Appendix A

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1. Definitions and boundaries

1.1. The circular economy

The circular economy is a debated concept linked with sustainable development's triple bottom line (economy, society, and environment). The circular economy aims for rational use of materials and energy along supply chains and product life cycles. circular economy is expected to contribute to sustainable development by maximising materials' value and creating cyclical material flows to reduce the material footprint of linear economic models[3]. Although the literature on circular economy has exponentially grown, no consensus has been reached on a single definition of circular economy[4].

After revising 114 definitions, Kirchherr, Reike, and Hekkert defined a circular economy as an economic system that aims to find second-life pathways for materials by reducing, recycling, or recovering them at different stages of their life cycles[5]. It can be applied at the micro level (e.g., firms, businesses, products, materials), meso level (productive sectors, eco-industrial parks), and macro level (cities, states, countries) to create long-term well-being in terms of economic prosperity, environmental quality, and social justice.[5] Their latest update analysed 221 newer definitions[6]. This work found that the circular economy understanding is consolidated but also more diverse, with reuse and recycling prominent as the two main strategies supporting circular economy and a significant increase in the macro-level perspective. The authors provided a graphical description (Figure 1) illustrating the relationship between the circular economy elements.

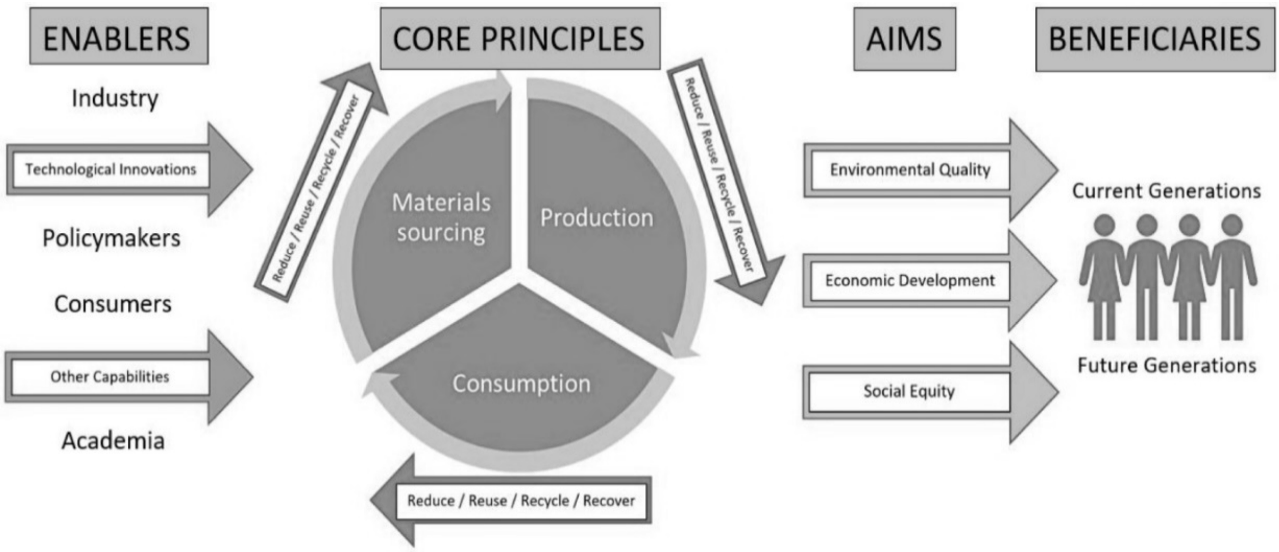

Figure 1. Circular economy principles, enablers, strategies and actions
Reproduced under a CC-BY 4.0 licence from Kirchherr et a.[6]. Industry, technology, and policy frameworks enable circular models. Circular strategies (e.g., reduce, reuse, recycle, and recover) may be deployed at all supply chain stages, creating environmental and social benefits from economic progression.

A more practical standpoint links circular economy with closed productive loops that minimise resource and energy inputs while avoiding waste outputs by implementing reducing, reusing, and recycling (3Rs) strategies at different stages in value chains[7].Theoretically, the circular economy offers a better alternative to a traditional linear economic model based on make-use-dispose systems, driven by the certainty that resources and waste could be better utilised[8] Still, circular economy is an economic approach that prioritises economic development and its interplay with environmental quality, while social benefits are commonly overlooked[5].

circular economy theory and practice are generally categorised according to three different levels of application: macro, meso, and micro. The micro level refers to products, materials, companies, and consumers. Although significantly less used, the meso level encompasses eco-industrial parks and industrial symbiosis. The macro level is highly relevant for policy and decision-making, and the purpose of this research includes cities, regions, nations, and beyond[5, 8].

This systemic perspective is consistently found across circular economy definitions. Kirchherr and collaborators found that the number of references to the macro perspective in the literature significantly increased from 2017 to 2022 (24% vs 65-69%), while the meso perspective reduced from 21 to 8-10%, presumably because eco-industrial parks have lost ground being replaced by the circular economy term. The concept of a supply chain is inherently connected to the circular economy, as green supply chains are critical functional units for circular economy implementation[6].

1.2. Operational frameworks

Circular economy operational frameworks include a combination of R's strategies for material efficiency, the waste hierarchy, and application scales. The R frameworks are seen as the operationalisation of the circular economy; therefore, some national indicator systems have built upon their realisation (see the case of China)[9]. The most accepted R framework is the so-called 3R principles (Reduction, Reuse, and Recycling), which scholars and policymakers have adopted when discussing waste management strategies[8].

However, the 3R principles fall short of encompassing all the alternatives to approaching a circular economy; thus, expanded R frameworks have emerged (now 10Rs). Likewise, a waste-oriented circular economy approach following the waste hierarchy is limited and jeopardises the circular economy's success. Actions downstream value chains (e.g., recycling or energy recovery from incineration) do not necessarily increase circularity and could be even more harmful[8].

Further expansions of the 3R framework were proposed to fill this gap as the 6Rs (reduce, reuse, repurpose, repair, remanufacture, recycle, and recover)[10] and the latest 10Rs ladder, shown in Figure 2, developed by Potting et al.[11], which added rethinking, refusing, and refurbishing as new strategies.

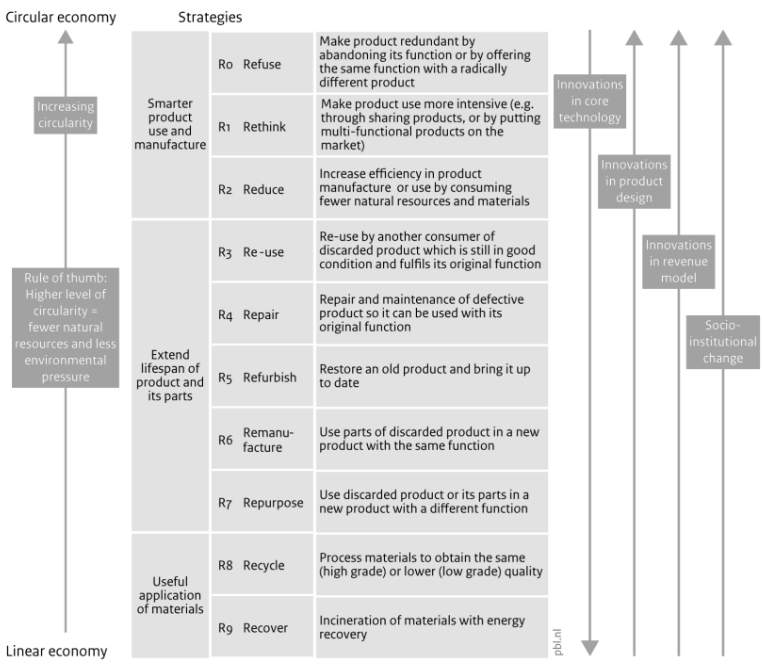

Figure 2. Circularity strategies within the production chain, in order of priority
Reproduced under a CC-BY 4.0 licence from Potting et al[11].

The model stresses the pivotal role of prevention measures higher up in the value chain to achieve fully circular ecosystems.

The 3Rs are predominantly used in the circular economy literature, while the 5Rs are commonly used in waste management and environmental sciences. 4Rs and 6Rs are primarily found in Green Supply Chain Management (GSCM) and design-focused products. Extended frameworks, e.g., 9Rs and 10Rs, are used less frequently despite their robustness[12]. Nonetheless, an agreement has yet to be reached on defining circular economy strategies. For example, 'reduce' can refer to waste generation, materials inflows, or less consumption. Regarding monitoring frameworks, some have focused on the efficacy of circular economy strategies to preserve functionality, the product itself, components, materials, or the energy embodied[13].

Kalmykova and colleagues expanded the debate by providing forty-five circular economy implementation strategies applicable at different value chain stages, serving as a concrete implementation tool. They were organised by 1) the scope of the strategy (e.g., product, system, sector, etc.), 2) the phase of the value chain in which it acts (e.g., design, sourcing, manufacturing, etc.), and 3) maturity level, (e.g., policies, research, knowledge, small scale or are ready to be implemented)[14].

Another well-known circular economy conceptual framework for closed-loop production systems considers a taxonomy based on ***slowing, closing and narrowing the resource loops***. Slowing refers to the product-life extension (e.g., through repair or remanufacturing), which leads to a minor resource flow input. Closing is addressed by recycling. Thus, the post-use product stage is closed, creating a circular flow of materials while the speed of the materials flow is not changed. Narrowing is associated with resource efficiency and lower resource consumption[7].

All these concepts envision a new way of waste management. In a CE, waste is seen as a resource that provides market opportunities and reduces environmental pressures[15]. We advocate for a system-based CE approach with R strategies implemented at different levels of supply chains, from the extraction of virgin materials to product manufacturing and waste disposal, supported by effective metrics measuring the transition to a CE.

1.3. Toward a consistent CE indicator framework

As introduced in the report, our literature review on circular economy and assessment frameworks showed a dispersion of indicators across different scales, —macro, meso, and micro— circular economy strategies i.e., 10Rs (see Figure 2), sustainability dimensions —environmental, economic, and social— and value chain stages —sourcing, manufacturing, consumption, end-of-life management, etc. — hindering a systemic analysis and practical applications. We have advanced the requirements of a consistent circular economy assessment framework based on a response model (see Report Section 1.4.): The DPSIR (Driving forces, Pressure, State, Impact, Response).

This framework, developed by the European Environment Agency (EEA), usually organises data on environmental impacts, including indicators for driving forces, pressure, state, impact, and response. Driving force indicators capture changes in social, demographic, and economic factors, as well as shifts in lifestyles and consumption patterns. Pressure indicators monitor the release of physical and biological substances, resource extraction, and land use changes. State indicators assess the quality of physical, biological, or chemical conditions in a given area. Impact indicators measure the harm caused to wildlife and human populations. Response indicators offer feedback to decision makers on the effectiveness of societal or political actions in preventing, compensating, or mitigating the issues identified by the other indicators[16].

The use of the DPSIR framework demonstrates several advantages. First, its structure, based on five indicator perspectives, makes it a practical method for organising data. This framework transforms raw data into meaningful information and provides clear explanations of the causes behind impacts. It connects scientific facts with real-world consequences and offers feedback on implemented policies, referred to as "responses." As a result, DPSIR enhances communication among researchers, stakeholders, and policymakers, aiding in decision-making[17]. Second, the DPSIR framework helps identify complex cause-and-effect relationships, key elements, significant actors, and control points within intricate networks[18]. Finally, the DPSIR has been used to reflect various policymaker levels on environmental issues [19], drawing on the multi-level perspective.

While the DPSIR framework has been widely used in sustainability science, it has not been widely applied to circular economy analysis. An extended version of the DPSIR model is expected to be part of a system-wide, multi-level and multi-actor circular economy framework, as developed in WATCH. Future research will seek to integrate different actor perspectives within a digital circular monitor. Although critics argue that the DPSIR framework often overlooks social and economic factors, integrating multiple dimensions, levels and actor perspectives within a circular economy framework may help overcome this limitation.

2. Case studies

2.1. City of Canning

Canning was selected as the metropolitan case study based on data availability and the City's circular economy aspirations. The city is in Perth's south-eastern suburbs, about 10 kilometres from the Perth CBD (Figure 21). According to the ABS data, Canning has an Estimated Resident Population (ERP) of 103,691 distributed over 64,95 square km, reaching a population density of 1,597 persons per square km[20].

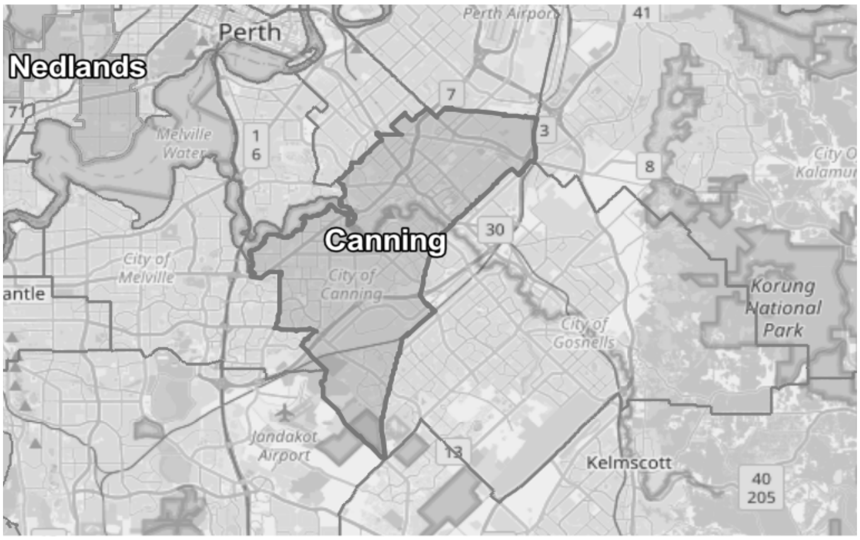

Figure 3. City of Canning administrative boundaries
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Manufacturing excels as the largest industry in the city based on employment figures, which provides opportunities for circular interventions. The estimated Gross Regional Product of Canning is $12.68 billion, accounting for 3.02% of WA's Gross State Product (GSP)[21]. The city provides 78,176 local jobs across 10,711 businesses[21].

2.2. City of Bunbury

Bunbury was selected as the regional case study based on data availability and the city's commitment to advancing circularity. The latest census revealed that Bunbury has a population of about 33,000 people[2]. Located 180 km south of Perth (Figure 22), Bunbury is an important economic hub of the South West region, positioned as the State's second major city.

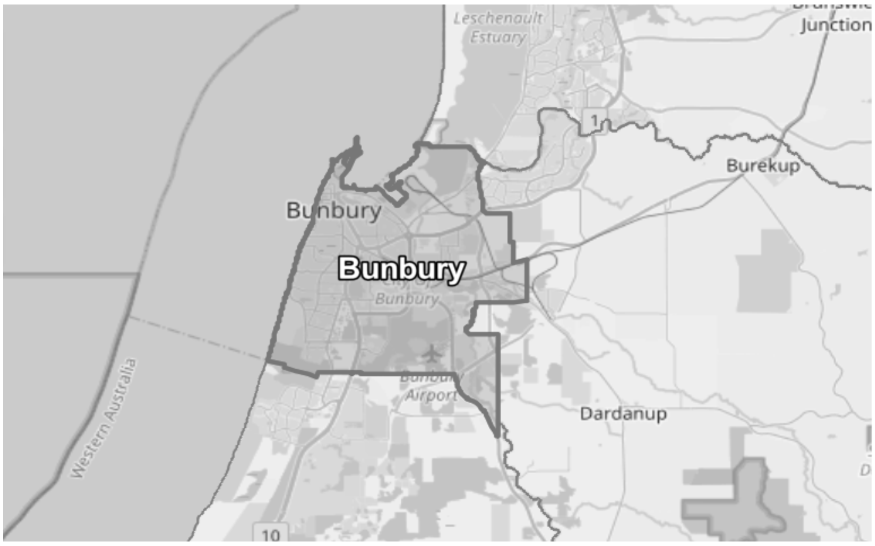

Figure 4. City of Bunbury administrative boundaries.
Reproduced under a CC-BY 4.0 licence from ABS (2021)[2].

Bunbury's Gross Regional Product is $5.37 billion and supports 26,364 jobs. The construction sector is the most significant contributor to the region's economic output, accounting for $2.0 billion, which constitutes 17.04% of the overall output. The Health Care and Social Assistance sector, employing 5,509 individuals or 20.9% of total employment, is the region's largest employer[22].

3. Leading indicators

We have conducted a literature review on leading circular economy assessment frameworks, metrics, and indicators and the methods underlying their application. From a selection of relevant keywords, a Boolean Research String was formed. The search was restricted to article titles to gather academic works pertinent to the topic. These search terms were applied to the Scopus database. The search scope included journal articles, conference papers, and reviews in the English language, as well as the subject area of environmental science, to retrieve relevant results. As the circular economy is an evolving topic, we considered articles published over the last five years (2019-2024). We have deemed MFA-derived indicators at the macro level as pertinent to the selected approach.

Non-academic contributions have been pivotal in expanding the circular economy-related body of knowledge. The most accepted circular economy definitions and frameworks come from the Ellen MacArthur Foundation (EMF) work and other reports that have contributed to the same direction. We have also explored these sources to understand the circular economy assessment frameworks thoroughly. Circle Economy Foundation, European Commission and Eurostat, Circular Australia, and City Loops stand out.

Mass-based indicators are commonly grouped in this category. These measure the magnitude of input and output flows and environmental closing loops[23]. De Pascale et al. (2021) reviewed 137 articles published from 2000 to 2019, surveying 61 indicators or indicator systems classified according to the circular economy level (e.g., macro, meso, micro) and the 3R strategies (reducing, reusing, recycling)[24].

As expected, MFA-derived indicator systems were categorised at the macro level. Table 2 summarises relevant information on MFA-derived indicators.

MFA indicators at the macro level have been available since about 20 years for many EU countries. Eurostat released a comprehensive handbook on MFA[25] and assistance on derived indicators[26]. The material balance from the economy-wide MFA allows for deriving a set of 'metabolic' indicators as presented in Table 2. Eurostat grouped this indicators as input, consumption and output indicators [26].

Table 1*.* MFA-derived circular economy indicator frameworks

Indicator System	*Indicator*	*Abbr.*	*Definition*	*Source*
Economy-wide material flow accounts and derived indicators	Direct material input	DMI	DMI equals domestic (used) extraction plus imports	Eurostat (2001)[26]
	Total material input	TMI	TMI includes, in addition to DMI, also unused domestic extraction	
	Total material requirement	TMR	TMR include in addition to TMI, the (indirect) material flows that are associated to imports but that take place in other countries	
	Domestic total material requirement	Domestic TMR	Domestic TMR includes domestic used and unused extraction	
	Domestic material consumption	DMC	DMC measures the total amount of material directly used in an economy (e.g., excluding indirect flows)	
	Total material consumption	TMC	TMC measures the total material use associated with domestic production and consumption, including indirect flows imported (see TMR) but less exports and associated indirect flows of exports	
	Net addition to stocks	NAS	NAS measures the 'physical growth of the economy', e.g., the quantity (weight) of new construction materials used in buildings and other infrastructure, and materials incorporated into new durable goods	
	Physical trade balance	PTB	PTB measures the physical trade surplus or deficit of an economy. PTB equals imports minus exports	

	Domestic Processed Output	DPO	The total weight of materials, extracted from the domestic environment or imported, which have been used in the domestic economy	
	Total domestic output	TDO	The sum of DPO, and disposal of unused extraction. This indicator represents the total quantity of material outputs to the environment	
	Direct material output	DMO	The sum of DPO, and exports. This indicator represents the total quantity of material leaving the economy after use	
	Total material output	TMO	TMO measures the total of material that leaves the economy. TMO equals TDO plus exports.	
Fundamental Plan for a Sound Material-Cycle Society (FPSMCS)	Resource productivity	RP	GDP per unit of material input (DMI)	Moriguchi (2007)[27]
	Rate of cyclical use of materials			
	Total amount of solid waste disposal			
Circularity Indicators based on the MFA approach	a) Net addition to stocks		The net addition to stocks as a share of PMs (%)	Haas et al. (2015) [28]
	b) Recycling within the economy		recycling as a share of PMs (%)	
	c) Biomass		biomass as a share of PMs (%)	
	d) Domestic processed output	DPO	DPO as a share of PMs	
	Flows either biodegradable or recycled in economy		lows either biodegradable or recycled in the economy as a share of PM	
	Fossil energy carriers;		Fossil energy carriers as a share of PM	

	Material for energetic use		Material for energetic use as a share of PM	
	Material for material use		Material for material use as a share of PM	
	Waste rock		Waste rock as a share of PM	
	Short-lived products material		Short-lived products as a share of PM	
	EOL waste;		EOL waste as a share of PM	
	Recycling		As a share of EOL waste (overall recycling rate)	
MFA of the Swiss Waste Management System	Collection rate	CR	Equal to the relationship between the quantity of material treated in separate collections and the overall quantity of waste	Haupt et al. (2016)[29]
	Recycling rate	RR	Equal to the ratio between recovered materials and waste produced	
Monitoring Framework for Economy-wide Material Loop Closing in the EU28	Domestic material consumption	DMC		Mayer et al. (2018)[23]
	Domestic processed outputs	DPO		
	Raw material consumption	RMC		
	Processed materials	PM	DMC + Secondary materials	
	Interim output	IntOut	EoL waste + DPO emissions	
	Input socioeconomic cycling rate	ISCr	Share of secondary materials in PM	
	Output socioeconomic cycling rate	OSCr	Share of secondary materials in IntOut	
	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	

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

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