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Full length article

Detailed waste flows and circularity rates reveal the limits of the circularity gap concept

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ABSTRACT

In recent discussions on circular economy metrics, the concepts of circularity rate and circularity gap have gained prominence. Countries have reached different levels of circularity, shaped by differences in their economic structures, yet still leaving a substantial gap. This article examines the limitations of the circularity gap concept, drawing on a counterfactual thought experiment that uses Japan, a leader in the 3Rs initiative, The Netherlands, a model of best practices, and Australia, which just developed its circular economy strategy. We discover that the three countries exhibit distinct levels of current and attainable circularity. However, when circularity is alternatively measured against each country's responsibility for primary material extraction, the three countries are strikingly similar. This outcome highlights the need to reevaluate the circularity gap concept, advocating for a narrative grounded in scientific evidence and reflecting what is realistically achievable for economies with diverse roles within global supply chains.

1. Introduction

In both science and policy, material flow analysis (MFA) underlies the development of national-level circular economy metrics and indicators such as the circularity rate, domestic material consumption, material footprint, and material productivity (Graedel, 2019; Mayer et al., 2019). Such metrics provide high-level insights and help guide policy formation by identifying priorities for investment, change in regulations, and for setting targets (De Pascale et al., 2021). Consequently, organizations such as the United Nations Environment Program (UNEP), the Organisation for Economic Co-operation and Development (OECD), and the International Standards Organisation (ISO) have adopted guidelines for measuring the circular economy (ISO 59020, 2024; UN Economic and Social Council, 2023). Many national governments have also implemented MFA-based frameworks, e.g., China (Wang et al., 2020), countries of the European Union (Smol, 2023), and multiple African nations under the African Circular Economy Alliance (Nijman-Ross et al., 2023). The development of MFA methodologies and datasets over the past three decades has largely been driven by collaborations between governmental departments, research institutes, and national statistical offices (Corona et al., 2019; Haas et al., 2015; Krausmann et al., 2017).

Besides the extensive scholarly work on the circular economy (Kirchherr et al., 2023), large global consultancy firms have recently entered the circular economy measurement domain, developing business models around it. A prominent example is the Circularity Gap Reporting Initiative, led by Circle Economy and Deloitte (Circularity Gap Reporting Initiative, 2024). This initiative promotes the concept of a 'circularity gap,' which, while attention-grabbing, can be misleading, as it may suggest that the gap can be fully closed. Political rhetoric calling for economies to become 'fully circular' overlooks the inherent complexities, including entropic constraints and material degradation, which limit the feasibility of complete circularity (Tong et al., 2021). As Cullen (2017) and Figge et al. (2023) argue, the idea of a fully circular system, where inputs and outputs are perfectly balanced, is unrealistic.

A more practical and effective approach would involve assessing concrete ways to improve an economy's circularity through targeted policies and business practices (Corvellec et al., 2022). Such practices include recognizing that circular practices already exist in specific niches, such as traditional agriculture (Duncan et al., 2023), and in economically viable activities, such as recycling of scrap steel, metals, and fly ash (Graedel et al., 2011; Teixeira et al., 2019). Ultimately,

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market regulations and cost structures need to evolve to reflect the true cost of environmental externalities (Buckley and Liesch, 2023; Wilken et al., 2024). This shift would create a favorable environment for businesses and consumers to adopt circular behaviors, where circular investment, procurement, and consumption practices become the norm.

While the physical aspects of the circular economy and material management are becoming established, integrating circular economy metrics into economic and national accounting frameworks remains underdeveloped. Although the System of Environmental Economic Accounting (SEEA) provides some guidance (United Nations et al., 2014), fully developed material flow satellite accounts—comparable to energy or greenhouse gas satellite accounts—are not yet available for waste. This data gap complicates efforts to assess the impacts of the circular economy at both the sectoral and economy-wide levels.

Without a robust economic accounting framework to guide circular economy policies, these challenges remain unresolved. This research aims to enhance our understanding of the limitations in closing the circularity gap—or maximizing the circularity rate—by examining inherent materials characteristics and their transformations throughout economic processes. We explore three research questions using data from Australia, Japan, and The Netherlands as case studies.

1. What is the relationship between material flow categories and waste data categories, and how do these countries differ, if at all, in terms of core waste?
2. How is the circularity rate influenced by each country's biophysical and economic structure and reflected in standard MFA metrics and indicators?
3. How would national-scale circularity outcomes change if common sustainability strategies were already implemented or if each country had to extract domestically all the materials it uses?

We selected these three countries because of their distinct economic structures and varying levels of engagement with circular economy policy frameworks. Japan has been a frontrunner in advancing the circular economy, leading the Group of Seven (G7) in implementing the 3Rs (reduce, reuse, and recycle). The 3Rs are based on Japan's Sound Material Cycle Society policy framework, introduced in 2001 (Takiguchi and Takemoto, 2008). Similarly, The Netherlands has a long history of policy development aimed at transitioning its economy toward greater circularity (Hartley et al., 2020). In contrast, Australia has only recently put forward a national circular economy framework (Australian Department of Climate Change, 2024), marking the early stages of its transition.

2. Methods

Much of the calculations around material circularity on the level of the whole economy rely on the indicators developed in the context of economy-wide material flow analysis (Fischer-Kowalski et al., 2011; Schandl and Miatto, 2018). These include individual indicators and composite indicators. Among the individual indicators, we use the domestic material consumption (DMC) metric, which measures the primary materials physically managed in a national economy, the flow of recycled materials, and the material footprint. DMC is calculated by summing a nation's domestic extraction and imports and subtracting exports. The material footprint attributes to the final users the mass of all raw materials needed to fulfill the needs of a national economy, regardless of where they are extracted or transformed (Lenzen et al., 2022; Wiedmann et al., 2015). In addition, we use several composite indicators.

2.1. Relating domestic material consumption, recycling, and circularity

The material circularity of an economy, also defined as the 'circular material use rate' by Mayer et al. (2019), can be calculated by determining the fraction of material use that is composed of secondary materials (Eq. (1)).

$$\textit{circularity rate} = \frac{\textit{secondary materials}}{\textit{domestic material consumption} + \textit{secondary materials}} = \frac{SM}{PM} \tag{1}$$

Where SM stands for secondary materials, and PM stands for processed materials, as defined by Mayer et al. (2019).

2.2. Waste pathways in Australia, Japan, and The Netherlands

For the analysis of the current conditions and our baseline scenarios, we collected waste generation and processing data for Australia, Japan, and The Netherlands from official national reports. For Australia, we used the 'Experimental Waste Statistics' developed by the Australian Bureau of Statistics (2023). This dataset provides a detailed input-output analysis of all waste generated in Australia and tracks its flows to final destinations (e.g., landfill, recycling). Unfortunately, this dataset appears to be a one-time release, with the most recent data available for 2019.

We retrieved Japanese waste data from the Japanese Ministry of the Environment (2023). This database provides annual data on waste generation, circular use, and final disposal for 2021. It includes both municipal and industrial waste, categorized into four main types: biomass, nonmetallic mineral, metallic, and fossil fuel-based waste.

Last, we gathered waste data for The Netherlands from the European Statistical Office Eurostat, using two key datasets: 'Generation of waste by waste category, hazardousness and NACE Rev. 2 activity' (Eurostat, 2024a) and 'Treatment of waste by waste category, hazardousness and waste management operations' (Eurostat, 2024b). These datasets are reported biennially. To align with Australia's 2019 data, we selected the 2020 data to represent The Netherlands in this study.

While waste data for the three countries are comprehensive, differences in categorization needed to be addressed. To ensure a meaningful comparison of waste pathways, we harmonized the datasets under a common framework, using Australia's waste categories as the reference. The Japanese and Dutch waste data were reclassified accordingly, with detailed matrices of the reallocation process provided in the supplementary materials. Finally, we normalized the waste data by population, using population figures from the United Nations (2024) to render the results comparable among countries with very different populations.

2.3. National material and waste flow indicators

In addition to the waste generation and recycling indicators from the waste datasets described in section 2.2, we compare the three countries across five more per-capita key indicators: domestic extraction, domestic material consumption, imports, exports, and material footprint (Table 1). Data for these five indicators were obtained from the Global Material Flows Database of UNEP (2022). To ensure comparability, we normalized all flows by population.

2.4. Sustainable strategies and circularity implications

Improving circularity can be achieved by increasing recycling, reducing domestic material consumption, or both. In this study, we employ counterfactual scenarios to test several strategies commonly discussed in the sustainability literature (Yang et al., 2023) to evaluate their potential impact on circularity. We do this by changing the values of relevant indicators and metrics from historical statistics to hypothetical values that reflect the counterfactual scenario. Compared to the baseline, we essentially explore what the indicators would look like under alternative conditions. This type of thought experiment using static MFA models has a long history in MFA (Brunner and Rechberger,

Table 1
Summary of the indicators present in this study.

Indicator	Description and formula	Coverage
Domestic extraction	Domestic extraction of materials (biomass, fossil fuels, metal ores and nonmetallic minerals)	Material harvested (agriculture, forestry, and fisheries) or extracted (mining and quarrying) domestically.
Domestic material consumption	Domestic Material Consumption [DMC = domestic extraction + imports – exports]	Materials that are managed and processed in the domestic economy.
Imports	Imports of primary materials and consumer goods	Materials and goods produced abroad and imported.
Exports	Exports of primary materials and consumer goods	Materials and goods produced domestically and exported.
Material footprint	Material Footprint [MF = DE + raw material imports – raw material exports]	Primary materials associated with final demand independent of where they are sourced (domestically or abroad).
Waste generation	Waste [waste = core waste + mining waste]	Waste generated within a country. It accounts for municipal, industrial, and mining waste.
Recycling	Domestic recycling of end-of-life materials.	End-of-life materials that are recycled domestically (municipal, industrial).

Note.
This table has been adopted by Krausmann et al. (2017); UNEP (2023).

2016), yet to the best of our knowledge, it is employed with economy-wide indicators here for the first time.

The first strategy we test is the complete removal of fossil fuels from energy generation, a direction many governments are pursuing, though at varying speeds and levels of commitment (Saurer and Monast, 2021). For example, Australia aims to generate 82 % of its electricity from renewable sources by 2030 (Australian Department of Climate Change, 2023a). Similarly, The Netherlands aims to produce 70 % of its energy sustainably by 2030 (Netherlands Enterprise Agency, 2024). Japan aims to achieve carbon neutrality by 2050 through a mix of renewables, nuclear energy, and hydrogen power (The Government of Japan, 2022). We test this strategy because, while fossil fuels are one-time-use materials and do not directly contribute to circularity, much of the ash generated during their combustion is recycled. In this strategy, we assume that the transition has already been completed and all other conditions are kept ceteris paribus. It is worth nothing that such transition will require considerable investment and additional mining activities, which would in turn generate additional mining waste (Osman et al., 2022). Because we intend this as a thought experiment and not a fully-fledged scenario modeling, we disregard the waste that should have been generated during this transition.

To assess how removing fossil fuels would impact the circularity of these three countries, we exclude two material flows from the calculation. First, we remove fossil fuels used for energy production from the overall material use while retaining those used for manufacturing plastics. Second, we remove recycled ash, which affects both the numerator (recycled flows) and the denominator (domestic material consumption) in the circularity equation (cf. Eq. (1)).

The second strategy we explore is landfill diversion, a key component of Australia's waste policy plan (Australian Department of Climate Change, 2019) and a strategy already implemented in The Netherlands (Scharff, 2014) and Japan (Japanese Ministry of the Environment, 2024). In this simulation, we envision that a complete diversion of waste from landfills has occurred. Organic waste is repurposed for agricultural use, although, following economy-wide material flow analysis standards, it would not be counted as part of the recycled flows (UNEP, 2023). All other materials are recycled. While we acknowledge the practical limitations of recycling, including the finite recyclability of certain materials and products (Gheewala, 2024), this scenario allows us to assess the hypothetical maximum impact of landfill diversion on material circularity under current socioeconomic conditions.

The third strategy focuses on the reuse of mining processing waste, which accounts for approximately one-third of Australia's DMC (Miatto et al., 2024). Currently, this waste stream remains largely unutilized, but the Australian Government is actively exploring potential applications. Geoscience Australia (2023) has been developing the Atlas of Mining Waste to assess how much of this material could be reprocessed (Geoscience Australia, 2022). However, to the best of our knowledge, no official data currently specify the percentage of mining waste that is reusable in Australia. For this study, we test the impact that a 5 % recycling rate of mining waste would have had on circularity. We selected 5 % as a conservatively optimistic estimate. The same recovery rate is applied to Japan and The Netherlands to ensure comparability.

Finally, we mimic a situation where countries are responsible for their upstream and downstream waste flows, corrected by the recycling efforts that have taken place outside of their territory, which hence need to be included in the circularity rate calculation. In the literature, circularity rates are calculated using domestically processed materials as part of the denominator, following established practice in the scientific literature (Haas et al., 2015; Mayer et al., 2019) and reports (Circularity Gap Reporting Initiative, 2024). However, countries that import highly manufactured products shift much of the upstream production waste to other countries. Thus, one could argue that relying solely on DMC for the circularity rate obscures upstream wastes, their potential recyclability, and the consuming country's responsibility for them, a concept similar to the distinction between the DMC and material footprint metrics. We examine this concept by changing Eq. (1) from the circularity rate of DMC plus recycling to MF plus recycling footprint (cf. Eq. (2)). The material footprint attributes extraction-related waste, such as mining residues, to the final users of the products, adjusting the denominator of the circularity calculation. This results in new equations of the circularity rate:

$$circularity\ rate_{footprint} = \frac{SM_{domestic} + SM_{RMI}}{material\ footprint + SM_{domestic} + SM_{RMI}} \quad (2)$$

$$SM_{RMI} = RMI * global\ circularity\ rate \quad (3)$$

Where 'SM_domestic' indicates the secondary materials recycled domestically and 'SM_rmi' indicates the secondary materials in raw materials imports. This term is present because part of the waste generated along the lifecycle of imported products will be recycled abroad. Because data limitations prohibit the exact accounting of the materials that are recycled abroad, we apply the global circularity rate to the RMI, i.e., the raw material equivalent of imports (Eq. (3)).

3. Results

3.1. Waste flows from generation to disposal

When we focus on core waste, i.e., residential, commercial, industrial, and construction and demolition waste, we find highly similar patterns in the advanced economies of Australia, Japan, and The Netherlands. Fig. 1 maps the waste flows of the three countries from generation to disposal. Each subplot disaggregates waste flows into the four main material groups reported in the Global Material Flows Database (UNEP, 2022) and then maps them to the types of waste products generated and traces their disposal pathways.

Australia generated approximately 3 t of core waste per capita in 2019 (Fig. 1A). Notably, this number excludes mining waste, which adds an additional 20 t per capita, as it is not considered part of the core waste, and including it would render it impossible to make a meaningful visual comparison with the other two countries. Waste generation in Australia was evenly split between biomass (1.1 t/cap) and nonmetallic minerals (1.0 t/cap). Regarding waste products, construction materials were the largest category (890 kg/cap), followed by organic waste (600

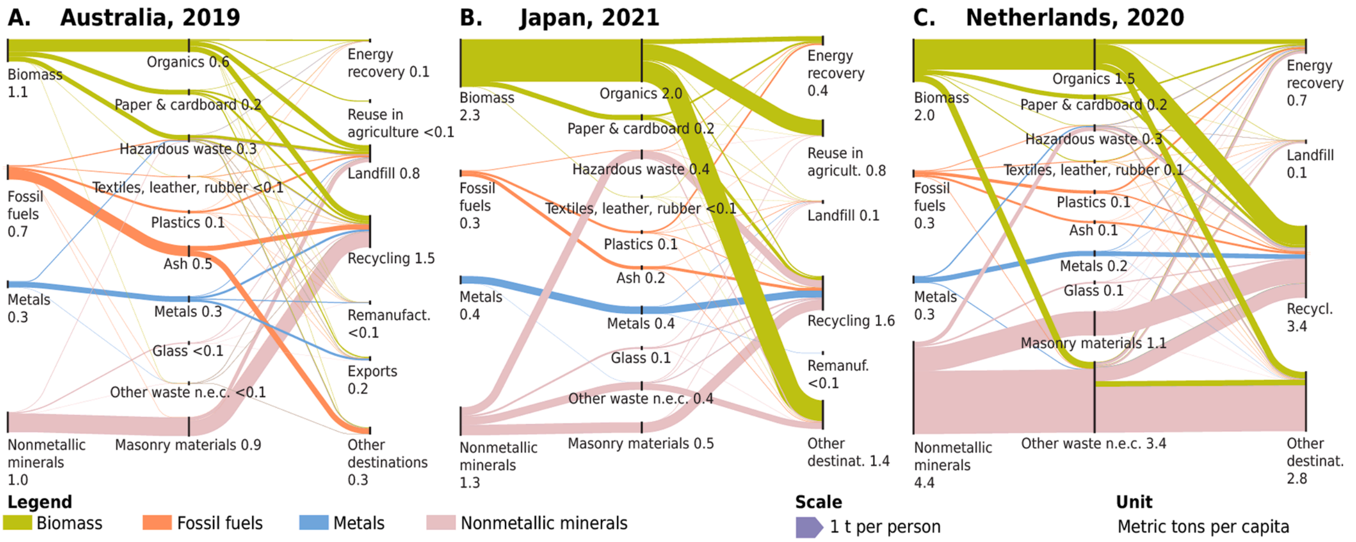

Fig. 1. A comparison of core waste flow generation and fate in Australia (A), Japan (B), and The Netherlands (C). All subplots share the same scale and are reported in metric tons per capita. Note that "n.e.c." stands for "not elsewhere classified".

kg/cap). Australia also produced more ash (490 kg/cap) than the other two countries. Although a substantial portion of waste was recycled (1.5 t/cap), a significant amount was sent to landfill (800 kg/cap).

Japan's core waste of 4.3 t per capita (Fig. 1B) is primarily composed of biomass (2.3 t/cap), the highest among the three countries, and nonmetallic minerals (1.3 t/cap). In terms of waste products, organic waste is the largest category (2.0 t/cap), followed by masonry materials (0.5 t/cap). Despite Japan's reliance on coal power plants (Normile, 2018), ash generation was only 150 kg/cap, or about one third of Australia's output. Regarding waste destinations, recycling was the largest (1.6 t/cap), followed by other pathways (1.4 t/cap). Most waste in this category consists of sewage sludge, which is dried and sold as fertilizer. We retained this label to align with the existing framework, as detailed data on sewage sludge pathways is only available for Japan. Energy recovery also plays a significant role in Japan, with 405 kg/cap of waste processed through this method in 2021.

The Netherlands' waste, which was reported to be 7.1 t/cap, is dominated by nonmetallic minerals (4.4 t/cap), a high figure driven by the large volume of dredging waste reported in official statistics. Excluding dredging waste brings the total waste figure of The Netherlands to 4.2 t/cap, with biomass accounting for a significant portion of The Netherlands' waste (2.0 t/cap), consisting mainly of organic waste (1.5 t/cap) and paper and cardboard (0.2 t/cap). In terms of waste destinations, The Netherlands recycles an impressive 3.4 t/cap, which is twice the amount recycled by the two other countries. While the other waste pathways are dominated by dredging waste, energy recovery emerges as the second most common waste disposal route (670 kg/cap). In contrast, landfills play a minor role, with only 150 kg/cap of

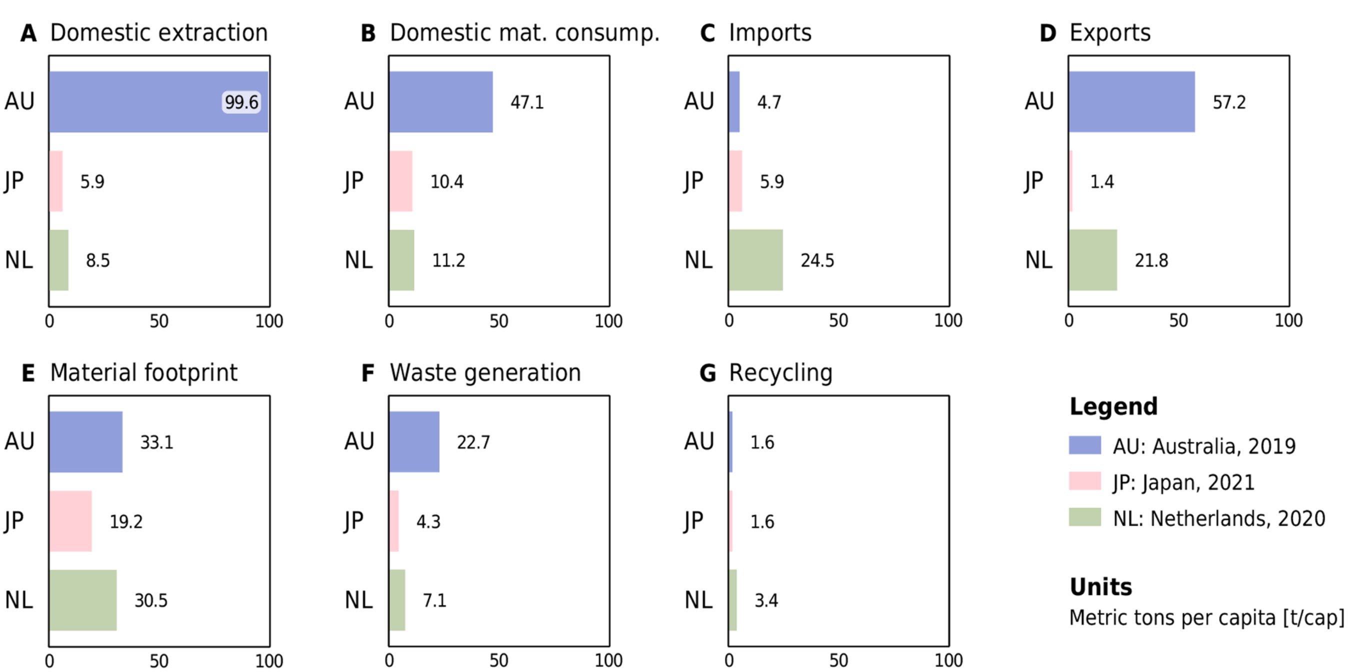

Fig. 2. Comparing headline material flow indicators for Australia, Japan, and The Netherlands. All subplots share the same x-axis for ease of comparison. Results are reported in metric tons per capita. A) Domestic extraction. B) Domestic material consumption. C) Imports. D) Exports. E) Material footprint. F) Waste generation. G) Mass of recycled materials.

waste directed there.

3.2. Key material flow indicators

Despite the similarity of core waste at around 3–4 t/cap, key material flow indicators (Fig. 2) differ greatly because of the very different economic structures of the three countries. All subplots share the same horizontal axis to make visual comparison of the results easy. Fig. 2A shows domestic extraction levels for the three countries. Australia extracts nearly 100 t of materials per resident, one of the highest per capita material extraction globally. In comparison, Japan and The Netherlands extract far less, with 5.9 t/cap and 8.5 t/cap, respectively.

DMC (Fig. 3B) is calculated when trade flows are included. This indicator reflects a production-based perspective by measuring the total mass of materials managed within a nation. Australia exhibits a notably high domestic material consumption (47.1 t/cap), which is approximately five times higher than Japan (10.4 t/cap) and The Netherlands (11.2 t/cap).

Fig. 2C focuses on imports, showing that Australia and Japan import similar amounts (~5.5 t/cap) while The Netherlands imports five times as much (24.5 t/cap). Interestingly, The Netherlands' imports exceed its domestic material consumption by more than double.

Exports, shown in Fig. 2D, follow a different pattern. Australia exports an exceptional 57.2 t/cap, amounting to more than half of its domestic material extraction. The Netherlands exports 21.8 t/cap, closely aligned with its import volume of 24.5 t/cap. Both figures significantly exceed the countries' domestic extraction and consumption, indicating that The Netherlands serves as a transit hub for materials moving through Europe. Japan's exports, by contrast, are much lower at just 1.4 t/cap and mostly comprise final consumer goods.

The material footprint (Fig. 2E) measures the raw material inputs required to produce all the goods and capital assets used within an economy, regardless of where production or processing occurs. Different from the previous indicators, results are somewhat closer across the three countries. Australia has the highest material footprint at 33.1 t/cap, followed by The Netherlands at 30.5 t/cap, with Japan trailing at 19.2 t/cap.

Regarding waste generation (Fig. 2F), Australia records the highest at 22.7 t/cap, primarily due to the enormous volume of mining waste. Mining waste alone accounts for 19.7 t/cap, meaning that without it, Australia's total waste generation would drop to around 3.0 t/cap. The Netherlands generates 7.1 t/cap of waste, with 2.9 t/cap attributed to dredging activities. Japan produces the least waste among the three countries, at 4.3 t/cap. Notably, if mining waste from Australia and dredging waste from The Netherlands were excluded, all three countries would have comparable waste generation levels.

Recycling amounts (Fig. 2G) are of a similar order of magnitude across the three countries. Both Australia and Japan recycle 1.6 t/cap, while The Netherlands leads with 3.4 t/cap, more than double the amount recycled in the other two countries.

3.3. Current circularity rates and alternative scenarios

Fig. 3 presents the current circularity rates for the three countries: 4.2 % for Australia, 16.4 % for Japan, and 25.1 % for The Netherlands. These results were estimated using Eq. (1), which defines the circularity rate as a ratio with recycled material as the numerator and the processed materials in the denominator. These rates are contrasted with alternative 'what-if' thought experiment scenarios of how to improve the circularity rates in the three countries through three strategies: a complete phase-out of fossil fuels, 100 % recycling of core waste currently sent to landfill, and recovery of a small fraction of mining waste. The 'what-if' assumptions are illustrative and do not represent full dynamic modeling of the historical transitions necessary to achieve these goals. For example, establishing the renewable energy generation capacity required for a complete phase-out of fossil fuels would result in additional demand for metals for photovoltaic panels, wind turbines, batteries, and additional transmission lines (Lee et al., 2024; Osman et al.,

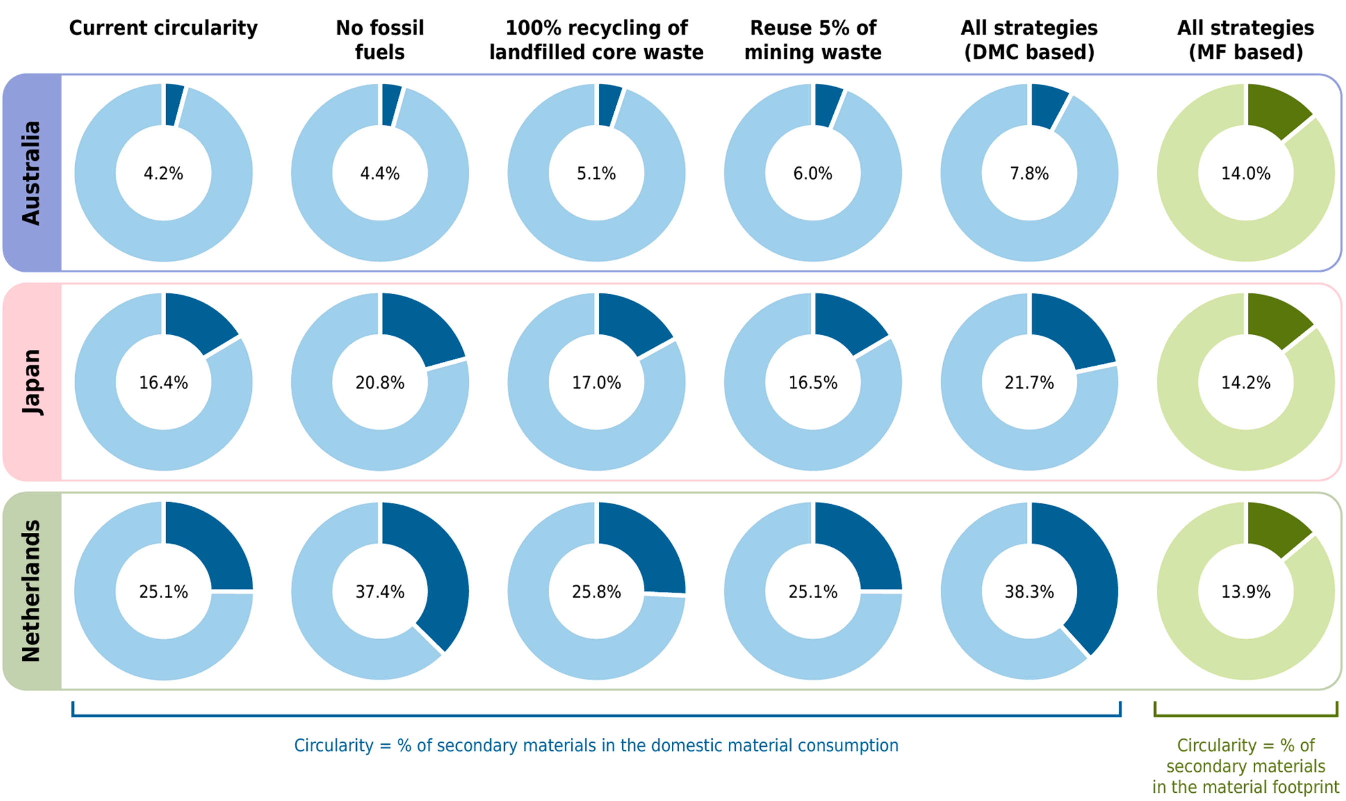

Fig. 3. Circularity rates for Australia, Japan, and The Netherlands. Current circularity, three alternative scenarios for improving the circularity rate, scenario combination (in blue), and circularity measurement for the material footprint (in green).

2022), which are not accounted for in this assessment.

We first assess the potential impact of having phased out fossil fuels on the circularity rate of each country. For Australia, the shift would result in a negligible increase of just 0.2 %, raising its circularity rate to 4.4 %. This limited improvement arises because, while fossil fuels would be removed from the DMC, the mass of recycled materials would also decrease due to the exclusion of recycled ash. Because 15 % of Australia's recycled flows consist of ash, and fossil fuels account for 14 % of its DMC, removing fossil fuels—despite being environmentally beneficial—makes little difference to the circularity rate. In contrast, this effect is not observed in Japan or The Netherlands. For Japan, removing fossil fuels results in a 5 % circularity uplift, bringing it to 20.8 %. The Netherlands would see a much more substantial jump, with its circularity rate rising from 25.1 % to 37.4 %. This dramatic increase occurs because fossil fuels represent 34 % of The Netherlands' DMC, while ash constitutes only 3 % of its recycled flows. As a result, removing fossil fuels has a far more pronounced positive effect on circularity for The Netherlands.

Our second scenario is to divert core waste currently landfilled into recycling streams completely. While we acknowledge the practical limitations of this scenario—not all waste can be recycled, and technical and economic constraints may further restrict recyclability (van Ewijk et al., 2021; Vogt et al., 2021)—we aimed to explore this idealized scenario to understand how reliance on landfilling affects material circularity. If all landfilled core waste were diverted to recycling, Australia's circularity rate would increase by 0.9 %, Japan's by 0.6 %, and The Netherlands by 0.7 %. These modest gains, due to the already modest landfilled mass compared to the overall DMC, suggest that further efforts to divert waste from landfills will not significantly improve circularity rates. However, it is important to emphasize that although landfill diversion contributes only incrementally to circularity, it plays a crucial role in promoting broader sustainability outcomes. Therefore, these findings should not be interpreted as a reason to abandon efforts to enhance recycling rates. It does nevertheless clearly show that recycling cannot be the focus of a country's circular economy effort.

We next explore the effects of recovering 5 % of mining waste. Mining waste represents a very minor portion of waste streams in Japan and The Netherlands but is the dominant source of waste in Australia. Most of this waste remains unutilized and is typically stored in tailing dams, which are engineered structures in the vicinity of the mine sites designed to contain fine-grained mining waste material. In this analysis, we explore how recycling just 5 % of mining waste, a reasonably low rate (Samir et al., 2018), would impact the circularity rates of the three countries. Given the minimal presence of mining waste in Japan and The Netherlands, their circularity rates remain virtually unchanged, with Japan gaining only 0.1 % and The Netherlands showing no meaningful change. In contrast, Australia's circularity rate increases by almost two percentage points, reaching 6.2 %. This result represents the most significant gain in Australia's circularity across the three strategies explored.

We furthermore examine how the synergistic deployment of the three strategies would impact circularity rates. For Australia, the circularity rate would nearly double and reach 7.8 %. Japan's rate would increase to 21.7 %, representing a 32 % increase over its current baseline. The Netherlands would experience the most significant increase, with its circularity growing to an impressive 38.3 %. The key impediment to improving Australia's circularity rate is its very large extractive sector, which produces a large amount of 'unusable' waste while exporting the primary materials to other countries for further use.

As a final thought experiment, we explore how the circularity rate in the three countries would change if they extracted and recycled domestically the materials they themselves consume. To mimic the assumption that every country extracts its own primary materials and just the amount required domestically, we calculate the circularity rate by replacing DMC with the material footprint in the denominator and recycling with an estimation of the recycling along the entire supply chain of products (Eq. (3)). In doing so, we assess the total amount of primary materials required to meet each country's final demand against its estimated recycling. This result shows that, when all the tested circularity strategies are applied, and the circularity rate is calculated as recycling over the material footprint, all three countries exhibit similar circularity levels: The Netherlands with 13.9 %, followed closely by Australia at 14.0 %, and Japan achieving a slightly higher rate of 14.2 %.

4. Discussion

The circular economy and its potential to address the current environmental crisis have become central to national policy debates and play a significant role in public discourse. The circularity rate has emerged as a key high-level indicator—for instance, Australia reports it as part of its Measuring What Matters framework (Australian Treasury, 2024). The concept of a circularity gap is also widely used.

We show that calculating the circularity rate as the ratio of recycled materials to DMC places extractive economies, like Australia, at a disadvantage (Fig. 3). Economies heavily engaged in agriculture, forestry, fisheries, and mining provide essential primary materials for the global economy. These materials support critical infrastructure and services, including housing, transportation, food, and energy (Lenzen et al., 2022). However, material extraction generates significant waste—most notably from mining, but this is true for all extracting activities—affecting DMC values. Countries importing semifinished or finished consumer products report lower DMC values, while extractive economies experience inflated DMC due to production waste. Despite Australia's 60 % recycling rate for core waste, its circularity rate remains low, in contrast with The Netherlands, which achieves higher circularity through extensive recycling and a reliance on imported products with low domestic extraction (cf. Fig. 2).

We thus tested a footprint-based circularity rate to address this imbalance. This "circularity footprint" suggests that these three countries yield comparable circularity results when using the material footprint. For the three countries we examined, this alternative metric yields circularity rates of around 14 %. This approach increases the circularity rate for extractive economies while reducing it for importing countries. As global trade is a zero-sum game, we can reasonably assume that some countries will continue to serve as primary suppliers of raw materials and that the demand for such materials will remain strong in the foreseeable future, which will protract the ongoing generation of extractive waste. As such, the material footprint presents a concept that could help offset circularity rates due to outsourced production waste.

However, it is important to note that the alternative circularity rate measured using the material footprint accounts for the proportion of the material footprint that is recycled in foreign countries—a 'recycling footprint'—which is not a straightforward exercise. While we find the results of this thought experiment insightful, we do not advocate for the adoption of this metric unless a method for integrating the material footprint of the recycled fraction can be developed.

Additionally, materials used for energy purposes (e.g., food and fossil fuels) are inherently linear. As a result, a global limit to the circularity rate may exist, potentially around 20 % (Schandl et al., 2019). Further research is needed to validate this hypothesis. If confirmed, it would call for a shift in focus toward the first two of the '3Rs'—reduce and reuse—as recycling, while essential, may not suffice to achieve fully circular economies, as we saw in our second thought experiment.

All countries in this study aim to increase their circularity, yet our findings highlight that the special case of extractive economies' efforts require attention and different approaches. In the case study of Australia, doubling its current circularity rate is a realistic goal. Australia is already planning to phase out fossil fuels and advance the transition to renewable energy, as outlined in Australia's Nationally Determined Contribution (NDC) pathway (Australian Department of Climate Change, 2023b). Its recycling rates could also increase from the current 60 % toward the 80 % target set by the Australian Waste Policy Action Plan 2019 (Australian Department of Climate Change, 2019). However, currently, there is no roadmap for reusing mining waste. With its already high circularity and minimal landfill waste, Japan could improve by 39 % over its current baseline, mainly by phasing out fossil fuels. In its aim for full circularity, The Netherlands will greatly benefit from pivoting away from fossil fuels. However, achieving full circularity will remain challenging when measured against material footprints, as this metric considers the entire supply chain of materials used by the economy. Further research is necessary to understand what full circularity entails at a national level.

Mining presents a huge challenge that, if properly addressed, could be a large opportunity. We expect mining to increase due to the increasing global demand for metals (Watari et al., 2021), posing unprecedented environmental challenges (Owen et al., 2024). However, mining waste can be reprocessed to extract further metals (Whitworth et al., 2022) or used as bulk material in road construction (Calandra et al., 2022; Segui et al., 2023) where economically feasible (Makhathini et al., 2023). Moreover, red mud, a residue from aluminum production, can be used to make bricks (Arroyo et al., 2020). However, technical, economic, and regulatory challenges remain. For example, most mining waste is legally labeled as hazardous (Lottermoser, 2010), rendering its recycling complex and mired with regulations. While, of course, regulations are in place to safeguard humans and the environment, they limit the capacity of repurposing mining waste. As extractive economies such as Australia transition to a circular economy, a holistic approach—combining strategies such as reducing, reprocessing, upcycling, downcycling, and planning for future use—will be essential for managing mining waste streams effectively (Kinnunen et al., 2022).

Similarly, the agricultural sector holds untapped potential for biomass use. Underutilized biomass could be repurposed for nutritional products and other valuable applications, contributing to a circular bioeconomy (Muscat et al., 2021). Developing this sector will require integrating life cycle analysis with economic assessments to identify and prioritize opportunities (Velasco-Muñoz et al., 2022). While these agricultural strategies may not directly increase the circularity rate under the current definition, they would yield significant environmental benefits.

The insights from this study on circularity measurement and the impact of different strategies on attainable circularity emphasize the need for policy shifts toward reduced material dependency. This argument is not new (Daly, 1972), yet meaningful progress in this direction remains limited (Schandl et al., 2018). While recycling plays a vital role in mitigating environmental pressures, it alone cannot achieve a fully circular future. Future research should explore circularity metrics that account for entire supply chains, providing more holistic measures that capture resource flows both within and across national borders.

5. Conclusions

Measurement is crucial in informing the public debate, shaping policies, guiding their implementation, and reviewing progress. Like other environmental policy efforts, the circular economy requires comprehensive metrics to support the policy process. Here, we measured the current circularity of Australia (4.3 %), Japan (19.0 %), and The Netherlands (32.8 %). It is evident that different countries have widely varying levels of achievable circularity. Extractive economies, like Australia, generate substantial extractive waste generation that, under current techno-economic conditions, remains largely unutilized. In contrast, importing economies like The Netherlands do not bear the burden of mining waste, resulting in higher attainable circularity rates. While the circularity rate serves as a useful high-level indicator, it is essential to complement it with additional metrics such as the material footprint, waste generation, and end-of-life recycling rates. We do not necessarily argue for the need for a new circularity indicator that attributes all extractive mass to the final user—for which we proposed herein an initial version that should be further refined—as this would introduce unnecessary complexity. Instead, we acknowledge that circularity rates differ dramatically based on a country's socioeconomic structure. Put simply, not all countries can achieve the same level of circularity as The Netherlands or Japan.

However, we argue the need to de-emphasize the notion of a "circularity gap" as the difference between the current circularity rate and a hypothetical 100 % circular economy. As we explored in our alternative scenarios, even aggressive environmental strategies could not get any circularity rate close to 100 %. This concept of a circularity gap creates a misleading illusion that 100 % circularity is achievable when it is not. One alternative would be to define the circularity gap as the difference between the current circularity rate and the realistic circularity potential of a country, as proposed by Miatto et al. (2024), or drop the notion of a circularity gap altogether.

Future research on the circular economy's potential and the limits to improving circularity will rely on comprehensive global and country-by-country waste and recycling datasets and must incorporate a comprehensive stock-and-flow framework. Such data would allow us to calculate circularity metrics, compare countries, and establish waste and recycling footprints. Stock and flow frameworks would help emphasize the importance of the retention time of materials within the economy and the lag between their initial use and availability for reuse or recycling. Retention time is especially important for fast-developing economies that build substantial new infrastructure, as they depend on additional primary materials that will only be available for recycling after a significant delay. Realistically, countries can improve their circularity to attain a global average circularity rate of around 15 %−20 %, which would take pressure off primary material supply, enabled by well-designed policies that focus on the material-intensive provision of buildings, mobility, food and energy as well as important consumer goods. This provision can be guided by the development of sectoral plans aimed at enhancing circularity while keeping material consumption within planetary boundaries.

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Data and materials availability

Correspondence tables for waste pathways of Fig. 1 and the underlying numbers of all the figures present in this manuscript are available in the supplementary materials.

CRediT authorship contribution statement

Alessio Miatto: Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Heinz Schandl:** Writing – original draft, Conceptualization. **Naho Yamashita:** Writing – review & editing, Data curation. **Tomer Fishman:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2025.108319.

Data availability

Data will be made available on request.

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