IMPORTANCE OF MEASUREMENTS FOR CIRCULAR ECONOMY AND GREEN TRANSITION

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ABSTRACT
Measurements are absolutely essential to drive and monitor both the circular economy and the green transition. By quantifying resource flows, waste generation, emissions, and overall efficiency, measurements create a common language for stakeholders — businesses, policymakers, investors, and communities — to understand where improvements are needed, track progress over time, and benchmark performance against defined targets. This paper ties together the economic, engineering, and design aspects of measurement in the circular economy and green transition. It emphasizes why accurate measurements are critical, explains the role of calibration, and highlights modern trends in metrology.

Keywords: Measurements, Calibration, Circular Economy, Green Transition

1. INTRODUCTION

Measurements are essential to driving and monitoring the circular economy and the green transition. By quantifying resource flows, waste generation, emissions, and overall efficiency, measurements create a common language for stakeholders—businesses, policymakers, investors, and communities—to understand where improvements are needed, track progress over time, and benchmark performance against defined targets.

The circular economy should be monitored to give out quantitative, measurable data. Quantifying Circular Economy can be achieved through Key Performance Indicators, Life Cycle Analysis, Material Flow Analysis, and the use and development of quality protocols (ISO/TC 323) [1]. Some authors propose different indicators of the green transition, such as the entropy weight method and green transition index (GTI) [2], the green quality of energy mix (GREENQ) [3] or Green Growth indices [4].

All these indicators require relevant and high-quality data, which can only be obtained through measurements, usually based on information technology [5, 6]. Quality infrastructure, such as metrology, accreditation, standardisation, and conformity assessment, must be integrated into the process of moving toward a circular economy, along with the government bodies that develop pertinent policies and strategies [7].

It is important to begin by defining the key terms used in this paper. The circular economy is an economic model that maximises waste reduction and resource efficiency by emphasising the 3R principle: Reduce, Reuse, and Recycle. The model is meant to be achieved through sustainable production and consumption. The term green transition means making the economy sustainable by shifting away from fossil fuel dependency and environmentally harmful practices. The green transition aims to achieve low-carbon and eco-friendly solutions in all human activities. Sustainable development balances economic growth, environmental protection, and social well-being while meeting current needs without compromising future generations' ability to meet theirs.

It is crucial to measure performance as measurements provide data-driven insights. This information enables organisations and policymakers to make well-informed decisions by identifying inefficiencies, assessing progress, and guiding policy and investment decisions. Performance measurement detects system, process, or resource allocation weaknesses, allowing for targeted improvements and cost optimisation. By tracking key performance indicators (KPIs) over time, organisations can compare outcomes with past performance, industry benchmarks, or competitors, ensuring continuous improvement. Reliable performance data is essential for strategic planning, enabling the effective allocation of resources, prioritising initiatives, and maximising impact on infrastructure, sustainability, and innovation. Measurements are relevant across various disciplines, including economics, civil engineering, and architecture. Economics influences cost-benefit analysis, transition finance, and sustainability metrics. In civil engineering, precise measurements are critical for efficient material use, infrastructure lifecycle assessments, and resource management. In architecture, performance measurement supports eco-design, material passports, and sustainable building performance, ensuring that structures align with environmental and energy efficiency goals.

2. MEASUREMENT FUNDAMENTALS & TOOLS

2.1. Key measurement methods

Transitioning to a circular economy requires robust measurement methods to assess resource efficiency, environmental impact, and sustainability performance. Several methodologies, including Material Flow Analysis (MFA), Life Cycle Assessment (LCA), and Circularity Indicators and Eco-Costs, provide a structured approach to quantifying and evaluating circularity. These tools enable policymakers, businesses, and researchers to make data-driven decisions that facilitate sustainable production and consumption.

2.2. Material Flow Analysis (MFA)

Material Flow Analysis (MFA) is a systematic approach used to quantify the flows and stocks of materials within an economic or industrial system. This method provides insights into resource consumption patterns, waste generation, and material utilisation efficiency.

MFA involves tracking resource inputs (raw materials, energy, and water) and outputs (products, emissions, and waste) within a defined boundary, such as a city, industry, or national economy. By mapping these flows, MFA helps identify inefficiencies, material leakages, and opportunities for improving resource circulation. For example, in the construction sector, MFA can be applied to analyse the flow of concrete, steel, and wood, enabling the development of strategies for recycling and reuse.

The benefits of MFA include enhanced transparency in resource use, improved waste management strategies, and support for circular economy policymaking. However, its effectiveness depends on data availability and the complexity of supply chains, requiring comprehensive and standardised data collection.

2.3. Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is a widely recognised methodology for evaluating the environmental impacts of products, services, or processes throughout their life cycle [8]. It encompasses four key stages: raw material extraction, production, use, and end-of-life disposal or recycling.

LCA provides a comprehensive perspective by assessing factors such as energy consumption, carbon emissions, water use, and pollution at each stage of a product’s life. This methodology

enables businesses and policymakers to identify environmental impact hotspots and implement improvements. For example, in the textile industry, LCA can compare the environmental footprint of natural versus synthetic fibres, informing more sustainable material choices.
Despite its advantages, LCA has limitations, including data intensity and variability in methodological approaches. Different impact assessment models and assumptions can lead to varying results, highlighting the need for standardisation in circular economy applications.

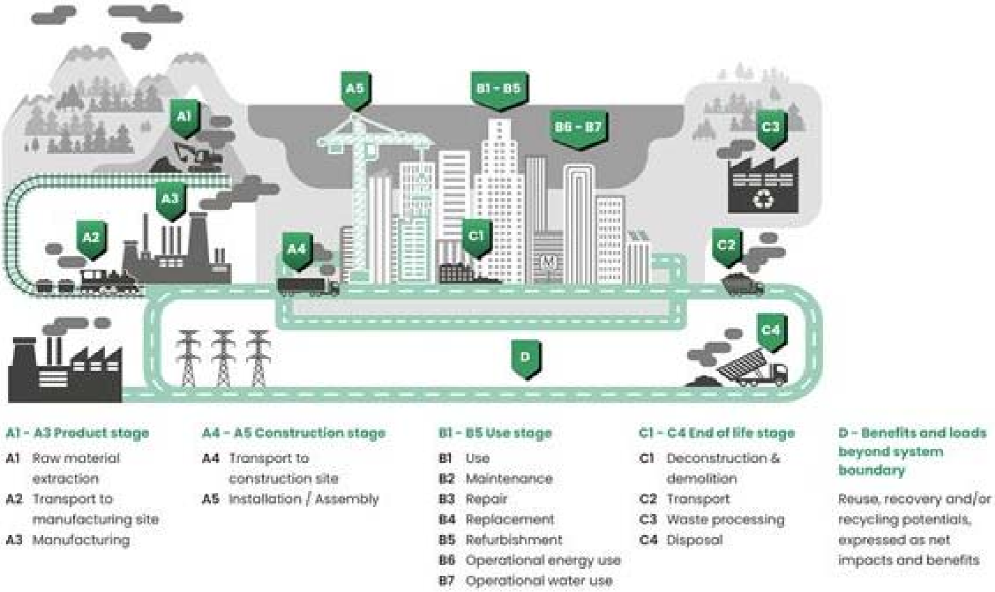

Figure 1. Life Cycle Assessment (LCA): Evaluating environmental impacts across a product's life [9]

2.4. Circularity Indicators & Eco-Costs

Circularity indicators are quantitative metrics designed to measure the degree of circularity within a system. These indicators assess resource recovery rates, material longevity, and the share of secondary materials in production. The Material Circularity Indicator (MCI), developed by the Ellen MacArthur Foundation, is one such tool that evaluates how effectively materials are cycled within a system, promoting closed-loop production [10].
Conversely, eco-costs assign a monetary value to the environmental burden of products or services. This concept helps businesses and policymakers integrate environmental costs into economic decision-making. Eco-costs consider emissions, resource depletion, and pollution, allowing for product comparisons based on their sustainability impact. For instance, eco-cost assessments can guide green procurement policies by favouring low-impact materials in construction and manufacturing.
While circularity indicators and eco-costs provide valuable insights, their effectiveness depends on data quality and sector-specific adaptability. Developing standardised frameworks for measuring circularity across industries remains a challenge that requires continuous refinement and integration of digital technologies such as blockchain and IoT-based tracking.

2.5. Examples

The EU Green Deal is a prime example of data-driven policymaking. It uses scientific research, environmental data, and economic analysis to guide sustainability initiatives. Key examples include:

- Carbon Emission Targets – The EU uses climate models and emissions data to set CO_2 reduction targets, such as a 55% cut by 2030 and net-zero emissions by 2050.
- Energy Transition – Energy consumption and renewable capacity data help shape policies promoting wind, solar, and hydrogen energy.
- Circular Economy Action Plan – Waste and resource-use data drive policies to increase recycling and reduce plastic waste.
- Sustainable Agriculture (Farm to Fork Strategy): Agricultural productivity and environmental impact data guide policies on pesticide use and sustainable food production.

In the USA, the online retail sales company Amazon uses big data and AI to optimize its supply chain and logistics. Machine learning models analyze shopping patterns, economic trends, and seasonal changes to accurately predict demand. Real-time data on warehouse stock and sales helps automate restocking, reducing waste and storage costs. AI-driven route planning based on traffic, weather, and delivery density improves efficiency and reduces fuel consumption. Customer behaviour data enhances product recommendations, increasing sales and customer satisfaction.

An example in the civil engineering sector is the Øresund Bridge/Tunnel connecting Denmark and Sweden. The bridge uses IoT sensors and real-time analytics for maintenance and safety. Sensors measure vibrations, stress, and weather impacts, allowing predictive maintenance and preventing failures. AI processes traffic data to improve toll systems and manage congestion. Smart LED systems adjust brightness based on real-time traffic and environmental conditions.

The successful implementation of a circular economy depends on precise measurement methodologies that assess resource efficiency, environmental impact, and circularity performance. MFA provides a quantitative analysis of resource flows, LCA evaluates the life cycle impact of products, circularity indicators, and eco-costs, and offers targeted metrics for assessing sustainability. By integrating these measurement methods, businesses and policymakers can develop data-driven strategies that drive the transition towards a more sustainable and resource-efficient economy. Standardization, technological innovation, and interdisciplinary collaboration will further enhance the effectiveness of these tools in shaping a circular future.

3. MODERN TRENDS IN METROLOGY FOR THE GREEN TRANSITION

3.1. Digitalization and Smart Technologies

Integrating IoT sensors, digital twins, and big data analytics revolutionizes real-time monitoring, predictive analysis, and decision-making for resource management and environmental sustainability.

Internet of Things (IoT) sensors are embedded in infrastructure, industries, and natural environments to collect real-time data on resource flows (energy, water, waste) and environmental parameters (emissions, pollution, noise).

A digital twin is a virtual model of a physical system (industrial plant, city infrastructure) that updates in real-time using IoT sensor data. They test different environmental policies (e.g., the impact of traffic restrictions on air quality), identify risks in infrastructure (pipelines, bridges) before failures occur, and simulate the impact of sustainable practices in industries and urban planning.

Big data analytics processes vast amounts of environmental and resource flow data from IoT sensors and digital twins to generate actionable insights.

Figure 2. Smart bins rely on sensors to minimize the transportation costs [11]

3.2. Advanced Materials & Eco-Metrology

To support the circular economy and sustainable construction, innovative methods for measuring material sustainability have emerged, such as material passports, eco-costs, and lifecycle assessment tools. These tools improve transparency, resource efficiency, and environmental impact analysis.

A material passport is a digital database containing information about the composition, origin, and environmental impact of materials used in buildings or products. Some examples are available online: https://madaster.com, https://dgnb.de, https://bregroup.com.

Eco-costs express the hidden environmental costs of materials and products in monetary terms, making it easier to compare sustainability impacts. The European Commission proposed the Product Environmental Footprint (PEF) and Organisation Environmental Footprint (EF) methods as a standard way of measuring environmental performance [12].

Life Cycle Assessment (LCA) is a standardized method for evaluating the environmental footprint of materials and products. The International Environmental Product Declarations (EPD) system was established in 1997. With an EPD, manufacturers report comparable, objective and third-party verified data that show the environmental performance of their products and services [13]. The EU's Carbon Border Adjustment Mechanism (CBAM) is the EU's tool to put a fair price on the carbon emitted during the production of carbon-intensive goods entering the EU and encourage cleaner industrial production in non-EU countries [14].

3.3. Standardization Efforts

As industries and governments shift towards circular economy models, standardized frameworks are crucial to ensure consistency, efficiency, and regulatory compliance. They provide guidelines for businesses and policymakers to implement circular strategies effectively.

The standard BS 8001:2017 [15] is the first circular economy standard. It guides businesses in adopting circular principles in design, production, and supply chains.

ISO established the Technical Committee ISO/TC 323 to develop global standards for the circular economy, covering guidelines, measurement tools, and certification frameworks, such as:

- ISO 59004:2024 General Guidelines on Circular Economy
- ISO 59010:2024 Business Model Guidelines

- ISO 59020:2024 Measuring Circular Economy Performance
- ISO/CD 59031 Circular Economy in the Supply Chain.

3.4. Interdisciplinary Collaboration

Modern metrology - the science of measurement - is evolving beyond traditional precision measurement techniques. The integration of engineering, economics, and design is transforming metrology into a multidisciplinary, data-driven field, enhancing its role in sustainability, circular economy, and digital manufacturing. Advancements in engineering are driving a shift from manual, laboratory-based metrology to real-time, in-situ, and AI-enhanced measurement systems. Metrology integrates economic models to assess the cost-effectiveness and sustainability of measurement techniques, influencing policy and business decisions.

3.5. Case Example

One of the best examples of sustainability in the building sector is the smart monitoring and energy-efficient retrofit of Edge building in Amsterdam, Netherlands. One of the world's most sustainable office buildings integrates IoT sensors, AI-driven analytics, and digital twin technology to optimize energy use and indoor environmental quality:

- IoT-Based Real-Time Monitoring – 28,000 sensors measure temperature, light levels, humidity, occupancy, and energy consumption
- Digital Twin for Predictive Maintenance – Virtual models simulate wear-and-tear of HVAC systems and optimize energy performance
- AI-Driven Energy Optimization – Self-learning algorithms adjust lighting, ventilation, and heating based on occupancy patterns
- Solar-Powered & Net-Positive Energy – Generates more energy than it consumes via rooftop and façade solar panels.

Figure 3. The collaborative app is used to reserve a workspace, adjust lighting and room temperature and to record exercise history [16]

The building owner claims that the Edge building consumes 70% less energy than standard office buildings [16]. Sustainable technologies enabled the Edge building to create a radically new working environment. Employees have no assigned desks but can choose their workplace anywhere in the building: work booths, focus rooms, concentration rooms, sitting desks, standing desks, balcony desks, and the workstation in the atrium. The building adapts to user preference with a smartphone app.

Performance-based assessments use data-driven metrics to evaluate a building's sustainability and occupant impact over time. The most widely used assessment frameworks include:

- Building Energy & Carbon Performance: LEED (Leadership in Energy and Environmental Design), BREEAM (Building Research Establishment Environmental Assessment Method), Passivhaus Standard
- Life Cycle Assessment (LCA) & Whole-Life Carbon Metrics: Cradle-to-Grave Carbon Footprint, Life Cycle Costing (LCC), Global Warming Potential (GWP)
- Health & Well-Being in Architecture: WELL Building Standard (focused on human health, air quality, and biophilic design)

6. CONCLUSION

Measurements are the cornerstone of effective circular economy strategies and the green transition by providing the necessary data to assess resource efficiency, environmental impact, and system performance. Without accurate and reliable measurements, decision-makers lack the insights to track progress, identify inefficiencies, and implement evidence-based policies. Methods such as Material Flow Analysis (MFA) enable a systematic understanding of resource inputs and outputs, ensuring that materials are efficiently utilized and waste is minimized. Life Cycle Assessment (LCA) supports sustainable design by quantifying environmental impacts across a product's lifespan, helping industries make informed choices that reduce carbon footprints and pollution. Additionally, circularity indicators and eco-costs provide metrics to evaluate sustainability efforts, ensuring that economic activities align with environmental and social goals. By integrating these measurement tools, businesses, governments, and researchers can develop targeted interventions that drive resource conservation, improve waste management, and accelerate the shift towards a regenerative economy. In essence, robust measurement frameworks transform sustainability ambitions into actionable strategies, ensuring the transition to a greener, more circular economy is effective and scalable.

7. REFERENCES

[1] Papamichael I et al. (2023) Measuring Circularity: Tools for monitoring a smooth transition to Circular Economy, Sustainable Chemistry and Pharmacy, Volume 36, 2023, 101330, ISSN 2352-5541, https://doi.org/10.1016/j.scp.2023.101330

[2] Zhai X, An Y, Shi X, Liu X (2022) Measurement of green transition and its driving factors: Evidence from China, Journal of Cleaner Production, Volume 335, 2022, 130292, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2021.130292

[3] Lau CK, Gozgor G, Mahalik MK, Patel G, Li J (2023) Introducing a new measure of energy transition: Green quality of energy mix and its impact on CO2 emissions, Energy Economics, Volume 122, 2023, 106702, ISSN 0140-9883, https://doi.org/10.1016/j.eneco.2023.106702

[4] Acosta LA, Maharjan P, Peyriere HM, Mamiit RJ (2020) Natural capital protection indicators: Measuring performance in achieving the Sustainable Development Goals for green growth transition, Environmental and Sustainability Indicators, Volume 8, December 2020, 100069, https://doi.org/10.1016/j.indic.2020.100069

[5] Abou Hogail R (2024) The New Era of Metrology and Its Role in Information Technology: A Survey. Journal of Measurement Science and Applications (JMSA), 4(1), 32-65. https://doi.org/10.21608/jmsa.2024.360347

[6] Li G, Röttger A, Zboril M, Werhahn O (2025) Metrology for climate action. Measurement: Sensors, 101850. https://doi.org/10.1016/j.measen.2025.101850

[7] Yadav S, Rab S, Wan M, Bhatnagar A, Jain A, Achanta VG (2024) Role of Conformity Assessment and Metrology in the Circular Economy for Sustainable Growth. In: Bhatnagar, A., Yadav, S., Achanta, V., Harmes-Liedtke, U., Rab, S. (eds) Handbook of Quality System, Accreditation and Conformity Assessment. Springer, Singapore. https://doi.org/10.1007/978-981-97-5750-3_19

[8] Fernandes J (2023) A Review on Life Cycle Assessment of Pavements in Brazil: Evaluating

Environmental Impacts and Pavement Performance Integrating the International Roughness Index. Sustainability, 15(19), 14373. https://doi.org/10.3390/su151914373
[9] Ramachandran A (2025) What is an LCA? 3 life-cycle assessment examples, One Click LCA Ltd. https://oneclicklca.com/en/resources/articles/life-cycle-assessment-examples-and-lca-defined/ (accessed 19.3.2025)
[10] Glogic E, Sonnemann G, Young S (2021) Environmental Trade-Offs of Downcycling in Circular Economy: Combining Life Cycle Assessment and Material Circularity Indicator to Inform Circularity Strategies for Alkaline Batteries. Sustainability, 13(3), 1040. https://doi.org/10.3390/su13031040
[11] ME Universal: Smart waste compactor, https://meuniversal.com/universal-ecube.php (accessed 19.3.2025)
[12] European Commission: European Platform on LCA | EPLCA, Environmental Footprint, https://eplca.jrc.ec.europa.eu/EnvironmentalFootprint.html (accessed 19.3.2025)
[13] EPD: The International EPD System, https://environdec.com/home (accessed 19.3.2025)
[14] European Commission: Carbon Border Adjustment Mechanism, https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en (accessed 19.3.2025)
[15] BS 8001:2017 Framework for implementing the principles of the circular economy in organizations, https://knowledge.bsigroup.com/products/framework-for-implementing-the-principles-of-the-circular-economy-in-organizations-guide (accessed 19.3.2025)
[16] The Edge, https://edge.tech/buildings/the-edge (accessed 19.3.2025)
[17] Worksight (2021) A pioneering smart building that cultivates „experiences“, https://www.worksight.jp/en/issues/538.html (accessed 19.3.2025)