NSW
Circular

Benchmarking and monitoring the Greenhouse Gas implications of a circular economy in NSW

March 2022

Prepared for NSW Circular by the Institute for Sustainable Futures with The University of Newcastle, The University of Sydney, UNSW Sydney, and Macquarie University.

This review was initiated by NSW Circular's Government Taskforce and conducted via a collaboration between the Institute for Sustainable Futures, UTS, the University of Newcastle, the University of Sydney, UNSW Sydney, and Macquarie University.
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Executive Summary

We are currently experiencing the detrimental environmental consequences of our ‘take-make-waste’ system, where ignoring the limitations of the physical world has resulted in the overshoot of several planetary boundaries

(IRP, 2018; Steffen et al., 2015; Wiedmann et al., 2020).

Leaders across the globe are calling for a shift from the linear ‘take-make-waste’ economic system to a circular economy (Australian Government, 2018; Circle Economy, 2021; Ellen MacArthur Foundation, 2014; European Commission, 2020; Government of Canada, 2021); signalling a collective recognition of the impact of human activity on the planet and a shared responsibility to take action. A shift that is necessary if we are to meet the Sustainable Development Goals, achieve Paris Agreement commitments, and provide for future generations.

Australian states and sub-national regions across the world understand the environmental, social, and economic value in shifting to a circular economy (CE), resulting in several policy statements and strategies (Flanders Circular Economy Policy Research Centre, 2021; Government of South Australia, 2020; NSW Circular, 2020; NSW Government, 2018; Queensland Government, 2021; Victorian Government, 2020).

A key challenge for policy makers at the sub-national scale is gaining clarity on the environmental, social, and economic benefits and trade-offs associated with circular initiatives. Our research found case studies from across the globe, that modelled the implications of sub-national circular policies. A similar modelling exercise would be valuable for New South Wales, where clarity on the opportunities and trade-offs embedded in circular interventions will enable informed decision making and guide target setting for a sustainable future.

The relative merits and weaknesses of methods that could be used to understand our impacts and monitor changes, particularly in relation to Greenhouse Gas (GHG) emissions, as a result of circular interventions at the sub-national scale are not well understood. A number of agencies representing EU member countries as well as researchers across the globe have provided detailed technical documents outlining applied impact assessment and accounting approaches at the macro (national, global) scale (Ellen MacArthur Foundation, 2015; PBL Netherlands Environmental Assessment Agency, 2018; UNECE, 2021), however applied GHG accounting approaches at the meso (industrial park, sector, city, state) scale or that link across scales are still emerging.

This review, initiated by the NSW Circular’s Government Taskforce and conducted via a collaboration between the Institute for Sustainable Futures (UTS), the University of Newcastle, the University of Sydney, UNSW Sydney, and Macquarie University, investigates the methods, tools, and data that could be applied to measure the GHG emissions implications of a CE in NSW.

Global case studies were collected using desktop research of those methodologies that have been applied by policymaking agencies to benchmark and monitor the GHG implications of CE initiatives. These case studies were then compared to the requirements identified in workshops with NSW policy, research, and industry stakeholders.

Stakeholders noted three key requirements:

1. The ability to benchmark GHG emissions at the state (and regional where possible) scales and monitor changes in GHG emissions as a result of CE policy interventions,
2. The ability of methodologies to integrate data from a range of sources that may be applicable at different scales,
3. The approach should be internationally standardised to meet national and international obligations.

Findings

Research indicates that Hybrid Life Cycle Assessment (H-LCA)[1] meets the requirements identified during our stakeholder consultations because:

- H-LCA is applied by policymaking agencies across the globe to benchmark and monitor changes in GHG emissions as a result of CE interventions,
- H-LCA is a common methodology with case study examples at the meso (industrial park, sector, city, state) and macro (nation, world) scales,
- H-LCA is named because of its ability to integrate both physical and financial data sources to create a more complete dataset, and
- H-LCA is an internationally standardised system of environmental-economic accounting

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[1] We use the term Hybrid Life Cycle Assessment (H-LCA) to describe the spectrum of hybridisation approaches, the final hybridisation method will depend on data availability, data resolution, and the preferences of the practitioner performing the modelling exercise. For more information on H-LCA approaches refer to (Crawford et al., 2018)

Our analysis found that H-LCA methods can address some of the data related challenges suffered by meso scale accounting. We also note that, as with any accounting approach, there are benefits and there are limitations, as modelling is inevitably based on assumptions and relies on the availability and accuracy of data (which can be time consuming and costly to collect). Based on the case studies collected during our literature review, we expand on some of these benefits.

Hybrid accounting approaches, named for their ability to blend data from different methodologies (Crawford et al., 2018), offer a pragmatic approach to incomplete data across scales. Data incompleteness has been reported by academic and business stakeholders as a challenge when calculating and monitoring meso scale impacts at a high resolution or detail. Macroeconomic input-output models typically use financial data to track material, product, energy, and trade flows across the economy, which is beneficial for analysing complex internationally connected supply chains. However, financial data is limited in its ability to accurately represent specific physical flows of materials due to valuation and price fluctuation issues. Hybrid approaches address this problem by integrating physical data from process methodologies (where possible) and monetary data from IO tables (where physical data is lacking) to comprehensively represent economy wide environmental-economic interactions and flows.

In most cases, macroeconomic input-output tables lump very different business practices into sector groups and often lack the detail required to accurately track sectoral variations, such as when new technologies or processes are introduced (e.g., new renewable energy entrants to the energy sector). One approach to better representation of sectoral practices is Hybrid Input-Output Analysis (HIOA). HIOA can consider the GHG profiles of new sectors, or new technologies (such as recycling processes) at the micro (material, product, company), meso (industrial park, sector, city, state), and macro (country, world) scales, by customising macroeconomic tables through augmentation. Augmentation describes integrating new products or sectors into macroeconomic tables, whereby data that represents these new practices is essentially ‘plugged in’ as a new commodity, or sector. This approach has been used by several case studies collected through our rapid review, including examples focused on Australia.

Evaluating case studies for adoption in NSW

We identified a total of 15 case studies from academic literature, and reports from government and private organisations. We then assessed the case studies according to coding parameters to rate the relevance of each case study to the state of NSW.

Three case studies in The Netherlands (CBS, 2015; PBL Netherlands Environmental Assessment Agency, 2018; Schmidt, 2010; Van Berkel & Delahaye, 2019), South Australia (Lifecycles, 2017), and Flanders, Belgium (Acker et al., 2018; Flanders Circular Economy Policy Research Centre, 2021) were considered of higher relevance according to our coding, indicating the emerging nature of CE modelling capability at the meso scale.

While these case studies show promise, considerable effort in terms of data collection, modelling development, and stakeholder coordination would need to be achieved to implement a solution in NSW. High level results are shown in Table 1, where blue indicates no barriers/issues/gaps, amber indicates some barriers/issues/gaps, and black indicates major barriers/issues/gaps. For more detail see ‘Evaluating Case Studies for Adoption in NSW’ section of the main report.

Table 1: Summary of case study assessment results

(Blue = No barriers/issues/gaps, Amber = Some barriers/issues/gaps, Black = Major barriers/issues/gaps)

Case Study					**Notes**
The Netherlands (CBS, 2015; PBL Netherlands Environmental Assessment Agency, 2018; Schmidt, 2010; Van Berkel & Delahaye, 2019) **2 points**	SCOPE	INDICATORS	DATA	FINAL ASSESSMENT	**Opportunities** The Netherlands modelling capability focuses on the macro scale, however, meso scale capability is developing. A suite of environmental, and social impact indicators is monitored. The Netherlands will be one to watch as higher data resolution and modelling capability develops at the meso scale. **Barriers** Modelling currently focuses on the national scale, meso scale data may take some time to collect, consolidate, and integrate. The study also noted a limit of physical data relating to repair services.

Case Study					Notes
South Australia (Lifecycles, 2017) **2 points**	SCOPE	INDICATORS	DATA	FINAL ASSESSMENT	**Opportunities** A hypothetical case study that shows the capability of Australian modelling at the sub-national scale. HIOA is applied at the state level using data sources that are currently available. The database used for this case study, IELab, is an Australian database that can be used to construct input-output base tables at the national, state, and regional resolution. These tables can then be used to integrate new business practices, production processes, and consumer behaviours via augmentation if necessary. **Barriers** The case study relies on data with limited sectoral detail. Assumptions that underpin modelling scenarios are simplified to simulate a hypothetical circular transition in this case study, however, significant additional efforts would be needed in terms of data collection, and sectoral disaggregation to use this approach for benchmarking and monitoring progress in NSW.

Case Study					Notes
Flanders, Belgium (Acker et al., 2018; Flanders Circular Economy Policy Research Centre, 2021) **3 points**	🟦 SCOPE	🟦 INDICATORS	🟧 DATA	🟧 FINAL ASSESSMENT	**Opportunities** The Flanders case study is a good example of what is achievable at the sub-national scale. A suite of circularity indicators has been developed to monitor both the technical and ecological spheres. Sufficiently disaggregated data is collected on an annual basis from waste treatment facilities, recyclers, and the manufacturing industry. This case study provides a good example of what could be achieved in NSW, albeit with a recycling focus. **Barriers** The case study notes the difficulty in linking data across scales. The Flanders example is predominantly focused on opportunities for raw material efficiency, supported by recycling – only one of the four Rs. Modelling could extend to consider changes in service industries and consumer behaviour that may indicate more meaningful shifts – Reduce and Reuse. An undertaking of this level in NSW is possible, however it would require focused time, expertise, and financial resourcing as well as efforts to overcome any barriers to linking data across scales i.e., industrial park, city, or regional scales.

Opportunities and barriers for NSW

Approaches to benchmarking GHG emissions performance and measuring GHG emissions reductions at the macro scale have received a large amount of focus in recent years (Ekins et al., 2019; Ellen MacArthur Foundation, 2015; PBL Netherlands Environmental Assessment Agency, 2018; UNECE, 2021). That has resulted in a growing collection of examples, employing hybrid methods to benchmark activities and measure progress towards a CE, however examples at the meso scale are few and emerging, highlighted by the lack of available case studies.

Several Australian opportunities could be leveraged to develop modelling capability that can benchmark and monitor NSW GHG emissions in the context of CE interventions:

1. The Australian Industrial Ecology Virtual Laboratory is a collaborative research platform that provides environmentally extended multi-region input-output tables (in supply and use table format) at high sectoral and regional resolution (Lenzen et al., 2014, 2017; Wiedmann, 2017). Carbon footprint analyses have been performed at the level of products and metropolitan areas (Chen et al., 2016; Teh et al., 2018; Wiedmann et al., 2016; Yu & Wiedmann, 2018). This platform provides a significant opportunity for decision makers to leverage research expertise and develop a customised modelling solution for NSW,

2. Some of the best examples of environmental-economic accounting being integrated into decision making can be found in the Australian construction sector. Where significant progress has been made to disaggregate sectoral data and produce detailed GHG profiles for a share of construction materials, via the EPiC database. The NSW residential building code, BASIX, is now extending to consider embodied emissions by including the emissions profiles provided by the EPiC database. Significant efforts have also been made to develop a process-based dataset for the agricultural sector. Similar exercises could be performed in other high impact sectors such as food, transport, manufacturing, and waste,

3. Research by the CSIRO on the use of sensors to collect data on methane emissions profiles has recently been performed in NSW (Day et al., 2016). These learnings could be integrated into future data collection procedures for those emissions that are harder to quantify.

However, barriers remain, highlighting a need for further research and development:

1. Industry experts indicate that organisations currently use a wide range of calculation approaches to estimate their GHG emissions resulting in varying degrees of accuracy. A common data management framework would need to be developed to ensure the consistency of data collected,

2. Some sectors will contain a share of both industry and household stakeholders, such as the transport sector; therefore, there is work to be done to determine the best approach for data collection from different stakeholder groups. One case study provided an alternative solution, by combining secondary data sources as proxies to infer household

activity at the municipal scale across Europe (Pichler et al., 2021). This approach may be a pragmatic solution; however, further research is needed to apply this method to NSW,

3. Sensor based data collection approaches may be more accurate for emissions data that is harder to quantify, such as methane emissions from gas seepage, but these methods can be costly (Day et al., 2016),
4. Research indicated a common tendency of CE interventions to emphasise the importance of recycling over interventions that may achieve more meaningful impacts – such as redesign, reduce and reuse (Bauwens, 2021; Kirchherr et al., 2017; Parrique et al., 2019; Wahl, 2016). Many of the modelling approaches reflected this bias, however, Donati et al. (2020) and Lifecycles (2017) demonstrate the potential for models to consider higher order interventions if appropriate scenarios were considered during the scenario design stage. To reap the full suite of environmental, social, and economic benefits offered by CE, future modelling and policy developments in NSW should consider higher order possibilities and resist the urge to over emphasise the importance of technical solutions like recycling,

Areas for future focus

Based on our analysis and discussion of current accounting capability, modelling approaches, opportunities, and barriers, we present several recommendations for future focus when developing NSW modelling capability. Recommendations have been divided into three time periods: short-term, mid-term, and long-term. These recommendations should not be taken as a complete list but offer a starting point on which stakeholders can build, expert advice should be sought to determine the specific approach[2].

Table 2: Short-term, mid-term, and long-term focus areas for stakeholders

SHORT-TERM FOCUS (1–3 years)	**MID-TERM FOCUS (3–5 years)**	**LONG-TERM FOCUS (5–10 years)**
1. Production or consumption? Define GHG emissions responsibility framing for NSW (i.e., production or consumption). Ideally, modelling should consider both. Determine environmental, social, and economic impact categories.	Monitor production v consumption responsibility GHG relationship to avoid the increase in 'offshoring' of responsibilities – this may include Australian states & territories, and/or other countries and their regions. Develop relationships with low and high emitting producers outside of NSW with an aim to influence the GHG intensity of consumption activities within NSW.	
2. Industries to focus on Perform initial footprint estimate for NSW and determine industries of focus.	Publicly report GHG intensity and compare results between CE and BAU practices. Report time-series CE related GHG reduction totals. Analyse and report on CE trends.	
3. Stakeholder mapping Stakeholder mapping and stakeholder directory for relevant sectors Set sector-based targets for GHG emissions reductions	Educate stakeholders via the stakeholder directory on sector-based targets and optimal CE business models	

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[2] Expert advisors for H-LCA modelling solutions including production vs consumption responsibility, baseline estimates, and data collection: Tommy Weidman (UNSW); Arunima Malik (USyd); Manfred Lenzen (USyd). Advisors for stakeholder mapping, target setting, scenario development and circular metrics: Melita Jazbec (ISF); Damien Giurco (ISF); Will Rifkin (UON); Ali Abbas (USyd); Rusty Langdon (ISF).

SHORT-TERM FOCUS (1–3 years)	MID-TERM FOCUS (3–5 years)	LONG-TERM FOCUS (5–10 years)
4. Targets Define CE interventions according to stakeholder groupings **5. Interventions & metrics** Define relevant metrics for monitoring the impact of interventions and progress against sector-based targets Define modelling scenarios for CE relevant GHG emissions comparisons	Monitor progress against CE metrics and targets and implement actions to encourage progress	Revisit sector-based targets as emissions profiles shift Redefine scope, data collection framework, and metrics of relevance where necessary
6. Identify quality data Once scale, responsibility, targets, scenarios, and stakeholders are established, a data availability and quality mapping exercise should be performed to identify what data is available and where further data needs to be collected Define a common data collection framework for stakeholder groups	Continue to collect detailed industry data to integrate new technologies and process improvements	
7. Collect and analyse Collect detailed industry data in focus sectors from stakeholder groups and augment NSW environmental-economic tables to integrate current and future CE practice. Common international practice for data collection is annually.		

Introduction

The Anthropocene, classified as such due to the dramatic impacts of human activity on the planet, is an era in which we experience the alarming environmental consequences of human consumption.

Our growth focused economic system ignores the limitations of the physical world, resulting in the overshoot of four out of nine planetary boundaries (Boyden, 2020; IRP, 2018; Wiedmann et al., 2020). Global warming, resource scarcity, and ecosystem collapse are dire examples all on their own, combined they create a perfect storm of environmental issues affecting the ability of current human activity to continue unabated.

The Intergovernmental Panel on Climate Change (IPCC) has recently released the first part of their sixth assessment report, indicating we are 'more likely than not' to exceed global warming of 1.5 degrees even if we reduce global greenhouse gas (GHG) emissions to net-zero by 2050 (IPCC, 2021). Our unsustainable resource consumption trend contributes approximately 50 percent of global GHG emissions (Boyden, 2020; IRP, 2019). The fossil fuel dependency of our economic system and our reliance on non-renewable resources has resulted in the continual growth of GHG emissions, locking in a warmer future.

Our growth driven, linear, take-make-waste, economic system is inherently unsustainable. 90 percent of global biodiversity loss and water stress is caused by global resource consumption (Boyden, 2020; IRP, 2019). The quantity of raw natural resources required to feed such a system indefinitely, equates to more than what is physically available on the planet. The negative impacts of affluence driven consumption are enabled by the linear system (Lamb et al., 2021; Wiedmann et al., 2020) and this is only expected to worsen as global affluence increases (Wiedmann et al., 2015a).

We are witnessing the impacts to life supporting ecosystems because our economic system is pushing up against the limits of the physical world (Circle Economy, 2021; Ellen MacArthur Foundation, 2014; European Commission, 2020). These life supporting environments are critical not only for the purpose of animal habitat and human need but also as carbon sinks. Healthy ecosystems are essential for drawing down the excessive GHG emissions already trapped in our atmosphere.

Given the dramatic changes to earth systems we are likely to experience over the coming decades, there is a call to change the current linear economic system if it is to serve humanity into the future (Circle Economy, 2021; Ellen MacArthur Foundation, 2014; European Commission, 2020). For a new economic system to reverse the impacts of human activity on the earth, it must respect planetary boundaries, value the environment, value humans, and work within rather than against these physical and social limits. A circular economy aims to do just this, by reflecting the circular relationships found within the environmental and social systems it seeks to organise, within planetary boundaries.

Circular economy – what is it?

Circular Economy (CE) is often offered as a solution to the ills of the current economic system. The complex foundations of CE theory have developed over many decades however, the common title now used was coined by Pearce and Turner (1991). The premiss is a socio-economic system that imitates nature, where materials, energy, and nutrients circulate around the system over and over, creating little-to-no waste.

As definitions have evolved over time, researchers have attempted to provide clarity. Kirchherr (2017) analysed 114 definitions of the CE and coded them according to a 4Rs framework (reduce, reuse, recycle, recover) with the most common definitions featuring 3Rs – reduce, reuse, recycle. Kirchherr's analysis also pointed to the overwhelming focus on the third R – recycle – a focus which has received criticism from others (Parrique et al., 2019; Wahl, 2016). One of the most popular visual representations of the CE is the butterfly diagram, developed by the Ellen Macarthur Foundation, (Ellen Macarthur Foundation, 2019)

Over the last ten years, the CE concept in its various forms has moved to the mainstream thanks to policy progress made in China, Canada, and the European Union, initiatives led by the Ellen MacArthur Foundation, and contributions from NGOs and academia.

Mainstream global CE initiatives are predominantly focused on the benefits that CE can offer for industry and governments in terms of material recycling and material efficiency (Bauwens, 2021; Kirchherr et al., 2017; Parrique et al., 2019), with the aim to decouple economic growth from raw material consumption and associated environmental impacts (Boyden, 2020; Stahel, 2010). However, the degree to which economic growth can be decoupled from raw material consumption is still contested. Current research critiques the way in which the CE concept becomes muddied when applied with a growth focus (Bauwens, 2021; Geissdoerfer et al., 2017; Hobson & Lynch, 2016; Parrique et al., 2019; Webster, 2021). Many have acknowledged the limitations of a focus on end-of-life solutions like recycling, as this ignores the broader issues associated with unabated consumption and reduces opportunities for more meaningful impacts upstream of waste management (Bauwens, 2021; Parrique et al., 2019; Wahl, 2016), such as the role of design (RSA, 2013), degrowth (Bauwens, 2021; Hobson & Lynch, 2016) and regenerative practices (Wahl, 2016).

Australian progress on circular economy

Australia has committed to reducing GHG emissions to net-zero by 2050 (Australian Government, 2021), however achieving this will be no mean feat, Australians have one the highest consumption footprints per capita in the world (Wiedmann et al., 2015a). Many of the products Australians consume are produced in other countries, which makes us particularly vulnerable to supply chain shocks (NSW Circular, 2020; Wiedmann et al., 2015). We also landfill more of our waste than most other developed countries in the world (NSW Circular, 2020) and future increases on landfill capacity are heavily constrained across the country (Pickin, 2009). Greater Sydney's landfills are expected to reach capacity by 2036, if current waste generation trajectories are maintained (NSW DPIE, 2021). In addition, China has recently placed a ban on receiving our contaminated and unsorted recycling via the China National Sword policy and developing nations lack the infrastructure to deal with our growing waste problem, a problem we should be dealing with ourselves. This suite of issues faced by policy makers over the coming decades has resulted in the consideration of CE as a promising multidimensional solution.

A holistically applied CE in Australia would put the country in good stead to reap the many environmental, social, and economic benefits it offers. But this would require a huge cultural, political, and economic shift, hence why most CE initiatives tend to focus on what can be done *within* a linear economic system - efficiency and recycling – rather than replacing the economic system with something better.

Currently, Australian national CE initiatives are focused on the growth opportunities at the end-of-life phase via the *National Waste Policy* and the *Circular Economy Roadmap* (Australian Government, 2018; Schandl, King, et al., 2020) and sadly neglect the plethora of CE opportunities upstream – design for durability, disassembly, repair, and reuse, sharing, de-growth, regeneration.

Modelling the circular economy in NSW

Australian states and territories such as New South Wales (NSW) (NSW Government, 2018), Queensland (QLD) (Queensland Government, 2021), Victoria (VIC) (Victorian Government, 2020), and South Australia (SA) (Victorian Government, 2020) are recognising the value in encouraging a more sustainable economic system at the sub-national level and are at the preliminary stages of implementing CE policy and initiatives.

Policymakers are also recognising the dual opportunities found in reducing the impact of material consumption whilst also reducing GHG emissions. However, there is currently a lack of clarity on the benefits and trade-offs associated with one CE initiative over another in terms of GHG emissions reductions. A study focused on SA has modelled the GHG emissions implications of state based CE policies (Lifecycles, 2017). A similar modelling exercise would be valuable for NSW, as it will enable decision makers to understand the future GHG emissions opportunities and trade-offs of future CE interventions.

This research sets up the NSW modelling exercise by gathering best practice examples of GHG emissions accounting methodologies and analyses their relevance for modelling the impacts of CE interventions in NSW. We acknowledge the limitations associated with a focus on a single environmental impact category when considering the CE. We acknowledge throughout the report the necessity to consider environmental impacts more holistically, to avoid shifting the environmental burden from one impact category to another. However, the scope of this research is to consider the potential to benchmark and monitor GHG emissions in light of CE interventions.

Within the NSW context, we are considering three levels of aggregation for measuring the GHG emissions of a CE. 'Macro' represents global and national figures, where over a decade of work has been undertaken in modelling and tracking material extraction and use and the emissions that accompany that. 'Meso' represents a focus on an industrial park, industrial sector, a region or city, or a state, where experience suggests that estimates of material use, and emissions tend to be more incomplete and therefore more uncertain. 'Micro' scale is used here to refer to a focus on a particular material, product, process or organisation, where environmental product declarations, process-based life cycle assessment (LCA) literature, or company purchasing records can be useful, if available. We also note that, as with any accounting approach, there are benefits and there are limitations, as modelling is inevitably based on assumptions and relies on the availability and accuracy of data (which can be time consuming and costly to collect and compile). We discuss the implications of these benefits, limitations, and assumptions and indicate a pragmatic approach for the NSW context.

Aim of this review

The focus of this review is to analyse the methodologies that could be used to measure the GHG emissions implications of circular economy in NSW.

Global case studies of methodologies applied by policymaking agencies to benchmark and monitor the GHG implications of CE initiatives were collected using desktop research. We also collected examples of novel approaches from academic and private sectors. The capabilities, opportunities, and gaps of methodology examples were compared against the requirements of NSW policy, research, and industry stakeholders. We found that Hybrid Input-Output Analysis meets most of the requirements identified during our stakeholder consultations and is the common methodology used by case study examples at the meso (industrial park, sector, city, state) scale.

Hybrid accounting approaches, named for their ability to blend data from different methodologies (Crawford et al., 2018), provide a more complete system coverage by integrating physical data (where possible) and monetary data (where physical data is lacking) to comprehensively represent economy wide environmental-economic flows. Hybrid methods can consider the GHG profiles of new technologies (such as new recycling processes) at the micro (material, product, company), meso (industrial park, sector, city, state), and macro (country, world) scales. Hybrid methods suit the requirements of policymaking agencies to benchmark and monitor the GHG implications of a CE in other countries and regions, however, to understand their readiness for adoption in NSW, we undertake an analysis of capability, data availability and gaps, and opportunities for further development and compare these with the requirements of decision-making stakeholders.

Scope of analysis

This review was initiated by the NSW Circular's Government Taskforce and conducted via a collaboration between the Institute for Sustainable Futures (UTS), the University of Newcastle, the University of Sydney, UNSW Sydney, and Macquarie University. The scope of the review was to investigate the methods, tools, and data that could be applied to measuring the emissions implications of a CE in NSW.

Methodology

A combination of desktop research and stakeholder engagement was used to inform this review. Desktop research was performed to collect academic and grey literature on the current drivers of circularity, frameworks for considering circularity, indicators for measuring circularity, leading environmental-economic accounting practice, current tools and databases, current gaps, and emerging capabilities. This was supplemented through workshop consultation with expert panels from academia, government, and industry to provide further insight on data availability, preferred methods, and potential barriers to adoption.

The first workshop with academic participants informed the identification of leading practices, potential sectoral cross sections or groupings, and gaps in data and methodologies. The second workshop involved both academic participants and government representatives to discuss the opportunities and barriers to implementing theoretical methods in practice at the state or regional level. The third workshop involved industry participants and sought to understand opportunities and barriers at the individual sector or industry level, a form of 'sense checking'.

Inputs from stakeholder workshops were collated, analysed, and synthesised according to common themes, namely requirements, current capability, opportunities, and gaps. These themes were then integrated with information collected through desktop research and used to inform an assessment of best practice that could be applied to the NSW CE context.

Criteria for assessing global case studies relevant for NSW

Assessment criteria was developed to analyse examples of current GHG accounting practices that have been applied in countries and regions across the globe to benchmark and monitor CE performance and assess their similarities to the New South Wales context.

To inform an evaluation of the most appropriate case studies, we gathered information according to four criteria:

1. The scope of consideration (production versus consumption) and scale at which the method is applied (micro, meso, macro),
2. Indicators used to benchmark performance and measure progress,
3. Is the accounting method currently being used by policymaking agencies to monitor CE progress,
4. Data availability and use.

The information categories are further described in Table 3.

Table 3: Information collected according to the following criteria is used to inform an evaluation of accounting methodologies and their appropriateness for measuring the GHG emissions implications of a CE in New South Wales.

ASSESSMENT CRITERIA	DESCRIPTION
Scope of consideration	What accounting methodologies are being applied in countries and regions across the globe that benchmark and monitor CE performance? (e.g., Process-based LCA, Monetary Input-Output Analysis, Physical Input-Output Analysis, or Hybrid LCA). What scale does the methodology consider (e.g., micro, meso, or macro)? Does the method measure CO2e emissions? Which other impact categories does it consider (i.e. energy use, water use, land use, minerals circulation, material use, etc)? Is there potential to extend the impact categories? What responsibility is assumed (i.e., production versus consumption responsibility)? How are boundaries applied?
Benchmarking and performance indicators	Which circular economy indicators are considered? Is there anything excluded that should be incorporated? What possibilities are available for extension of the methodology?
Case study examples	Are the accounting approaches being applied to benchmark, monitor, and evaluate GHG emissions reductions at the meso scale in the context of CE transitions? Is the accounting method used by policymaking agencies to monitor progress against CE strategic goals or targets? Are there case study examples applied in other Australian States and/or Territories?
Data availability	What data sources are currently available and used globally? Are these data sources available in Australia? Would new or additional data need to be collected for NSW? How difficult is it to access new or additional data for NSW?
Final assessment of appropriateness based on the above criteria	Summary of key findings and discussion of appropriateness for the NSW context.

We then assessed the case studies according to three coding parameters to rate their appropriateness to the state of NSW. Case studies were deemed appropriate here according to these coding parameters:

- The use of hybrid modelling (1 point),
- Application of CE modelling at the sub-national or meso scale (1 point),
- Use by policymaking agencies to monitor economy wide GHG reductions related to CE initiatives (1 point).

A score of two points or above was considered 'highly relevant', while a score of 1 points or below was considered of lower relevance. Case studies identified with high relevance for NSW requirements were then further evaluated, with the results presented as a traffic light assessment. Where blue indicates no barriers/issues/gaps, amber indicates some barriers/issues/gaps, and black indicates major barriers/issues/gaps. An example of the traffic light assessment framework can be found in Table 4.

Table 4: Example framework for traffic light assessment (blue= no barriers/issues/gaps, amber = some barriers/issues/gaps, and black = major barriers/issues/gaps

CASE STUDY	TRAFFIC LIGHT INDICATOR	DESCRIPTION
Scope	🟧	
Indicators	🟦	
Data availability	⬛	
Final assessment	🟦	

Methodological approaches to benchmarking and monitoring performance

Benchmarking CE performance and measuring progress can be achieved by applying various environmental-economic accounting methodologies; this is within the bounds of the ability for CE to limit GHG emissions.

Accounting for GHG emissions of circular production and consumption within the context of a globalised economy relies on the ability to monitor material and energy flows. CE initiatives are designed to influence the material and energy that flows into processes used to produce, use, and dispose of the products and services that industry, households, and government organisations consume every day.

Broader dissemination by the European Union (EU) of information on applied GHG accounting methodologies relevant for the CE has been called for by the Ellen MacArthur Foundation and the Institute for European Environmental Policy (Carmen Valache-Altinel et al., 2021). A number of agencies representing EU member countries as well as researchers across the globe have provided detailed technical documents outlining applied environmental-economic accounting approaches at the macro scale (Ekins et al., 2019; Ellen MacArthur Foundation, 2015; PBL Netherlands Environmental Assessment Agency, 2018; UNECE, 2021), however applied GHG accounting approaches at the meso (industrial park, sector, city, state) scale or that link micro-meso-macro scales are still lacking.

The scope of this research is to collect case study examples of applied accounting approaches that could be used to quantify GHG impacts of CE flows at the meso scale and analyse the ability of these accounting approaches to consider complex supply chain interactions across micro-meso-macro scales. We note that while GHG emissions are an important environmental impact category and reducing GHG emissions should be a core objective for any future CE interventions in order to meet net-zero commitments, it should not be the single focus. Interventions that reduce GHG emissions in one product, process, or sector may shift the burden to another impact category. CE interventions to date are often narrowly focused on reducing material waste through recycling and are the object of scrutiny from a range of CE stakeholders. Therefore, it is recommended that any future accounting approach used to monitor the implications of CE transitions in NSW should consider a holistic suite of environmental, social, and economic metrics.

To understand the relevance and limitations of possible accounting approaches, it is important to assess the historical development of certain applications, the scale of system boundaries applicable to each and their implications, and the types of CE indicators that could be considered to measure the impact of CE initiatives on GHG emissions reduction.

Historical development of environmental-economic accounting approaches

Modelling the environmental flows into, within, and out of our economic system has been the focus of environmental economists since the 1970s. A rise in the awareness of environmental impacts, constraints on finite resources, and incidents of environmental pollution resulted in the environmental accounting methodologies we use and continue to develop today.

The application of environmental-economic accounting approaches has increased in recent years largely because of efforts to standardise methods to account for environmental impacts with national level socio-economic statistics. In 2006, the first iteration of the System of Environmental Economic Accounting (SEEA) was introduced by the UN Statistics Division (United Nations Statistics Division, 2007). This system of environmental accounting parallels the statistical modelling of financial flows used in countries across the globe, via the System of National Accounts (SNA). Shortly after the development of the SEEA, in 2008, OECD member countries developed guiding documents highlighting the various methodologies that could be applied to environmental-economic based material flow accounting at various scales (OECD, 2008). Process based Life Cycle Assessment (LCA), which focuses on product and organisation level impacts at the micro scale, also rose to prominence during this time, with the International

Organisation for Standardisation (ISO) releasing the ISO 14040 and 14044 LCA standard guidance.

These developments, and a push for harmonisation of methods across countries has enabled researchers, government agencies, and specialised consultancies to model global trade flows (Lenzen et al., 2021; Schandl, Lu, et al., 2020; Wiedmann & Lenzen, 2018; Wiedmann et al., 2015). However, modelling detailed material flows at the organisational and sub-national level using these macro focused methods poses a challenge due to data resolution constraints. But this trend may be changing.

Progress towards CE strategies and associated monitoring methodologies has been made in Europe, China, Canada, and Japan. In Europe, early implementation of a 'circular action plan' for the region in 2015 has enabled significant modelling progress, supported by a multi-regional material flow monitor that was implemented in 2008 (European Commission, 2020). Economy wide, national level material flow monitoring continues to form the backbone of a CE monitoring program in the EU. CE monitoring frameworks are slowly emerging at the sub-national or regional level, as well; however, sub-national or regional indicators to measure progress against the frameworks are often qualitative rather than quantitative in focus. And only a few examples consider GHG emissions due to a lack of collected and compiled data at this resolution.

Modelling material flows at the sub-national scale (meso and micro) requires time and resource intensive data collection and compilation to achieve the required level of detail. For this reason, very few meso scale applications of environmental-economic accounting methods are available. A couple of examples of capability emerging has been observed in the region of Flanders (Belgium), Amsterdam (The Netherlands), and in South Australia. The details of these case study examples are explored further in the case study evaluation section.

System boundaries, scale, and implications

Benchmarking and monitoring the performance of environmental-economic systems requires initial identification of the scale of focus for the modelling exercise. The system being studied must be given a boundary at the relevant scale. Methodologies for calculating circularity and GHG emissions can be applied at the micro scale (material, product, process, organisation), meso scale (industrial park, sector, city, state), and the macro scale (nation, globe) (OECD, 2020), as alluded to above.

Important considerations underly defining a system boundary at each scale. System boundary considerations are particularly relevant for the NSW context as in order to develop the appropriate CE modelling capability, certain decisions will need to be made on where the system boundary falls. These decisions will form assumptions that underly the modelling of interactions across supply chains at different scales. For example, if we are to focus a system boundary based on the NSW state border, are we measuring the direct emissions only within that state border (production responsibility) or are we also considering the emissions produced via products and services that enter and exit the system boundary (consumption responsibility)?

Defining the system boundary has legal, political, and financial implications for governments and businesses, and therefore needs to be considered carefully when benchmarking the GHG emissions of a region.

GHG emissions totals will vary significantly depending on the system boundary and responsibility assumed. For example, in Australia, our direct or territorial GHG emissions per capita is significantly smaller than our indirect or consumption based GHG footprint per capita, this is because a large proportion of the products we consume are imported (Wiedmann et al., 2015a). Defining system boundaries will also need to consider the data availability of export regions (those regions exporting product consumed in NSW). For example, if we are considering products and services imported from other states and countries, sufficient data will be required to model the GHG intensities of those products and services. Technology assumptions can be made where data is lacking, however, this approach introduces uncertainties.

Table 5 overleaf, highlights the various considerations and methodological examples used to measure progress at the micro, meso and macro scales.

Table 5: Common methodologies, what they measure, scope of application, data availability, and barriers to adoption.

SCALE	MICRO	MESO	MACRO
	Material, product, process, business	Industrial park, Industry sector, city, state	National, global
Scope of consideration and system boundaries	• Physical flows: inputs-outputs for products, processes, and services and assesses their environmental impacts, • Efficiency improvements of products, production processes, and business activities, • Calculations can be performed with publicly available software on personal computers, • Smaller system boundary means that, exclusions from scope are necessary, cut-off assumptions are applied, • Predominantly production-based or direct responsibility for GHG emissions (Scope 1, 2) but can integrate consumption or indirect impacts (Scope 3)	• Physical and financial flows: inputs-outputs and complex trade interactions, • Modelling capability can integrate the appropriate detail required to represent sectoral production variations (e.g., manufacturing businesses that integrate a percentage of recycled content into their production), • Ability to identify impacts of imports and exports, • Global standardisation via alignment with the System of Environmental Economic Accounting (SEEA), • Flexible resolution for modelling micro-meso-macro level flows and interactions, • Multi-regional physical and monetary interactions at the regional, state, and national scale, • Ability to consider production (direct) or consumption (indirect) impacts • Can represent flows across borders, however global interactions are difficult to assess at a high resolution	• Economy- wide monetary interactions and flows, • Multi-regional monetary transactions at the state, national, or global scale, • Can incorporate other physical flows and social impact categories at the national scale via satellite accounts (e.g., energy, water, GHG, employment), • Global standardisation via the System of National Accounts (SNA) and the System of Environmental-Economic Accounting (SEEA), • Ability to consider production (direct) or consumption (indirect) impacts, • Ability to represent flows across borders via consideration of imported and exported goods and services

SCALE	MICRO Material, product, process, business	MESO Industrial park, Industry sector, city, state	MACRO National, global
Data availability	Organisational data · Process data · LCA databases such as Exiobase, AusLCI, Ecoinvent, Agri-footprint, etc. · Academic literature	· Mixture of data sources from national statistics to process- level or organisational data. · Higher resolution sectoral data can be collected via survey methods, process-based LCA, and/or Environmental Product Declarations (though Life Cycle Inventory (LCI) data sources are a long way from comprehensively covering all products and materials). · Where process-based physical data is unavailable, monetary data from macro tables can be used to estimate product units (note that the preference is for physical units as there is a higher uncertainty in using monetary units as a proxy for product level flows and impacts).	· Limited sectoral detail, averages often hide variation in business practices within sectors, · Data sourced from national statistical agencies. E.g., Australian Bureau of Statistics (ABS), Environmental Protection Agency (EPA), National Greenhouse Gas and Energy Reporting Scheme (NGERS), National Pollutant Inventory (NPI).
Barriers to adoption	· Time and cost intensive data collection, · Data collection often limited to larger businesses with resources to invest in consulting expertise (i.e., environmental or sustainability consultants), · Data sensitivity issues (e.g., proprietary production recipes, sensitive financial information) · Databases and software are not freely available and sometimes come at considerable cost	· Time and cost intensive data collection to represent sub-sectoral detail (ANZIC 4-digit or finer), · Large database and processing capability required, · Use of secondary or proxy data (i.e., financial data to represent physical flows) increases uncertainty of results.	· Large database and processing capability required at high sectoral resolution or when representing multiple regions, · Use of financial data to represent physical interactions increases the uncertainty of results due to price fluctuations and valuation issues.

SCALE	MICRO Material, product, process, business	MESO Industrial park, Industry sector, city, state	MACRO National, global
Units measured	Physical unit flows (materials, GHG emissions, pollutants, water use, energy use, land use) and their impacts (global warming potential, ozone depletion, acidification, eutrophication, depletion of abiotic resources, human toxicity, eco-toxicity, particulate matter emissions).	Physical and monetary unit flows (materials, products, GHG emissions, pollutants, water use, energy use, taxes, finance, employment)	· Monetary unit flows (industry government and household financial flows, taxes, wages, value add) · Environmental and social extension of financial tables via satellite accounts (energy use, water use, GHG emissions, land use, employment)
Common terms used to describe methodologies	Process-based Life Cycle Assessment, ISO 14040 and ISO 14044, Environmental Product Declarations	Hybrid Input-Output Analysis, Mixed Unit Input-Output Analysis, Hybrid Life Cycle Assessment	Environmentally Extended Input-Output Analysis, Multi-regional Environmentally Extended Input-Output Analysis

Calculating GHG emissions factors

GHG emissions factors are calculated for products, processes, or organisations (micro scale) and then averaged to represent an industry sector at the meso or macro scale, however methods used to generate GHG emissions intensities can vary. In some cases, sensors are used to monitor emissions from the production processes of larger organisations (e.g., energy generators like coal fired power plants), in most other cases, use of sensors is not a mandatory requirement by reporting agencies and involves a high cost for smaller organisations and so GHG emissions are often estimated using nationally available emissions factors (in Australia, these are supplied by the National Greenhouse and Energy Reporting Scheme). Some organisations are not required to report emissions or energy use because they do not meet reporting thresholds, national emissions totals estimate these contributions via monetary data collected by statistical agencies.

Product level GHG calculations use process-based Life Cycle Assessment (LCA) methods to represent physical product units and unit processes. Methods are internationally standardised via the International Organisation for Standardisation (ISO) 14044 and 14040 methods. Several software packages (e.g., Simapro, OpenLCA) are available to calculate the environmental impacts of a product over its life cycle. These software packages integrate data on product level impacts via compatible databases, however, data contained within databases can be regionally specific (dependant on the GHG intensity of electricity generation within the region), data can be 'old' or lack representation of newer production technologies, and in the case of some products or materials, not available. LCA studies result in an inventory of product related impact information called Life Cycle Inventories (LCI) and can then be integrated into meso and macro tables to represent physical materials, products, and their impacts.

Measuring circularity: material flow and circularity indicators

Once GHG intensities are established, the next step is to benchmark current performance and measure progress, this requires the establishment of agreed metrics (or indicators) of progress. A range of metrics have been used to benchmark and monitor progress against CE strategies and objectives, differing depending on the scale at which they are applied (Humphris-Bach et al., 2016; Moraga et al., 2019; OECD, 2020; Pacurariu et al., 2021; Saidani et al., 2019; The Data and Statistical Studies Department France, 2021; Van Hoof et al., 2018; WBCSD, 2021).

Two types of indicators are relevant for measuring the GHG emissions implications of a CE, those are scale indicators, and circularity indicators (Jacobi et al., 2018; Mayer et al., 2019). Scale indicators consider the volume of inputs, stocks, and outputs that flow through an economy, in terms of materials, energy, and environmental impacts (e.g., GHG and substance emissions, water use, land use, etc). Circularity indicators measure the extent to which raw material or non-renewable energy flows are reduced per unit of production, or where flows circle back through the economy.

Indicators that represent industry or sector specific practices at the meso scale require more detailed data than at the macro scale, and so benefits are found in linking indicators across scales (Van Hoof et al., 2018). However, it can be difficult to link indicators across scales due to several issues: data is often unavailable at the meso scale and so mass balance estimations are required, introducing uncertainties in results (Flanders Circular Economy Policy Research Centre, 2021); collecting data at the micro and meso scales is time and resource intensive; and there is also a need to extend scale indicators to consider product lifetime extension (e.g., how long will each product spend in stocks) (Flanders Circular Economy Policy Research Centre, 2021; Van Hoof et al., 2018) and integrate production processes such as regenerative practices (e.g., reforestation, regenerative farming practices).

Scale indicators are used to quantify the material and energy flows of an economy over a given period (usually per year) and their associated GHG emissions impacts. Quantification of material flows and environmental footprints (such as GHG emissions) establish a current baseline estimate and then adjustments can be made over time to represent increases in circularity and monitored using circularity indicators. Examples of both scale and circularity indicators are highlighted in Table 6 below.

Table 6: Scale and circularity indicators used to monitor the CE.

Indicator	Description	Source
Scale Indicators		
DMC	Domestic material consumption	(Jacobi et al., 2018)(Mayer et al., 2019)
RMC	Raw material consumption	
PM	Processed materials (DMC + secondary materials)	
DPO	Domestic processed outputs	
DMI	Domestic material input	
RMI	Raw material input	
DE	Domestic extraction	
NAS	Net additions to stock	
eUse	Energy use	
DPOe	Emissions of DPO	
DPOw	Waste of DPO	
IntOut	Interim outputs (EoLw + DPO emissions)	
EoLw	End of life waste (e.g., waste generation, waste generation by waste type, food waste, municipal waste per capita, waste per DMC unit)	(Mayer et al., 2019)(OECD, 2020)(European Commission, 2018)
Consumption footprint	Total material consumption of the region	
Consumer footprint	Total material consumption of households	
Production footprint	Resources in the production chain	
Circularity Indicators		

Indicator	Description	Source
DMC per capita	Domestic material consumption per capita measures the reduction in demand for materials	(The Data and Statistical Studies Department France, 2021)
Resource productivity	Ratio of gross domestic product to domestic material consumption. Measures transitions in resource efficiency	(The Data and Statistical Studies Department France, 2021)
Recycling rates	Share of waste recycled (municipal waste, all waste)	(European Commission, 2018)
Recycling rate for specific waste streams	Share of waste recycled by waste stream (e.g., packaging waste, plastic packaging waste, wooden packaging waste, electrical and electronic waste, biowaste per capita, construction and demolition waste)	
Secondary raw materials	Contribution of recycled materials to raw materials demand (e.g., EoL recycling input rates, circular material use rate)	
	Trade in recyclable raw materials	
MCI	Material circularity indicator (at the product or company level)	(Ellen MacArthur Foundation, 2013)
CEPI or CPI	Circular economy performance indicator (considers the quality of material recycled). Requires detail on specific materials (e.g., plastic types)	(Huysman et al., 2017)
Socioeconomic Cycling (SC)		(Acker et al., 2018; Flanders Circular Economy Policy Research Centre, 2021)
ISCr	Input socioeconomic cycling rate = Share of secondary materials in processed materials	
OSCr	Output socio economic cycling rate = Share of secondary materials in IntOut	
Ecological cycling potential (EC)		
IECrp	Input ecological cycling rate potential = Share of DMC of primary biomass in PM	
OECrp	Output ecological cycling rate potential = Share of DPO biomass in IntOut	
Non-circularity		
INCr	Input non-circularity rate = Share of eUse of fossil energy carriers in PM	
ONCr	Output non-circularity rate = Share of eUse of fossil energy carriers in IntOut	
CI	Circularity Index = waste recovered compared to total material input.	
CGI	Circularity Gap Index = material wastes passed through treatment sectors not reintroduced as recovered materials	

Defining circular modelling scenarios

Product, organisation, or material comparison analysis aids the decision making process when comparing CE initiatives, this relies on defining and modelling alternative scenarios, also known as counterfactual scenarios (Donati et al., 2021). Counterfactual scenarios stipulate the assumptions used when manipulating data to integrate new product or sectoral information and compare results with a baseline. For example, if we want to analyse the impacts of product reuse compared to consumption of new products, we need to define the sectors that may be impacted by the intervention and the adjustments to be made to simulate the impact.

Several studies have defined scenarios to model the CE using a range of approaches that can be integrated into meso scale hybrid models (Aguilar-Hernandez et al., 2018, 2019; Donati et al., 2020, 2021). Examples of scenario settings are presented in Table 7 and then further elaborated according to the appropriate modelling application. Most scenarios are particularly focused on monitoring changes in material flows, which are extended to consider GHG emissions by using the appropriate multipliers, however, Donati et al. (2020) and Lifecycles (2017) consider the dynamics of a share or reuse economy via an extended lifetime scenario.

Table 7: Examples of scenario approaches to modelling CE interventions and their modelling applications

CE Categories	**(Donati et al., 2021)**	**(Donati et al., 2020)**	**(Aguilar-Hernandez et al., 2019)**	**(Lifecycles, 2017)**
Scenario description	Replacement of primary (raw extraction) steel for secondary (recycled) steel	Increase lifetime of final consumer vehicles through reuse	Modelling the circularity gap of nations	Substitute fossil fuel energy sources with renewable or low carbon Increase lifetime of consumer products
Reduce	-	Reduce sale of vehicles to final consumers	-	2% PA material efficiency for all sectors Reduced consumption of fossil fuels by manufacturing and transport
Reuse / Lifetime extension	-	Reduce sale of vehicles to final consumers and increase repair service	-	Reduced consumption of furniture, clothing, vehicles, and buildings
Repair		Increase repairing service		Increased consumption of repair services

Recycle	Secondary steel for treatment, reprocessing of secondary steel into new steel (increase 30%) Basic iron, steel, and ferro-alloys and first biproducts (reduce 8%)	-	Stock additions: Material added to the economy's stocks Stock depletion: Material removed from stocks as demolished buildings, and disposed durable goods Waste recovery: Reprocessing, recycling, bio gasification, and composting products.	Increased expenditure from waste services Increased activity from transport, storage, wholesale, retail, and services
Modelling application[3]	EE IOA	EE IOA	HIOA	HIOA

A common approach to defining and designing a counterfactual scenario is to group sectors or products according to their common industry interactions. For example, in designing a counterfactual scenario for increased product lifetime of consumer vehicles, Donati et al. (2020) grouped the vehicle retail, and vehicle repair sectors and adjusted the primary and secondary impacts of the intervention – that is new vehicle sales are reduced and repair services are increased. Counterfactual scenarios are currently used for hypothetical modelling to compare alternative pathways; however, this approach can equally be applied to model real world changes in GHG emissions for a region over time.

Current modelling approaches for benchmarking and measuring progress

Micro scale data (material, product, process, organisation) is important for understanding the impacts of specific operations or production processes; however, it is limited in its ability to represent impacts outside of the direct control of an organisation. In contrast, macro scale data can represent complex supply chain interactions between states and nations, but often lacks the detail required for product, material, or organisation level analysis. Therefore, the ability to integrate both approaches at the meso scale is an important development for environmental-economic modelling. The integration of methodological approaches at both scales is called hybridisation (Crawford et al., 2018).

Integration of micro scale data with macro scale data requires customisation of the macro scale economic tables. This process is referred to as augmentation, it describes the introduction of a new sector into the macroeconomic table to represent a specific product, process, or activity. Augmentation has been used in several studies, to model the introduction of advanced technologies into the Australian economy and other regions (Joshi, 1999; Lave, 1995; Malik et al., 2014). The augmentation process is important for developing modelling capability at the meso

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[3] *Note: EE IOA = Environmentally Extended Input Output Analysis; HIOA = Hybrid Input Output Analysis.*

(industrial park, sector, city, state) scale, as it allows the integration of micro scale product information with macro scale intersectoral and interregional trade activity data. For example, if detailed production information could be collected to represent the material and product flows of an eco-industrial park, this information could be augmented into an input-output table as a new sector to model the impacts of changes to production on wider economic flows. Augmentation enables the integration of micro scale industry and consumption changes into meso scale economic modelling to monitor broader shifts in GHG emissions impacts.

Hybrid environmental-economic accounting methods can integrate both micro and macro accounting approaches, combining the best of both methodologies in terms of data, scope, and CE indicators. A review of global case studies highlighted the wide application of the method, including by policymaking agencies, in Europe, the United States, and China (CBS, 2015; X. Chen et al., 2016; Hafner et al., 2005; Jacobi et al., 2018; Jiang et al., 2017; PBL Netherlands Environmental Assessment Agency, 2018; Schmidt, 2010; Van Berkel & Delahaye, 2019), particularly at the macro scale. A few case study examples of hybrid modelling applications were focused on the Australian economy (Lifecycles, 2017; Teh et al., 2017; Yu et al., 2021); and a significant proportion of these case studies and wider research employing hybrid models is focused on the built environment.

The presence of Australian case studies using hybrid methods at the meso scale highlights the potential for future hybrid models to be developed with sufficient detail to monitor the GHG implications of CE interventions in NSW. However, there is further work to be done. This includes benchmarking current practice, mapping relevant stakeholders, collecting more data, and designing counterfactual scenarios that align with strategic CE policies. We evaluate the requirements, capabilities, opportunities, and barriers in the next section and provide some guidance on next steps for policy makers.

Evaluating case studies for adoption in NSW

Identifying stakeholder requirements

Workshops with NSW policy, research, and industry stakeholders were conducted to understand the requirements of each group. Stakeholders noted three key requirements:

- The ability to benchmark GHG emissions at the state (and regional where possible) scales and monitor any changes in GHG emissions as a result of CE policy interventions,
- The ability of methodologies to integrate data from a wide range of sources that may be applicable at different scales,
- The approach should be internationally standardised to meet national and international obligations,

Case studies of global capability

A total of 15 case studies were collected based on the above requirements. We then assessed the case studies according to three coding parameters to rate their applicability to the state of NSW. Case studies were deemed relevant here according to these criteria:

- The use of hybrid modelling (1 point),
- Application of CE modelling at the sub-national or meso scale (1 point),
- Use by policymaking agencies to monitor economy wide GHG reductions related to CE initiatives (1 point).

A score of two points or above was considered ‘highly relevant’, while a score of 1 points or below was considered of lower relevance. Case study examples are provided in Table 8. Those case study examples identified with high relevance for NSW requirements were then further evaluated, with the results presented as a traffic light assessment.

Only three case studies scored two points or higher, indicating the emerging nature of modelling capability at the meso scale. The three case studies showing ‘higher relevance’ were in The Netherlands, South Australia, and Flanders, Belgium and while these case studies show promise, considerable effort in terms of data collection, modelling development, and stakeholder coordination is needed to adapt these approaches and implement a solution in NSW.

Table 8: A list of relevant case studies considered for evaluation against NSW requirements

Methodology	Scale	Location	Relevance (high/lower)	Reference
Hybrid method	Macro	US	Lower	(Chen et al., 2016)
EE-MRIOA (monetary)	Macro	Global	Lower	(Circle Economy, 2021)
Hybrid method	Macro (Meso developing)	The Netherlands	High (2 – points)	(CBS, 2015; PBL Netherlands Environmental Assessment Agency, 2018; Van Berkel & Delahaye, 2019)
Hybrid method (FORWAST project)	Macro	Europe: Denmark, Austria, France, Germany	Lower	(Hafner et al., 2005; Schmidt, 2010)
Hybrid method	Macro	Austria	Lower	(Jacobi et al., 2018)
Hybrid method	Macro	US	Lower	(Kucukvar et al., 2014)
EE-MRIOA (monetary)	Macro	Global	Lower	(Wood et al., 2015)
Hybrid method	Macro	China	Lower	(Jiang et al., 2017)
Hybrid method	Meso	South Australia	High (2 – points)	(Lifecycles, 2017)
Hybrid method	Meso	South Australia	Lower	(Yu et al., 2021)
Hybrid method	Meso-Macro	Australia – construction sector	Lower	(Teh et al., 2017)
EE-MRIOA	Macro-Meso	Australia	Lower	(Fry et al., 2016)
EE-MRIOA	Meso-Macro-Meso	Australia-China	Lower	(Fry et al., 2021)
EE-IOA (RaMa-Scene platform)	Macro	Global	Lower	(Donati et al., 2021)
Hybrid method	Meso	Flanders, Belgium	High (3 – points)	(Acker et al., 2018; Flanders Circular Economy Policy Research Centre, 2021)

Assessment of case studies relevant for NSW

Monitoring a circular transition in Flanders, Belgium

Flanders is a region in Belgium focused on integrating CE strategies and monitoring frameworks that are applicable at the meso scale, but also feed up to the macro scale. The CE monitor was initiated by the Policy Research Centre Circular Economy (Steunpunt Circulaire Economie) and the first assessment of circularity in Flanders was published in 2021. The modelling approach used in the Flanders case study is Hybrid Input-Output Analysis however it is described as economy-wide material flow analysis (EW-MFA) in this study (the integration of physical material flows with input-output tables). The results of our assessment are found in Table 9.

Table 9: Traffic light assessment of the Flanders case study, Belgium

(Blue = No barriers/issues/gaps, Amber = Some barriers/issues/gaps, Black = Major barriers/issues/gaps)

Case Study 1

Flanders Belgium	🚦	**Description**
Scope	🟦	Environmental-economic accounting method Hybrid Input-Output Analysis - described as economy-wide material flow analysis (EW-MFA) in this study but involves the integration of physical material flows with input-output tables - hybridisation. Responsibility Assumed Consumption responsibility Environmental impacts monitored Carbon dioxide CO_2 Sulphur dioxide SO_2 Methane CH_4
Benchmarking and performance indicators	🟦	Materials monitored · Biomass · Fossil fuel · Metal · Minerals Scale indicators (total Tonnes) · Domestic Material Input (DMI) · Domestic Extraction (DE) · Domestic Material Consumption (DMC) · Domestic processed outputs (DPO) · Raw Material Consumption (RMC) · Net additions to stock (NAS) · End of life waste (EoLw) · Processed materials (PM) = DMC + secondary materials · Interim outputs (IntOut) = EoL waste + DPO emissions · Emissions in domestic processed output (DPOe) · Waste in domestic processed output (DPOw) Circularity indicators

	🟦	Socioeconomic Cycling (SC) • Input socioeconomic cycling rate (ISCr) = Share of secondary materials (SM) in processed materials (PM) • Output socio economic cycling rate (OSCr) = Share of secondary materials in IntOut • Ecological cycling potential (EC) • Input ecological cycling rate potential (IECrp) = Share of DMC of primary biomass in PM • Output ecological cycling rate potential (OECrp = Share of DPO biomass in IntOut • Non-circularity • Input non-circularity rate (INCr) = Share of eUse of fossil energy carriers in PM • Output non-circularity rate (ONCr) = Share of eUse of fossil energy carriers in IntOut • Circularity Index (CI) - waste recovered compared to total material input. • Circularity Gap Index (CGI) - material wastes passed through treatment sectors not reintroduced as recovered materials Gaps • Could extend to consider other environmental and social impact categories for example water use, land use, employment, acidification, eutrophication, etc. • Lacks consideration of product lifetime extension • Could extend to consider particular material types and their quality. • Mass balance estimates to fill data gaps introduce uncertainties • Future work to consider the time gap appropriate for products flowing into NAS (stocks).
Data availability	🟧	Data sources • EW-MFA assessment report - Import, export, and domestic extraction data • Waste statistics data from OVAM - detail on secondary resources (i.e., no further processing required), composted materials, recycled materials, and reused materials. SM from industries and waste treatment activities are included. • Where data is unavailable, scientific literature (Mayer et al. 2019) (Haas et al. 2015) (Wang et al. 2007) (Cullen et al. 2016) (Allwood et al 2010) is used to model inputs and outputs. • VMM statistics on Flanders GHG emissions • VEA energy balance of Flanders Data unavailable • Traded products containing recycled materials • Direct trade in secondary materials • Waste exports (these were estimated via mass balancing) • Secondary material produced in domestic recovery plants (waste recycled in domestic recovery plants is used) • Some data unavailable for the study year so the previous years data was used Sources in Australia • National statistics at statistical area 4 - major cities and regions (e.g., census) • Product stewardship schemes • Environmental Product Declarations • Certifications • Waste data • Industry associations • LCI databases

	🟧	• LCA literature
Final assessment	🟧	Opportunities The Flanders case study presents a good example of what is achievable at the regional scale. Significant progress has been made on developing a suite of circularity indicators that monitor both the technical and ecological spheres. Sufficiently disaggregated data is collected on an annual basis from waste treatment facilities, recyclers, and the manufacturing industry. This case study provides a good example of what could be achieved in NSW, albeit with a recycling focus. Barriers Like most other global case studies, the Flanders example, is predominantly focused on opportunities for material efficiency and recycling – only one of the four Rs. Modelling could extend to consider changes in service industries and consumer behaviour that may indicate more meaningful shifts – Reduce and Reuse. An undertaking of this level in NSW would require focused time, expertise, and financial resourcing.
References	(Acker et al., 2018; Flanders Circular Economy Policy Research Centre, 2021)	

Monitoring a circular transition in the Netherlands

The Netherlands monitors economy wide material flows of production and consumption activities via the Material Flow Monitor (MFM). The MFM is a HIOA model used to monitor progress towards CE strategies in five priority themes (Biomass and food, plastics, manufacturing, construction, consumer goods) where the main objective is to reduce primary resources by 50% by 2030 (PBL Netherlands Environmental Assessment Agency, 2018). The results of our assessment of this case study are found in Table 10 below.

Table 10: Traffic light assessment of The Netherlands case study

(Blue = No barriers/issues/gaps, Amber = Some barriers/issues/gaps, Black = Major barriers/issues/gaps)

Case study 2

The Netherlands	🚦	**Description**
Scope	🟦	Environmental-economic accounting method Hybrid Input-Output Analysis Responsibility Assumed • Monitors production and consumption responsibility and includes actions that manage both direct and consumption-based impacts. Environmental categories monitored • CO_2 emissions per unit output • Natural resource use (total) • Water use per unit output • Land use per unit output • Jobs per unit output • Value added per unit output Sector Groupings 1. Biomass and food - sector group includes agriculture, food and beverages industry, textile, wood, and paper production 2. Plastics - sector group includes the rubber and plastics industry and basic chemicals 3. Manufacturing industry - sector group includes base metal, metal products, electrical engineering, electrical equipment, machines and transport equipment industries, furniture and other goods and repair services 4. Construction - sector group includes construction materials industry, building activities, demolition and construction related services such as estate agents and architects 5. Consumer goods - non-sector focused purely consumer perspective
Benchmarking and performance indicators	🟧	Materials monitored Biomass, fossil fuel, metal, minerals Scale indicators Domestic Material Input (DMI) Domestic Material Consumption (DMC) Domestic Material Input (DMI) of Resources Raw Material Input (RMI) Raw Material Consumption (RMC) Consumption footprint (total consumption) Consumer footprint (household consumption) Production footprint (resources in production chain) Circularity indicators Natural resources performance (material productivity, waste production per kg product) Cyclical use rate (recycling) Gaps

	🟧	Could extend to consider other environmental impact categories for example acidification, eutrophication, etc. Lacks consideration of product lifetime extension Doesn’t consider the quality of recycled plastic flows Does not integrate sub-national data in all categories
Data availability	🟧	Data sources Recycled and incinerated waste data via the 'Waste Database' and 'Dutch waste in figures'. Packaging containing recycled material data from the Framework Agreement Packaging 2 High level of material flow data for the construction industry Proposed use of available municipal data with data collection activities likely once a year Organisation level data collected through the Netherlands Enterprise Agency National statistics 'regional accounts' from the national accounts department - monetary Data unavailable Product lifespan extension - e.g., number of times products are repaired, or growth in specific second hand markets. Potential data sources in Australia National statistics at statistical area 4 (SA4) Product stewardship schemes Environmental Product Declarations Certifications Waste data Industry associations LCI databases LCA literature Where possible, centralised data collected and held by organisations such as Product Stewardship Councils could provide valuable data on product streams.
Final assessment	🟧	Opportunities The framework and modelling methodology used to measure and monitor the impacts of CE initiatives implemented by the Netherlands is relevant for the NSW context. However, there is work to be done to integrate higher resolution data at the sub-national level. Barriers Time and resource intensive to collect, consolidate, and integrate data from sources representing sub-national, product, or process specific detail. Sources noted a potential limit of physical data relating to repair services
References		(CBS, 2015; PBL Netherlands Environmental Assessment Agency, 2018; Schmidt, 2010; Van Berkel & Delahaye, 2019)

Modelling a hypothetical circular economy in South Australia

Lifecycles quantified the potential GHG benefits of a hypothetical future CE in South Australia using two scenarios: a BAU and CE. The CE scenario featuring two distinct elements, a material efficiency scenario, and an efficient and renewable energy scenario. The base year used to model the transition is 2016 and the comparison year is 2030. CE interventions are modelled by categorising impacts according to sector groups, a description of sector groups is provided in Table 11 below.

Table 11: Traffic light assessment of the South Australian case study

(Blue = No barriers/issues/gaps, Amber = Some barriers/issues/gaps, Black = Major barriers/issues/gaps)

Case study 3: South Australia

Criteria	🚦	Description
Scope	🟦	Environmental-economic accounting method Hybrid Input-Output Analysis Responsibility Assumed Production based responsibility assumed for energy use and employment, consumption responsibility for GHG emissions. Impacts monitored GHG emissions Employment Sector Groupings Energy efficiency and renewables 1. Energy sector (reduced carbon emissions factor) 2. Commercial buildings and households, manufacturing, and transport (energy consumption reduced per unit output) 3. Manufacturing industry, transport, and households (substitute petroleum-based manufacturing and transport fuel with electricity) 4. Manufacturing industry, transport, and households (substitute petroleum-based fuels with lower carbon alternatives) Material efficiency 1. All companies, sectors unclear (2% PA material efficiency improvement per output) 2. Furniture; clothing; vehicles; and buildings (reduced expenditure) 3. Personal services; construction services for buildings, renting, and leasing; professional, scientific, and technical services (increased expenditure) 4. Manufacturing sector (increased purchase of secondary materials from local waste services and manufacturing sectors) 5. Manufacturing support sectors - transport; storage; wholesale; retail; and services (increased purchase of services) 6. Natural gas production; municipal waste/sewage treatment; livestock industries (substitution of natural gas for biogas) 7. Construction industry; non-metal production; metal products; wood-based products (material substitution for renewable materials)
Benchmarking and performance indicators	🟧	Materials/flows monitored • Waste flows (considered secondary material flows) • Energy CE indicators • Energy efficiency • Material efficiency • Energy and material substitution Gaps • The case study lacks a holistic framework for modelling a comprehensive suite of CE interventions like those specified in case studies found in the EU. • The case study does not integrate industry data to model specific production processes within industry sectors but applies changes to sectors as a whole. This method can create uncertainties due to the averages applied across a range of business practices.
Data availability	🟧	Data sources • The Australian Industrial Ecology Virtual Laboratory (IELab) multi-regional input-output table for South Australia

Criteria		Description
	🟧	• The Regional Industry Structure and Employment (RISE) input-output model for South Australia • Australian Greenhouse Emissions Information System (AGEIS) • Australian Bureau of Agriculture and Resource Economics and Sciences (ABARES) Energy Statistics series • Australian Life Cycle Inventory database (AusLCI) • Green Industries SA waste data for 2014 Data gaps No data gaps identified at this resolution. However, the study is a theoretical projection. If real world data needed to be collected to measure progress against CE strategies or initiatives in these sectors, detailed data would need to be collected on specific business practices, production processes, recycling rates, changes in consumption of final goods and services. Potential NSW data sources Similar data sources could be utilised to compile a state level multi-regional input-output table for the NSW economy. However, real world data would need to be collected to model actual changes in specific business practices, production processes, recycling rates, and consumption changes.
Final assessment	🟧	The SA case study is a hypothetical model; however, it shows the potential of Australian modelling capability at the sub-national scale. The case study provides an example of the use of HIOA at the state level using data sources that are available to all states and territories. The database used is IELab, which is an Australian database that can be used to construct input-output base tables at the state and regional resolution. These tables can be used to integrate new business practices, production processes, and consumer behaviours via augmentation if necessary.
References		(Lifecycles, 2017)

Opportunities and barriers for NSW

Approaches to benchmarking GHG emissions performance and measuring GHG emissions reductions at the macro scale have received a large amount of focus in recent years. That has resulted in a growing collection of examples, which are highlighted in Table 8 above, employing hybrid methods to benchmark activities and measure progress towards a CE. The Australian Industrial Ecology Virtual Laboratory is a collaborative research platform that provides environmentally extended multi-region input-output tables (in supply and use table format) at high sectoral and regional resolution (Lenzen et al., 2014, 2017; Wiedmann, 2017). Carbon footprint analyses have been done at the level of products and metropolitan areas (Chen et al., 2016; Teh et al., 2018; Wiedmann et al., 2016; Yu & Wiedmann, 2018). This platform provides a significant opportunity for decision makers to leverage research expertise and develop a customised modelling solution for NSW.

Best practice examples of material flow accounting can be found in the construction sector in Australia. Significant progress has been made to collect sufficient data to represent the material flows and associated GHG emissions of the sector. Progress in this sector can be attributed to the large volumes of a relatively small array of materials – e.g., cement, aggregate, steel - employed in specific projects, such as roadways, bridges and other urban infrastructure. As well as the significant impact of the sector on energy use, waste, and associated GHG emissions. In Australia, recent research and development has resulted in a detailed representation of construction materials and their associated GHG emissions intensities via the EPiC database (Crawford et al., 2021).The emissions intensities represented in the database rely on hybridisation of physical unit, process-based LCA data and monetary unit, supply-use data, resulting in greater sectoral resolution. The NSW building code BASIX is evolving to consider the embodied emissions of materials via the EPiC database, as a prerequisite to building approvals.

Similar methods could be used to compile representative data from other sectors (such as the food, waste, and manufacturing sectors). An undertaking such as this would require development of a common data management framework to collect primary physical data (energy use, material use) from relevant stakeholders and expand current data availability to inform a detailed material flow account for the NSW economy.

Organisations currently estimate their GHG emissions using a wide range of calculation approaches, scopes, and cut off criteria, with varying degrees of accuracy. This introduces uncertainties when using this data to inform meso or macro level policy interventions. Providing a better representation of GHG emissions in those sectors where data is currently not representative of practices will enable better informed decision making at the meso and macro scales.

An extension of this work would be to determine the best approaches for data collection to represent sectors with activity from both industry and households, such as the transport sector. In these cases, data collection methods such as surveys or process-based LCA (aimed at businesses) may not capture the complete picture in terms of sectoral activity. Better emissions representation could be achieved via sensors, or surveys, however both approaches can be time consuming and costly.

Survey methods could be used to capture data from consumers, but one needs to determine how many consumers need to be surveyed – or have their credit card purchases analysed – to have confidence in the data derived. An alternative approach is to use secondary data sources as proxies for primary data on consumer activity. For example, Pichler et al., (2021) uses GIS data to explore household activity at the municipal resolution where data on fuel station locations in 116,572 municipalities across Europe are combined with data on the population serviced by fuel stations to estimate fuel consumption by residents (Pichler et al., 2021). The result is a pragmatic example of a detailed estimate of fuel consumption per capita, where least-cost data collection is applied to infer estimations rather than relying on survey methods or sensors.

GHG multipliers used to calculate national emissions are based on IPCC 5th assessment methods. In some cases, they rely on older or averaged data that may not be representative of individual operations and may not be up to date with the emissions profile of new sectoral entrants such as new recycling processes, renewable energy users, or organisational level material efficiency gains. Higher resolution GHG multipliers may need to be developed in some sectors for a more accurate and up to date representation of sectoral emissions.

Sensors may need to be integrated at key emissions locations where emissions (such as methane) are harder to quantify. (Lauvaux et al., 2020) has proposed the use of sensors to collect onsite emissions data across the city of Indianapolis. This method could be applied in NSW where GHG emissions are harder to estimate. For example, the dairy industry, waste management sites, gas extraction locations, and coal mining sites. The EPA recently used mobile sensors to gather data on flows of methane emissions at these types of locations (Day et al., 2016), and satellite assessments of methane emissions are emerging. However, Day's study highlighted the barriers to sensor-based monitoring due to the costs involved. Further investigation will be necessary to determine a best cost approach for those sectors that need better data representation that rely on using sensors. This sort of 'return on investment' in measurement can be seen to deserve careful scrutiny.

Areas for future focus

Based on our analysis and discussion of current accounting capability, modelling approaches, opportunities, and gaps, we present several recommendations for future focus when developing NSW modelling capability. Recommendations have been divided into three time periods: short-term, mid-term, and long-term. These recommendations should not be taken as a complete list but offer a starting point on which stakeholders can build, expert advice should be sought to determine the specific approach.[4]

Table 12: Short-term, mid-term, and long-term focus areas for stakeholders

SHORT-TERM FOCUS (1–3 years)	**MID-TERM FOCUS (3-5 years)**	**LONG-TERM FOCUS (5-10 years)**
1. Production or consumption? Define GHG emission responsibility framing for NSW (i.e., production or consumption). Ideally, modelling should consider both. Determine environmental, social, and economic impact categories.	• Monitor production v consumption responsibility GHG relationship to avoid the increase in 'offshoring' of responsibilities – this may include Australian states & territories, and/or other countries and their regions. • Develop relationships with low and high emitting producers outside of NSW with an aim to influence the GHG intensity of consumption activities within NSW.	
2. Industries to focus on Perform initial footprint estimate for NSW and determine industries of focus.	• Publicly report GHG intensity and compare results between CE and BAU practices. • Report time-series CE related GHG reduction totals. Analyse and report on CE trends.	
3. Stakeholder mapping Stakeholder mapping and stakeholder directory for relevant sectors Set sector-based targets for GHG emissions reductions	• Educate stakeholders via the stakeholder directory on sector-based targets and optimal CE business models	
4. Targets Define CE interventions according to stakeholder groupings *5. Interventions & metrics* Define relevant metrics for monitoring the impact of interventions and progress against sector-based targets Define modelling scenarios for CE relevant GHG emissions comparisons	• Monitor progress against CE metrics and targets and implement actions to encourage progress	• Revisit sector-based targets as emissions profiles shift • Redefine scope, data collection framework, and metrics of relevance where necessary

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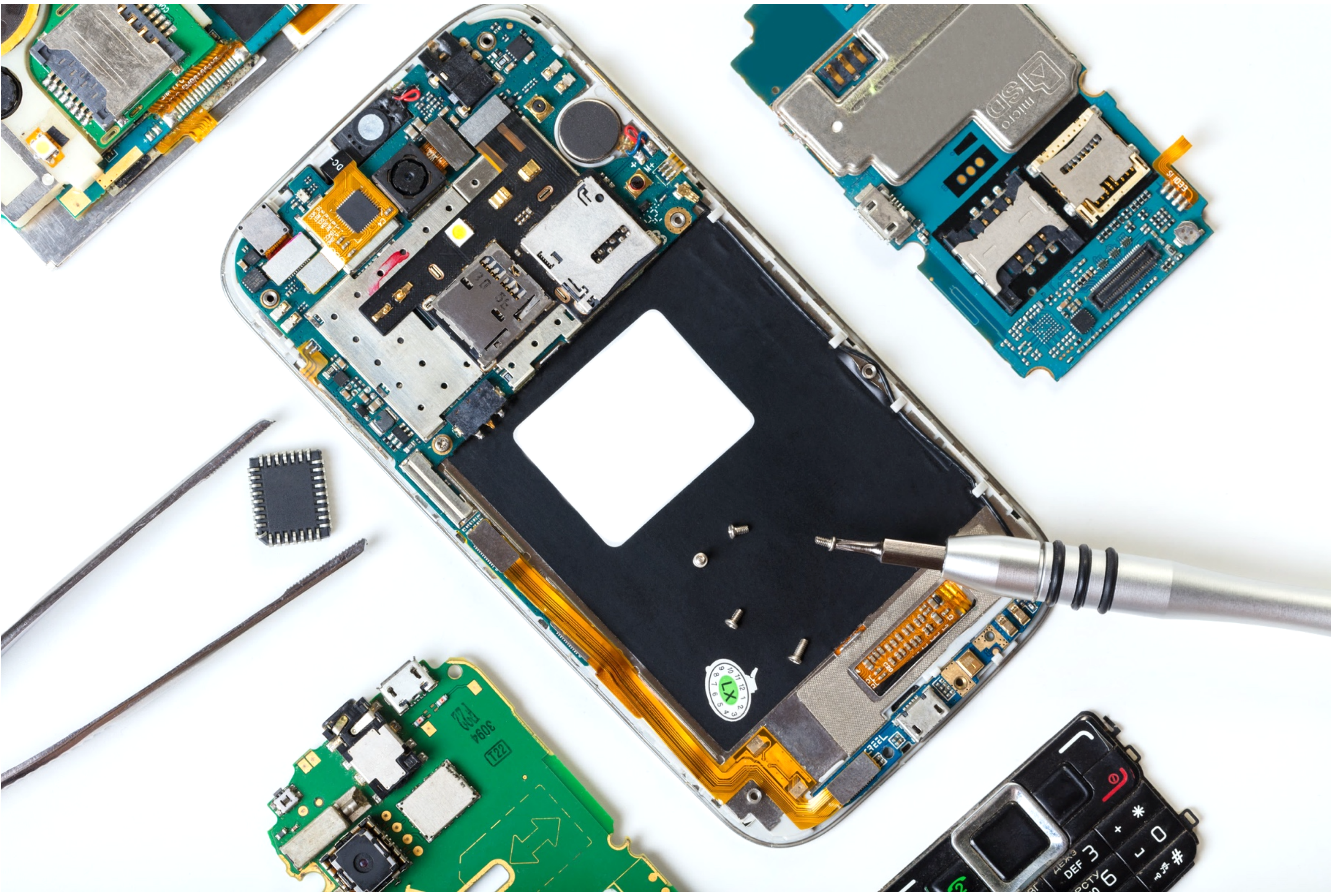
[4] Expert advisors for H-LCA modelling solutions including production vs consumption responsibility, baseline estimates, and data collection: Tommy Weidman (UNSW); Arunima Malik (USyd); Manfred Lenzen (USyd). Advisors for stakeholder mapping, target setting, scenario development and circular metrics: Melita Jazbec (ISF); Damien Giurco (ISF); Will Rifkin (UON); Ali Abbas (USyd); Rusty Langdon (ISF).

SHORT-TERM FOCUS (1–3 years)	MID-TERM FOCUS (3-5 years)	LONG-TERM FOCUS (5-10 years)
6. Identify quality data Once scale, responsibility, targets, scenarios, and stakeholders are established, a data availability and quality mapping exercise should be performed to identify what data is available and where further data needs to be collected Define a common data collection framework for stakeholder groups	Continue to collect detailed industry data to integrate new technologies and process improvements	
7. Collect and analyse Collect detailed industry data in focus sectors from stakeholder groups and augment NSW environmental-economic tables to integrate current and future CE practice. Common international practice for data collection is annually.		



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