks in, the processes that comprise the system of interest (Myers et al., n.d.)– is thus essential in LCA to quantify the impacts of different life cycle stages. Understanding the impacts associated with material flows through resource extraction, use and recovery, provides insights into how circular practices can contribute to resource conservation.

However, it is often difficult to base LCA on a full MFA, due to gaps in the data needed to perform this analysis, which are often particularly difficult to overcome because of factors such as time constraints, poor integration and compatibility of data collection systems, and business sensitivities.

One of the key challenges in understanding material flows lies in tracking the fate of materials, particularly when they leave the formal economy. For example, a significant portion of scrapped vehicles in the UK disappears from the system, and these as well as small and valuable items, such as mobile phones, often end up in illegal markets or exported to other countries (Favarin et al., 2023; Kapoor et al., 2021).

A variety of techniques are available to bridge the data gaps in MFA (e.g., Myers et al., n.d.), but their use inevitably results in some uncertainty regarding the quantitative resource flows and an LCA that depends on them. It is critical to calculate or estimate, and report, the uncertainty associated with the resource flows in a system, since this affects the accuracy of the LCA.

It is important to engage with these challenges and resolve them to the extent possible, since a high quality MFA is fundamental to LCA and its application to identification of opportunities for resource efficiency and sustainable practices. Collaborative interdisciplinary efforts to improve data availability are essential for overcoming these challenges and advancing our understanding of material flows.

Using simulations to assess full scale impacts

Very often, LCA is conducted by comparing an emerging technology, such as carbon capture or ionic liquid production, with more traditional practice. In these cases, process simulation can be employed to model the foreground system (Bernardi et al., 2024). This simulation helps to estimate the inputs, emissions, and energy requirements if the emerging technology were scaled up. By doing so, a more accurate representation of the potential environmental impacts and efficiencies of the new technology compared to the established one can be achieved.

Impacts of Interventions in Textile Flows

The Textile Circularity Centre combined MFA with LCA and scenario modelling to assess the amount of clothing flowing in the UK economy and its environmental impact, and identify interventions to reach policy targets (e.g. the 2035 Carbon Budget). Of the 1 million tonnes of clothing consumed annually, 25% are reused in the UK, 40% enter residual waste and the rest are exported. Data on carbon emissions was highly variable, ranging from 15 to 40 Mt CO_2 per year from cradle to consumer. Despite this, scenario modelling made it clear that, on their own, cleaner production, increased recycling or less consumption will not achieve policy targets; all of these interventions must be combined.

Insight Seven

Manage uncertainties, especially in scaling early-stage technologies

Circular economy often involves the adoption of innovative technologies, such as those for resource recovery and recycling. The consideration of uncertainties is an important aspect of the MFA that underlies impact assessment (Insight Six); e.g., when resource flows for scaled-up early-stage technologies must be estimated for LCA of potential environmental impacts at full scale. In fact, uncertainty associated with the availability of data is a challenge for all steps of an LCA, and a lack of reliable quantitative information to characterize this uncertainty is also problematic. By breaking down the analysis into manageable steps and focusing on key variables, analysts can conduct indicative LCAs that provide valuable insights into the potential environmental impacts of scaling up innovative technologies.

Transparency of LCA, including understanding of the quality and uncertainty of inventory and impact data, is hampered by use of proprietary data hidden behind paywalls. Open inventory data would be preferred and such databases are being established, e.g., the Inventory of Carbon and Energy (ICE) database (Global Alliance for Buildings and Construction, 2024), though this is limited to carbon and energy.

Understanding and expressing uncertainties in LCA studies is essential for interpretation of their results in decision-making. It is therefore necessary to propagate uncertainties, e.g., arising from simulated scale-up of early-stage technologies, through all steps of the LCA, to the midpoint and endpoint impacts. Analysts often rely on specialised LCA software such as SimaPro (Goedkoop et al., 2008), which facilitates the propagation of uncertainty from background data for uncertainty analysis of the LCA results. However, it is worth noting that not all LCA software platforms offer this capability, highlighting the need for continued innovation and improvement in LCA methodologies and tools.

Another key challenge lies in accounting for uncertainties in impact assessment methods. While efforts have been made to propagate uncertainties from data inputs, uncertainties inherent in the impact assessment methods themselves are often overlooked. Addressing this gap is essential for ensuring the robustness and reliability of LCA findings.

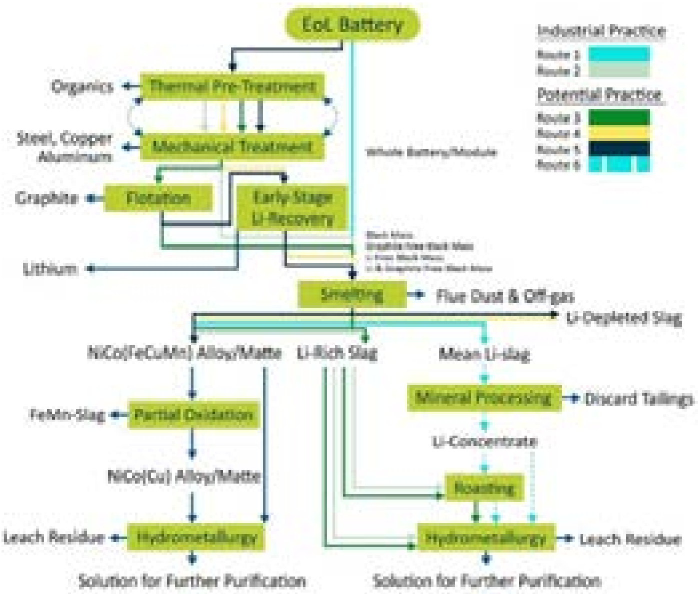
Validating results with other sources

In an LCA for cement and concrete, separately and in the context of a reinforced concrete (Josa & Borrion, under review), the impact assessment was performed using impact factors from ReCiPe (Goedkoop et al., 2009; Rybaczewska-Blazejowska & Jezierski 2024). As a check of their accuracy, the results were compared to those obtained with impact factors from other sources (i.e., EPD, CML (Durao et al., 2020; Rybaczewska-Blazejowska & Jezierski 2024)).

Uncertainties for new technologies

Harper et al. (2023) described sources of several uncertainties linked to the end-of-life (EOL) of lithium-ion batteries (LIB). There is a wide range of potential options as shown in Figure 4.

Figure 4. Industrial and potential process routes for pyrometallurgical battery recycling (Source: Harper et al., 2023)



Insight Eight

Consider geographical location

The Circular Economy is a global concept with varying regional contexts. Circular Economy initiatives can have diverse environmental, economic, and social impacts depending on the geographic location. To enable the accuracy and relevance of LCA, it is therefore imperative to tailor data inputs to the specific geographic context. This entails accounting for regional differences in infrastructure, regulations, and social dynamics that may influence the effectiveness and outcomes of circular practices.

Understanding the geographic origins of materials is crucial, especially in mining activities where the environmental impacts vary significantly based on the location and the technologies employed. Yet, obtaining precise data on material sourcing remains a challenge, particularly in regions like the UK where data sources may not indicate the origins of materials.

In environmental LCA, it is also important to take into account geographical variations in electricity grid mixes. Indeed, since many environmental impacts depend strongly on electricity sources, LCA loses much of its utility if the source of electricity is not defined. Using databases like Ecoinvent (Steubing et al., and Wernet et al., 2016), with its focus on local data, can aid in capturing geographic nuances. However, challenges persist, such as geographical variations in the prevalence of illegal exports and material movements, which complicate efforts to track and assess circular flows accurately.

Engaging diverse stakeholder groups across various locations can provide more nuanced insights into the social impacts of circular initiatives in S-LCA.

Production and recycling of batteries and metals

LCA of battery recycling is complicated by the fact that end-of-use lead-acid batteries may be collected locally, but are then exported for management, disrupting circularity efforts that involve local manufacturers. Similarly, metals collected for recycling may undergo complex and poorly documented material movements dictated by market forces, rather than proximity to sources.

Importance of context in social impacts assessment

An S-LCA comparing retrofitting and rebuilding of a building was carried out as part of the research programme of the ICEC-MCM (Josa & Borrion, under review). Indicators such as working conditions and disturbance on the local community were assessed. The results from evaluating these indicators are context-specific, as regulations, behaviours and acceptance levels in different neighbourhoods, cities, and countries can vary significantly.

Insight Nine

Communicate assumptions, scope, and generalisability

Clear articulation of assumptions, scope, and generalisability of an LCA study is essential for providing transparent and credible information to help decision-makers develop, support and adapt policies for adoption of circular practices.

When data gaps pose challenges to conducting a comprehensive LCA, transparent communication becomes even more critical. By acknowledging the limitations imposed by data scarcity and articulating the areas where information is lacking and/or uncertain, analysts can still provide valuable insights. Rather than devaluing the LCA process, clear information about the challenges encountered in the analysis enables the identification of key areas for future research and intervention.

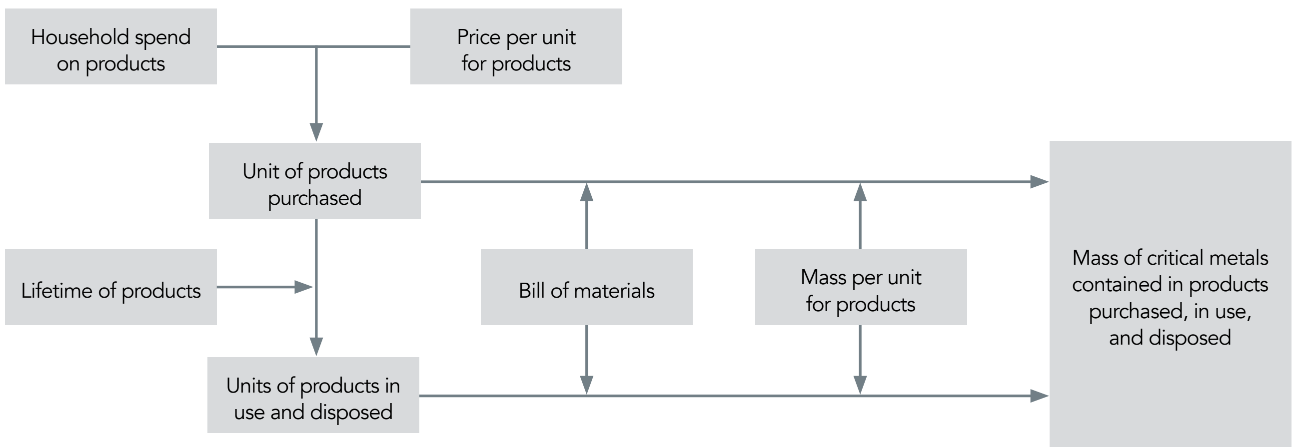
Additionally, it is crucial to recognise the temporal limitations of LCA findings. For example, as the energy landscape evolves and average energy mixes shift annually, the relevance of LCA results may diminish over time. Thus, researchers must communicate the temporal constraints of their findings, emphasising the need for ongoing monitoring and adaptation to ensure policy decisions remain informed by the most current data.

A novel approach to estimate WEEE generation

The Waste from Electrical and Electronic Equipment (WEEE) data reported by the UK government only accounts for electronic waste collected by local authorities. This excludes illegally dumped waste or electronic equipment hoarded by households, leading to an underestimation of the total WEEE generated. Additionally, the data is categorised broadly, making it difficult to assess the environmental impact or recycling efficiency for different types of e-waste.

To address this limitation, Hu and Yan (2023) developed a new approach to estimate household WEEE generation for over 40 typical households EEE (Figure 5). This approach, based on product price and lifetime, along with household spend and EEE composition, enabled them to analyse the critical metal footprint, defined as the amounts of critical metals contained in the EEE products purchased, owned, and disposed of by UK households and conduct an LCA of the environmental impacts of reducing, reusing, and recycling WEEE.

Figure 5. An overview of the methodology, with rectangles showing the input parameters and ovals showing the outputs (Hu and Yan 2023)



Insight Ten

Be aware of the limitations of LCA

Notwithstanding the significant advantages that LCA can offer in supporting decisions to implement more sustainable practices for a Circular Economy, some limitations need to kept in mind. Some of these limitations have become apparent in the foregoing discussion of insights regarding LCA practice, including:

- LCA results are strongly affected by the definition of the system boundary, and any comparison between alternatives must use the same system boundary.
- There is a high degree of uncertainty associated with most types of data used in LCA, including resource flows (especially for supporting processes) and impacts, and this uncertainty can be difficult to quantify.
- It can be difficult to allocate impacts appropriately across several co-products in a production system.
- Although LCA of static social impacts is becoming more common, it cannot capture the complex dynamics between social behaviour and other aspects, including environmental outcomes.

LCA studies are specific to their scope, system boundaries and other constraints. Therefore, transfer of LCA results to another context is often inappropriate. Additionally, LCA is:

- Only suitable for comparison between options, not as a stand-alone analysis.
- Prone to a lack of transparency and potential manipulation when multi-parameter modelling involves too many parameters, or the underlying data is not made available for inspection or audit.
- Limited by a restricted number of impact categories, which may not capture all potential impacts.

Thus, to make more informed and balanced decisions that support the transition to a Circular Economy, LCA results should be used as part of broader decision-making frameworks. For example, LCA may be complemented with other tools and analyses (e.g., risk assessments) to provide a more comprehensive understanding of sustainability performance.

Examination of other impacts

In the ICEC-MCM, postdoctoral research projects employed other techniques to investigate impacts that cannot be captured by LCA, including:

Computed General Equilibrium (CGE) modelling of the impact of circular practices in the cement and concrete section on macroeconomic indicators (Piskin & Calzadilla Rivera, in preparation).

Experiments to examine:

- the effects of cascading of construction minerals on soil health (Kourmoli et al., 2023)
- the mineral forms of pollutants in cements produced by co-processing of industrial wastes in cement plants (including, Chen et al., in preparation), which is related to their behaviour in the built environment and the risk they pose to humans and ecosystems;
- the effect of recycled concrete aggregates on concrete durability (Fernandez et al., 2024).

References

Bernardi, A., Danaci, D., Symes, A., & Chachuat, B. (2024). Alternative pathways to sustainable aviation fuel from CO_2 and H2: an enviro-economic assessment. In 34th European Symposium on Computer Aided Process Engineering / 15th International Symposium on Process Systems Engineering (pp. 2149-2154) **https://doi.org/10.1016/b978-0-443-28824-1.50359-8**

Chen, D.T., Roy, A., Bogush, A, Stegemann, J.A. (in preparation), Fate of zinc and copper in co-processing of metal finishing filter cake in Portland cement manufacture (Part I), University College London

Durão, V., Silvestre, J. D., Mateus, R., & de Brito, J. (2020). Assessment and communication of the environmental performance of construction products in Europe: Comparison between PEF and EN 15804 compliant EPD schemes. Resources, Conservation and Recycling, 156, 104703. **https://doi.org/10.1016/j.resconrec.2020.104703**

Favarin, S., Berlusconi, G., Aziani, A., & Corradini, S. (2023). Transnational trafficking networks of end-of-life vehicles and e-waste. Global Crime, 24(3), 215-237. **https://doi.org/10.1080/17440572.2023.2217101**

Fernandes, B., Krishnan, S., Macente, A., Villagrán-Zaccardi, Y., Black, L., Bernal. S. (2023). The combined roles of cement type and recycled concrete aggregate on the formation of the interfacial transition zone, V International Conference Progress of Recycling in the Built Environment (Weimar, 2023). **https://www.rilem.net/publication/publication/542?id_papier=13545#**

Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., & Van Zelm, R. (2009). ReCiPe 2008. A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level, 1, 1-126. **https://www.rivm.nl/sites/default/files/2018-11/ReCiPe%202008_A%20lcia%20method%20which%20comprises%20harmonised%20category%20indicators%20at%20the%20midpoint%20and%20the%20endpoint%20level_First%20edition%20Characterisation.pdf**

Goedkoop, M., Oele, M., Leijting, J., Ponsioen, T., & Meijer, E. (2008). Introduction to LCA with SimaPro 7. PRé Consultants, The Netherlands. **https://pre-sustainability.com/files/2014/05/SimaPro8IntroductionToLCA.pdf**

Harper, G. D. J., Kendrick, E., Anderson, P. A., Mrozik, W., Christensen, P., Lambert, S., Greenwood, D., Das, P. K., Ahmeid, M., Milojevic, Z., Du, W., Brett, D. J. L., Shearing, P. R., Rastegarpanah, A., Stolkin, R., Sommerville, R., Zorin, A., Durham, J. L., Abbott, A. P., . . . Boons, F. (2023). Roadmap for a sustainable circular economy in lithium-ion and future battery technologies. Journal of Physics: Energy, 5(2). **https://doi.org/10.1088/2515-7655/acaa57**

Hu, X., Pierce, J. M. T., Taylor, T., & Morrissey, K. (2021). The carbon footprint of general anaesthetics: A case study in the UK. Resources, Conservation and Recycling, 167. **https://doi.org/10.1016/j.resconrec.2021.105411**

Hu, X., & Yan, X. (2023). Estimation of critical metal consumption in household electrical and electronic equipment in the UK, 2011–2020. Resources, Conservation and Recycling, 197. **https://doi.org/10.1016/j.resconrec.2023.107084**

Iacovidou, E., Hahladakis, J. N., & Purnell, P. (2021). A systems thinking approach to understanding the challenges of achieving the circular economy. Environ Sci Pollut Res Int, 28(19), 24785-24806. **https://doi.org/10.1007/s11356-020-11725-9**

International Organization for Standardization [ISO]. (2006a). Environmental management — Life cycle assessment — Principles and framework. In ISO 14040:2006. **https://www.iso.org/standard/37456.html**

Kourmouli, A., Quinton J. & Stevens, K., (2023). Impacts of mineral-based construction and demolition waste on soil functions and ecosystem services, Presented at the British Society of Soil Science (BSSS) and Soil Science Society Ireland (SSSI).

International Organization for Standardization [ISO]. (2006b). Environmental management — Life cycle assessment — Requirements and guidelines. In ISO 14044:2006. **https://www.iso.org/standard/38498.html**

Kapoor, N., Sulke, P., & Badiye, A. (2021). E-waste forensics: An overview. Forensic Science International: Animals and Environments, 1, 100034. **https://doi.org/10.1016/j.fsiae.2021.100034**

Leonzio, G., Chachuat, B., & Shah, N. (2023). Towards ethylene production from carbon dioxide: Economic and global warming potential assessment. Sustainable Production and Consumption, 43, 124-139. **https://doi.org/10.1016/j.spc.2023.10.015**

Maselli, G., Oliva, G., Nesticò, A., Belgiorno, V., Naddeo, V., & Zarra, T. (2024). Carbon capture and utilisation (CCU) solutions: Assessing environmental, economic, and social impacts using a new integrated methodology. Science of The Total Environment, 948, 174873. **https://doi.org/10.1016/j.scitotenv.2024.174873**

Millward-Hopkins, J., Purnell, P. & Baurley, S., (2023). Scenarios for reducing the environmental impacts of the UK clothing economy, Journal of Cleaner Production, Vollume 420, 138352. **https://doi.org/10.1016/j.jclepro.2023.138352**

Millward-Hopkins, J., Purnell, P. & Baurley, S., (2023). A material flow analysis of the UK clothing economy, Journal of Cleaner Production, Volume 407, 137158. **https://doi.org/10.1016/j.jclepro.2023.137158**

Myers, R.J., Bide, T., Calzadilla Rivera, A., Hopkinson, P., Zils, M., Yayla, A., Wang, J., Mason, A.R., Domenech, T., van Ewijk, S., Stegemann, J.A. (2025). MATERIAL FLOW ANALYSIS. NICER Programme Insight Report.

Newman, A. J. K., & Styring, P. (2023). The pursuit of methodological harmonization within the holistic sustainability assessment of CCU projects: A history and critical review. Frontiers in Sustainability, 3. **https://doi.org/10.3389/frsus.2022.1057476**

Nyhus, A. H., Yliruka, M., Shah, N., & Chachuat, B. (2024). Green ethylene production in the UK by 2035: a techno-economic assessment. Energy & Environmental Science, 17(5), 1931-1949. **https://doi.org/10.1039/d3ee03064d**

Piskin M., & Calzadilla Rivera, A (in preparation). Spatial Economic Impact Assessment for Circular Economy with a Framework Spatial Computable General Equilibrium Model.

Rodríguez-Vallejo, D. F., Valente, A., Guillén-Gosálbez, G., & Chachuat, B. (2021). Economic and life-cycle assessment of OME3–5 as transport fuel: a comparison of production pathways. Sustainable Energy & Fuels, 5(9), 2504-2516. **https://doi.org/10.1039/d1se00335f**

Rybaczewska-Błażejowska, M., & Jezierski, D. (2024). Comparison of ReCiPe 2016, ILCD 2011, CML-IA baseline and IMPACT 2002+ LCIA methods: a case study based on the electricity consumption mix in Europe. The International Journal of Life Cycle Assessment, 1-19. **https://doi.org/10.1007/s11367-024-02326-6**

Stegemann, J.A. (2017) UCL CircEL – The Circular Economy Lab, UCL internal presentation.

Steubing, B., Wernet, G., Reinhard, J., Bauer, C., & Moreno-Ruiz, E. (2016). The ecoinvent database version 3 (part II): analyzing LCA results and comparison to version 2. The International Journal of Life Cycle Assessment, 21, 1269-1281. **https://doi.org/10.1007/s11367-016-1109-6**

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment, 21, 1218-1230. **https://doi.org/10.1007/s11367-016-1087-8**

Zante, G., Elgar, C. E., Hartley, J. M., Mukherjee, R., Kettle, J., Horsfall, L. E., Walton, A., Harper, G. D. J., & Abbott, A. P. (2024). A toolbox for improved recycling of critical metals and materials in low-carbon technologies. RSC Sustainability, 2(2), 320-347. **https://doi.org/10.1039/d3su00390f**

CE-HUB
UKRI National Interdisciplinary Circular Economy Research

NICER PROGRAMME

University of Exeter

UK Research and Innovation

2024BS024