CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2023-2

5th Conference on Production Systems and Logistics

# Scenarios Of Glass Disposal In Australia From Circular Economy And Life Cycle Assessment Perspective

Brian Smith[1], Shiva Abdoli[1]

[1]*School of Mechanical and Manufacturing Engineering, The University of New South Wales, 2052, Australia*

**Abstract**

The growing rate of consumption has drawn attention to measurable environmental impacts leading to the development of sustainability tools that can inform environmental, economic and social decisions. Façade glass is a widely used material that is highly recyclable material and is an important material for sustainable assessments as it promotes ideas of Circular Economy if it is done properly after taking into account the quantification of environmental impact associated with recycling activities. Design of sustainable products requires having a lifecycle perspective, including analyzing various End-of-Life (EoL) scenarios. This paper aims to investigate scenarios of when glass is disposed to demonstrate the applicability of glass in a Circular Economy. Life Cycle impact Assessment (LCA) and Circular Economy (CE) literature is critically reviewed to identify progress in research, methodologies employed and areas that require more research which this paper aims to resolve. It was determined recovery, also known as EoL, strategies for glass used in the Australian built environment lacked research despite the growing imperative of sustainable consumption. A typical glazing unit in a facade system was selected for assessment along with three (3) disposal scenarios. Quantifying the environmental impacts are to be interpreted in a LCA along with glass recovery strategies involving recycling, landfill and/or incineration with heat recovery. A CE assessment is performed by interpreting LCA environment impacts associated with the activities required to achieve circularity in a typical apartment in Sydney, Australia. This provides insights supports decision-makers who seek sustainable consumption through ideas of Circular Economy.

**Keywords**

Life Cycle impact Assessment; Circular Economy; Glass Disposal

## 1. Introduction

In this section first the importance of sustainable development and Circular Economy are explained. Then LCA as a method to quantify environmental impact is explained, followed by glass production/consumption as the focus of this paper, which is about analysing various disposal scenarios to assess their effectiveness from the Circular Economy perspective by using the LCA method. This section is concluded by clarifying the paper scope.

### 1.1 Sustainable development, Circular Economy, and LCA

Sustainable development seeks solutions to reduce environmental impact of various activities including product development. LCA is a widely used method for quantifying environmental impact of a product in its lifecycle from material to End-of-Life (EoL). “Circular Economy” was first seen in 1988 in Population and Development Review journal discussing the economics of natural resources [1]. It was not until a decade

DOI: https://doi.org/10.15488/15275
ISSN: 2701-6277

ago that the idea became receptive on an international level. During this era, it was understood that Circular Economy presented an opportunity to enable economic growth all the while not comprising the environment. A focus on disposal of materials helps to generate a cyclical model of production allowing value to be recaptured that would otherwise be lost [2].

### 1.2 Glass Product System

Glass has critical applications in industry and has paved the way for a growing glass industry. The $155.16 billion glass industry in 2021 has been expected to grow by 6.35% to $165.01 billion in 2022 [3]. Glass is commonly used in construction as glazing units and are essential elements, which provide vision, daylight, solar heat gains, and acoustic comfort. Critically, glass can be melted, recycled, and repurposed for many industrial applications all the while being non-toxic to the environment. This can promote a Circular Economy whereby the efforts to recycle glass are environmentally sound. Despite these favourable properties, a lack of focus persists in the waste management sector when capitalizing on these potential environmental benefits [4]. The current rate of glass recycling in NSW, Australia is around 46% [5]. In 2017-2018, 0.58 million tons of glass packing was recycled in Australia, however this was a 200,000 reduction since the year 2006-07 with indications this rate has fallen in the past five years [6].

The current consensus estimates the built environment consumes about 35-40% [7] of the world's energy and emits about 30% of the worlds CO2 [8]. With this contribution the International Energy Agency (IEA) estimates direct building CO2 emissions needs to be reduced by 50% and indirect emissions by 60% by 2030 to achieve a net-zero target by 2050 [9]. Current estimates for the global building and construction markets growth are approximately ~3% with Australia in 2022 commencing 50,200 dwelling units for construction [10]. Due to the multidecadal lifetime of a building, it is known the operational energy use is a significant contributor to environmental load for a typical residence. A 2001 study in Hong Kong showed the embodied energy for a building can contribute as much as 40% of the total life cycle energy [11]. Further, two other studies found the embodied energy may account for up to 43% [12] and 60% [13] of the total energy.

### 1.3 Scope

All levels of government in Australia endorsed the National Waste Policy Action Plan (NWPAP) issued in 2019 [14]. This plan proposes targets to guide national efforts through to 2030 such as reducing waste generated by each person by 10% and obtain a national waste recovery rate of 80%. In January 2021, Commonwealth Scientific and Industrial Research Organisation (CSIRO) published a guiding report [15] on how to integrate highly consumed materials such as plastic, glass, and paper into a Circular Economy. This was in response to a sweeping need to switch from waste management to a Circular Economy. To support sustainable product development, it is needed to have a lifecycle perspective at the design stage and addressing the sustainability from material to the EoL. Particularly from the Circular Economy perspective, it is needed to analyze various EoL scenarios at the design stage [16-18]. This study presents a comparative evaluation of the environmental impact of a typical glazing unit in Sydney Australia under different EoL treatment scenarios for the glass. A LCA is undertaken to support the hypothesis that glass recyclability can promote a Circular Economy all the while being environmentally sound.

## 2. Literature Review

Many studies have been in the context of Circular Economy, LCA, and glass production. This paper only reviews those literature that used LCA as method to quantify various glass production and recovery scenarios.

LCA is a powerful tool that can compare various products and/or scenarios environmental impact. A study compared three (3) concrete mix designs using SimaPro to assess the performance of sustainable concrete

[19]. Ensuring compliance by designing concrete blends according to a British standard, it was identified that it is possible to produce concrete that is more sustainable with minimal impact to its structural performance. However, this case study contained many assumptions that were highly specific to the assessed location and may produce results that are not applicable to a different study. Moreover, the study had a primary focus on CO2 emissions and did not consider other impact categories (section 5.3). In built industry, SimaPro Software has been used to perform an LCA of an Egyptian residential building [20]. All phases of the life cycle are incorporated including disposal (recycling, landfill and/or incineration) using a functional unit of 1m2 area of the building. Over a lifetime of 50 years, it was found the operation phase of the building contributed 71% of the environmental load and disposal strategies positively impacted environment by 12%. The LCA results aligned with the established need of energy conservation and sustainable fuels which would have the greatest impact to offset the operational usage. The study provides insights that would lead to more sustainable consumption however did not consider various scenarios of production, construction, and disposal. LCA has been used in studies to assess the improvements by implementing energy conservation technologies. Insulated externals walls, energy efficient windows (double-glazed) and rubber gaskets to reduce drafts were assessed in school buildings in Mendoza, Argentia [21]. It was discovered most conservative technologies applied at this school improved the environment, except for brick baking which used wood as fuel to increase photochemical ozone formation. All calculations used the SBID database provided by the Danish Building Research Institute and is unclear how comparable these results are to the proposed study located in Australia. Crushed glass that is remelted is known as cullet and studies have been performed to use this cullet in alternative industrial processes. Post-use glass packaging underwent a LCA to document the environmental burdens when cullet is recycled into sodium silicate which can be used in various products (cement, refractory, textiles) [22]. It was identified that the electricity required for this recycling process was the biggest contributor to environmental load. It was stated using cullet in this manner led to downstream processes that were more environmentally benign but offered no specific impact categories or comparison detailing the range of improvement. A 2021 paper in the journal of applied energy assessed ways to recycle the constituent materials that make up a photovoltaic (PV) panel [23]. This study compared the results to other publications and was found using two recovery lines; one for glass recovery and the other for secondary raw material such as aluminium, copper, silver and silicon, was environmentally favourable. It reflected the current standard of recycling whereby disposal methods are chosen based on the material to be recycled. It was identified in the reviewed literature that scant attention has been paid to quantify the environmental load of glass under various disposal scenarios in Australia to inform circularity possibilities, which this paper aims to address this research gap as its contributions.

## 3. Context of Research

A typical glass unit presents a recovery challenge as it is a hybrid of a mixture of materials and assemblies from which it is not feasible to repurpose the salvaged raw material without planning and coordination from interested parties. Recycled glass known as cullet can be used to produce more glass or processed as an input to another process. Due to the increased use of glass in the built environment, strategies and consideration for disassembly and recovery are highly relevant. Glazing units used in facade systems have grown in variety and installation methods and may require different recovery methods. Advanced glazing may be more difficult to dismantle and repurpose. Further, glass with a special treatment (e.g., non-reflective coatings and low-emissivity coatings) may be more challenging to recycle and used in industrial processes that require glass of a certain composition. This presents a trade-off wherein designing for end-of-life recovery can come at the disadvantage of operational performance (thermal, daylight, acoustic comfort), and vice versa. However, there remains no major technical challenge in repurposing glass for some processes and a glass bottle that is used from recycled glass (cullet) can reduce the energy required for production up to 75% [24]. Further, glass has the favourable property of being inert, however, because of this it becomes relatively cheap and easy to send to landfill. The primary method of dismantling involves an excavator that pries the metal frames of the facade. The glass falls as a mixture with concrete and other materials where it is separated on-site. Metal is separated and are sold to a recycling facility whereas the mixed glass is sold as an aggregate at a cheaper price or simply sent to landfill [25]. In the event of successful glass recovery some downstream problems may occur. These include the demand for reuse is low due to lack of supply and material failures, structural testing required for reused materials, bespoke nature of glazing makes compatibility challenging and limited capacity to separate composite glazing units.

Despite these challenges, potential energy conservation can be realized through direct replacement of glazing units or proper recycling as there are no major technical issues when transporting them to be recycled in a furnace. Glass may also be incinerated with some proportion of useful heat recovery that can be used to generate electricity [26]. More commonly, glass is crushed with other buildings elements and sent to landfill [27]. Other elements in a typical glazing unit such as sealants, gaskets, packers and spacers are assumed to be the same in all scenarios and are excluded from the proposed study. The production of glass is a significant environmental burden and scenarios of manufacturing to produce the glass can prove to be insightful. However, the variety of manufacturing is limited to the predominant float glass process and databases do not account for specialized processes such as magnetron sputtering which is used to deposit thin films on glass. Further, there is no recognized standard or protocol for the waste management, recycling and reuse of materials for a building during demolition and predicting the material flows at the end of the lifetime of a building (50-60yrs) can create significant uncertainty. For this reason, disposal scenarios are necessarily simplified. This paper highlights the importance of engineering design at the level of individual processes and at a system level. Engineering decisions around the design of production processes, transportation logistics and disposal facilities all directly influence the extent to which the environment is impacted.

## 4. LCA and Circular Economy Methodology

LCA requires an inventory of resources and processes implemented and the corresponding environmental impact. The account of these factors is based on the scope of the study and the system boundary. LCA aims to gives an understanding about the environmental impact associated with industrial activities from the initial extraction of raw materials, until the constituent materials from which the product is made are returned to the earth. It is therefore sometimes referred to as a ‘cradle-to-grave assessment’ As per ISO 14040, LCA consists of four (4) phases: goal and scope definition, life cycle inventory analysis, life cycle impact assessment and life cycle interpretation. These phases are classified as interdependent as results from one phase inform results for another phase. For Circular Economy opportunities, it is important to note which parties govern a particular stage. Raw material extraction, manufacturing, logistics and retail operations are controlled by supplier, whereas use phase and disposal are typically controlled by the consumer. Each product may split these categories differently or are not concerned with a particular category. Understanding the processes and parties that govern each stage facilitates greater communication which is imperative when discussing ideas of a Circular Economy. Since LCA is a tool to examine environmental impact during a product life cycle, it does not account for technical, social, and economic aspects and interactions happening outside product foreground and background system. Other methods can be used to assess these factors and are outside the scope of this paper.

It remains important to all sectors of production to prolong the value of products and resources in the economy for as long as possible. This is typically accomplished through the repurposing of material which provides a supply chain that is designed to be environmentally sound, regenerative, and restorative [28]. This is the essence of circular economies which use all means necessary (reuse, recycle, refurbish, sharing, remanufacturing, repair etc.) to create a closed-loop system. Historically, most production systems follow a linear consumption model in which a products life has a definite start and finish at which point it provides no further purpose. It is understood transforming the dominant model enshrined during the industrial revolution requires key changes to our production and consumption patterns. The growing necessity of conserving natural resources and the environment coupled with the unsustainable nature of waste management had led to a growth of research, policy curation and other sustainable initiatives in the service of these needs.

CE is a relatively new concept. In this context, a comprehensive framework for evaluating the circularity of a process remains difficult due to the variations of industries and sectors, the interactions between various indicators and the lack of agreed upon terms. Many papers review the various metrics and taxonomy for a circularity assessment and call attention to the lack of a consensus on these terms [29]. A review [30] of 62 papers concluded little work has been done to integrate relevant technologies into information systems that can deal with the complexity of a circularity assessment. A more comprehensive Circular Economy study of 318 papers [31] in the built environment similarly detailed the need for a business model that included Circular Economy principles and integrates stakeholders in the value chain. CE frameworks and principles have been proposed, and some tested, which offer some signs of progress for a settled circularity assessment [32]. LCA is the predominant method to determine circularity and is the method by which Circular Economy scenarios are evaluated in this paper. Other methods such as Material Circularity Indicator (MCI) [33], Environmentally Extended Input-Output Analysis [34], Material Flow Analysis [35], Operations Research [36] have been proposed to evaluate circularity of a product system. Examining LCA impact categories is a strategy by which circularity will be determined and is discussed in next section.

## 5. System Modelling

The software used for LCA is OpenLCA 1.11.0 and databases Ecoinvent and Environmental Footprint were imported for this assessment. The impact assessment used is IPCC 2013 GWP 100a. Certain processes are parameterized in the model to produce these scenarios. The boundary of the system in consideration accounts for production, transportation, and disposal. As mentioned, glass production may contain a proportion of crushed recycled glass known as cullet. The percentage of cullet used in production can be assigned and is set at values to match that of the recycling rate. For example, if 80% of the glass is recycled, 80% of the production will use cullet. This is meant to reflect the circular nature of this assessment whereby all recycled glass is reused as cullet in production. Parameters are applied to the waste processes of landfill, recycling, and incineration, and are adjusted to reflect a given disposal scenario. Fig. 1 demonstrates the developed model in OpenLCA, demonstrating the phases of the life cycle accounted for in this assessment.

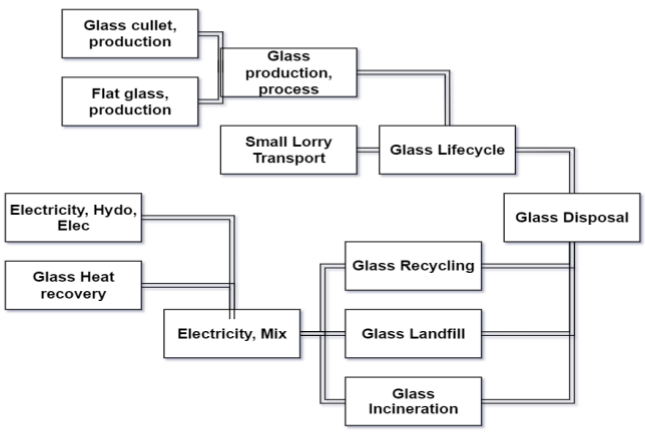


Figure 1. Developed product system model including lifecycle phases in OpenLCA 1.11.0

It was ensured processes demonstrated above were selected that were local to reflect the disposal scenarios in Sydney, Australia. Databases used in this LCA are limited to those that have been verified and tested for inclusion into the software, primarily in the region of Europe and North America. Research for the various

LCA databases was undertaken to determine which was the most available and comprehensive. EcoInvent and Environmental Footprint databases were selected and specific processes for the region of Australia were limited, and substitutions are made where possible. A reference flow of 20kg of glass was considered to reflect the mass of one standard 2100mm x 2650mm single glazing unit. A small lorry is assumed to be the only mode of transportation and the small lorry transportation process demonstrated in Fig. 1 accounts for the total distance travelled between facilities for a given scenario. Transportation in the model has the unit of 'tons multiplied to kilometer' and is adjusted depending on the amount of glass the truck carries and the distance it must travel between facilities. Basic flows of carbon dioxide and electricity were assigned as outputs to all three (3) disposal scenarios. The amount of electricity and carbon dioxide produced for a kilogram of glass that is recycled, incinerated and/or sent to landfill is summarized in the table below.

Table 1: Electricity and CO2-eq associated with developed EoL Scenarios

| Disposal Scenario | kgCO2-eq / kg glass | kWh energy / kg glass |
|---|---|---|
| Recycling | 0.5 [37] | 1.1 |
| Landfill | 0.3 [38] | 0.5 |
| Incineration | 1.7 [39] | 3.15 [40] |

The results are general estimates based on the current literature and are derived from a typical tone of waste. They are to represent the energy and CO2 equivalent associated when machinery and processes conduct a given disposal scenario. Further, estimates for the energy consumption was only found for incineration. Estimates for landfill and recycling were approximated from this value assuming recycling glass consumes more energy than transporting it to landfill.

To quantify the burdens due to transportation, a recycling facility, incineration facility and landfill location is selected in NSW, Australia as shown in Fig. 2.

- Recycling facility – Glass Recycling NSW (Ingleburn, NSW) [41]
- Incineration with heat recovery facility – Energy recovery from Waste (West Lithgow precinct) [42]
- Landfill – Greenwood Landfill (Mona Vale) [43]

The assessed glass unit is located in Sydney CBD, and approximate distances from this location to the above locations are shown in the figure below.


Figure 2. Distances between disposal scenario facilities NSW, Australia

## 6. Results

Impact assessment results using IPCC 2013 GWP 100a are provided for three (3) scenarios, optimistic, neutral, and pessimistic. The optimistic scenario in context of Circular Economy allows analyzing situation where the majority of the glass is recycled. The developed scenarios are outlined below.

Table 2: End of Life Disposal Scenarios

| Treatment | Optimistic (%) | Neutral (%) | Pessimistic (%) |
|---|---|---|---|
| Recycling | 80 | 50 | 20 |
| Landfill | 10 | 25 | 80 |
| Incineration | 10 | 25 | 0 |

Table 3: Results of Scenarios (optimistic, Neutral, Pessimistic) against Impact Categories

| Impact Category | Optimistic | Neutral | Pessimistic |
|---|---|---|---|
| Acidification | 0.18270 mol H+ eq | 0.22022 mol H+ eq | 0.23640 mol H+ eq |
| Climate Change | 15.7551 kg CO2 eq | 15.9998 kg CO2 eq | 16.73456 kg CO2 eq |
| Ecotoxicity, freshwater | 8.481385 CTUe | 8.65432CTUe | 8.79701 CTUe |
| Eutrophication, freshwater | 0.00098 kg P eq | 0.00078 kg P eq | 0.00068 kg P eq |
| Human toxicity (cancer & non-cancer) | 4.869e-6 CTUh | 3.4532e-6 CTUh | 1.00032e-6 CTUh |
| Land Use | 290.09208 Pt | 201.06712 Pt | 64.773 Pt |
| Resource Use, fossils | 608.39560 MJ | 807.42356 MJ | 851.46431 MJ |

The total transportation distance for the pessimistic scenario is changed because no glass is sent to landfill. Comparing the disposal scenarios against impact categories provides the basis for a circularity assessment. The results are shown in Table 3 for optimistic, neutral, and pessimistic scenarios. Impact categories such as marine eutrophication and ionizing radiation (human health) recorded negligible results and are excluded from table of results. Optimistic, neutral and pessimistic scenarios have cullet proportions set as 80%, 50% and 20%, respectively.

Based on the demonstrated results; the following observations are made:

- Acidification approximately is 30% higher in the pessimistic scenario. This is likely associated with the high emissions from landfills and the low cullet content used in production.
- Climate Change impact category for pessimistic has 1kg more CO2-eq than optimistic case. Subject to further data quality checks, this shows some degree of circularity where the environmental costs of recycling can outweigh alternatives of landfill and incineration.
- Pessimistic Scenario fossils resource use 200MJ more than the optimistic scenario. Subject to further data quality checks, this indicates high recyclability may lead to lower energy consumption overall.
- Land use for the optimistic case (290 Pt) is much greater than the pessimistic case (65 Pt). This category measure soil quality and indicates recycling can lead to poorer soil quality.
- Neutral Scenario provided impact category results that were between optimistic and pessimistic cases.

## 7. Conclusion and future work

The impact category results show that additional efforts to recycle glass (optimistic scenario) can promote a Circular Economy that is restorative and environmentally benign. To this end, this study uniquely shows under the given assumptions, limitations, and disposal scenarios that additional efforts to recycle do not always lead to further environmental impacts, particular with respect to glass and its favorable recycling properties. However additional data quality checks, system boundaries and scenarios can further interrogate this conclusion. Future work can assess the environmental impact of directly replacing facade systems plus on other systems and identify possible unintended consequences of such replacement [44]. Though this scenario may be challenging to specify in industry as direct replacement of glazing systems remains an uncommon practice. Further, more advanced glazing system can be assessed. These systems result in lower operational energy during their usage phase. It would be insightful to examine whether extra production costs of these advanced systems outweigh energy savings during its lifetime [45, 46].

## Appendix

The appendix should be placed before References section. Headings should have the style used above.

## References


[1] C. Sassanelli, P. Rosa, R. Rocca, and S. Terzi, "Circular economy performance assessment methods: A systematic literature review," Journal of Cleaner Production, vol. 229, pp. 440-453, 2019.

[2] G. Kamateros and S. Abdoli, "Automated Disassembly of Lithium Batteries; Methods, Challenges, and a Roadmap," Procedia CIRP, vol. 119, pp. 1216-1221, 2023/01/01/ 2023.

[3] D. D. F. Del Rio et al., "Decarbonizing the glass industry: A critical and systematic review of developments, sociotechnical systems and policy options," vol. 155, p. 111885, 2022.

[4] S. Abdoli and Decisions, "A framework for analysing the environmental impact and support decision making in sustainable development context," Environment Systems and Decisions, vol. 43, no. 2, pp. 281-297, 2023.

[5] P. Allan, "Assessment of Australian recycling infrastructure-Glass packaging update," Department of environment energy Policy, 2019.

[6] S. Victoria. Market summary–recycled glass. 2014 [Online]. Available: https://assets.sustainability.vic.gov.au/susvic/Report-Market-Analysis-Glass-Sept-2014.pdf

[7] C. Filippín and S. F. Larsen, "ENERGY EFFICIENCY IN BUILDINGS."

[8] I. B. E. E. Taskgroup, "Building Energy Performance Gap Issues: An International Review," ed: International Partnership for Energy Efficiency Cooperation, IPEEC., 2019.

[9] U. Programme, "2020 Global Status Report For Buildings and Construction: Towards a Zero-Emission, Efficient and Resilient Buildings and Construction Sector. United Nations Environment Programme Nairobi, Kenya."

[10] A. B. o. Statistics, "Building Activity, Australia. ABS," 2021, December, Available: https://www.abs.gov.au/statistics/industry/building-and-construction/building-activity-australia/dec-2021.

[11] T. Chen, J. Burnett, and C. K. Chau, "Analysis of embodied energy use in the residential building of Hong Kong," Energy, vol. 26, no. 4, pp. 323-340, 2001.

[12] N. Mithraratne and B. Vale, "Life cycle analysis model for New Zealand houses," Building environment, vol. 39, no. 4, pp. 483-492, 2004.

[13] N. Huberman and D. Pearlmutter, "A life-cycle energy analysis of building materials in the Negev desert," Energy Buildings, vol. 40, no. 5, pp. 837-848, 2008.

[14] Australian Government, "NATIONAL WASTE POLICY, ACTION PLAN," 2019, Available: https://www.agriculture.gov.au/sites/default/files/documents/national-waste-policy-action-plan-2019.pdf.

[15] H. Schandl, S. King, A. Walton, A. Kaksonen, S. Tapsuwan, and T. Baynes, "National circular economy roadmap for plastics, glass, paper and tyres," ed: CSIRO: Canberra, Australia, 2020.

[16] S. Abdoli, "A modelling framework to support integrated design of production systems at early design stages," nternational Journal on Interactive Design Manufacturing, vol. 17, no. 1, pp. 353-370, 2023.

[17] X. Ji and S. Abdoli, "Challenges and Opportunities in Product Life Cycle Management in the Context of Industry 4.0," Procedia CIRP, vol. 119, pp. 29-34, 2023/01/01/ 2023.

[18] S. Abdoli and B. Bahramimianrood, "A target-driven framework for assessing the effectiveness of product-service-system development approaches at System of Systems level," Procedia CIRP, vol. 119, pp. 229-234, 2023/01/01/ 2023.

[19] M. W. Tait and W. M. Cheung, "A comparative cradle-to-gate life cycle assessment of three concrete mix designs," The International Journal of Life Cycle Assessment, vol. 21, pp. 847-860, 2016.

[20] H. Dullah, M. Malek, and M. M. Hanafiah, "Life cycle assessment of nile tilapia (Oreochromis niloticus) farming in Kenyir Lake, Terengganu," Sustainability, vol. 12, no. 6, p. 2268, 2020.

[21] A. A. M. M. Ali, A. M. Negm, M. F. Bady, and M. G. Ibrahim, "Environmental life cycle assessment of a residential building in Egypt: a case study," Procedia Technology, vol. 19, pp. 349-356, 2015.

[22] A. Arena and C. De Rosa, "Life cycle assessment of energy and environmental implications of the implementation of conservation technologies in school buildings in Mendoza—Argentina," Building Environment, vol. 38, no. 2, pp. 359-368, 2003.

[23] M. U. Siddiqi et al., "Low cost three-dimensional virtual model construction for remanufacturing industry," Journal of Remanufacturing, vol. 9, pp. 129-139, 2019.

[24] J. K. Daljit Singh, G. Molinari, J. Bui, B. Soltani, G. P. Rajarathnam, and A. Abbas, "Life cycle assessment of disposed and recycled end-of-life photovoltaic panels in Australia," Sustainability, vol. 13, no. 19, p. 11025, 2021.

[25] Department of Climate Change and Energy Efficiency, "Baseline Energy Consumption and GHG Emissions in Commercial Buildings In Australia Part 1," November 2021, Available: https://www.energy.gov.au/sites/default/files/baseline-energy-consumption-part_1-report-2012.pdf.

[26] R. Hartwell and M. Overend, "Unlocking the re-use potential of glass Façade systems," Glass Performance Days, vol. 2019, pp. 273-280, 2019.

[27] J. Giesekam, J. R. Barrett, and P. Taylor, "Construction sector views on low carbon building materials," Building research information, vol. 44, no. 4, pp. 423-444, 2016.

[28] C. F. Dunant, M. P. Drewniok, M. Sansom, S. Corbey, J. M. Allwood, and J. M. Cullen, "Real and perceived barriers to steel reuse across the UK construction value chain," Resources, Conservation Recycling, vol. 126, pp. 118-131, 2017.

[29] J. Kirchherr, D. Reike, and M. Hekkert, "Conceptualizing the circular economy: An analysis of 114 definitions," Resources, conservation recycling, vol. 127, pp. 221-232, 2017.

[30] J. Walzberg, G. Lonca, R. J. Hanes, A. L. Eberle, A. Carpenter, and G. A. Heath, "Do we need a new sustainability assessment method for the circular economy? A critical literature review," Frontiers in Sustainability, vol. 1, p. 620047, 2021.

[31] Y. Yu, D. M. Yazan, V. Junjan, and M.-E. Iacob, "Circular economy in the construction industry: A review of decision support tools based on Information & Communication Technologies," Journal of cleaner production, vol. 349, p. 131335, 2022.

[32] M. R. Munaro, S. F. Tavares, and L. Bragança, "Towards circular and more sustainable buildings: A systematic literature review on the circular economy in the built environment," Journal of cleaner production, vol. 260, p. 121134, 2020.

[33] E. M. Foundation, "An approach to Measuring Circularity" Cirularity Indicators Methodology. ," 2019, Available: https://emf.thirdlight.com/link/3jtevhlkbukz-9of4s4/@/preview/1?o.

[34] T. B. Consul and J. M. F. de Paiva, "MATERIAL CIRCULARITY INDICATOR APPLIED TO RECYCLED HIPS AND CLAY COMPOSITES."

[35] F. Krausmann, H. Schandl, N. Eisenmenger, S. Giljum, and T. Jackson, "Material flow accounting: measuring global material use for sustainable development," Annual Review of Environment Resources, vol. 42, pp. 647-675, 2017.

[36] I. M. Voskamp, S. Stremke, M. Spiller, D. Perrotti, J. P. van der Hoek, and H. H. Rijnaarts, "Enhanced performance of the Eurostat method for comprehensive assessment of urban metabolism: A material flow analysis of Amsterdam," Journal of Industrial Ecology, vol. 21, no. 4, pp. 887-902, 2017.

[37] A. W. Larsen, H. Merrild, and T. H. Christensen, "Recycling of glass: accounting of greenhouse gases and global warming contributions," Waste Management Research, vol. 27, no. 8, pp. 754-762, 2009.

[38] S. Manfredi, D. Tonini, T. H. Christensen, and H. Scharff, "Landfilling of waste: accounting of greenhouse gases and global warming contributions," Waste Management Research, vol. 27, no. 8, pp. 825-836, 2009.

[39] B. Johnke, "Emissions from waste incineration," Good Practice Guidance Uncertainty Management in National Greenhouse Gas Inventories, pp. 455-468, 2000.

[40] UK WIN, "Evaluation of the climate change impacts of waste incineration in the United Kingdom," October 2018, Available: UKWIN-2018-Incineration-Climate-Change-Report.pdf.

[41] Glass Recycling NSW. Available: https://glassrecyclingnsw.com.au/

[42] NSW EPA. Energy Recovery Facilities. Available: https://www.epa.nsw.gov.au/error-pages/404?item=%2fyou+environment%2fwaste%2fwaste-facilities%2fenergy-recovery&user=extranet%5cAnonymous&site=website

[43] Kimbriki. Kimbriki Recycling and Resource Centre, Mova Vale. Available: https://kimbriki.com.au/

[44] S. Abdoli, S. Kara, and M. Hauschild, "System interaction, System of Systems, and environmental impact of products," CIRP Annals, vol. 68, no. 1, pp. 17-20, 2019.

[45] S. Abdoli, S. Kara, and M. Hauschild, "Green paradox and the role of life cycle engineering," Procedia CIRP, vol. 90, pp. 159-164, 2020.

[46] S. Abdoli, S. Kara, and M. Hauschild, "An investigation into environmental impact of system of systems," Procedia CIRP, vol. 80, pp. 584-589, 2019.

## Biography

**Brian Smith** is an undergraduate student in School of Mechanical and Manufacturing Engineering, UNSW. He works in the built environment, performing building science studies.

**Shiva Abdoli** (*1970) is a lecturer in School of Mechanical and Manufacturing Engineering, UNSW. She worked as a researcher in KTH University, Sweden. She received her Ph. D in 2019 from UNSW. After her post-doctoral fellowship, she started as a Lecturer in 2020 at UNSW. She has led industry-based research projects. Her research field includes System design, Industry 4.0, Sustainable Production, and Circular Economy.