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A critical evaluation of digitalisation and green measures for advancing twin transition metrics¹

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Abstract

The global economy has undergone two significant shifts in recent decades: digitalisation and the green transition. While each has been studied extensively, their intersection remains underexplored. This study reviews metrics for assessing digital and green transformations, both separately and jointly, and identifies key challenges in evaluating their complementarities and trade-offs. By mapping current approaches and offering a comprehensive framework, the paper highlights gaps. The paper proposes a theory-driven metrics framework to support integrated strategies for sustainable innovation and structural transformation toward a green and digital economy.

Keywords: Digitalisation, Greening, Sustainable Development, Metrics

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JEL codes: O33, L86, Q01, Q51, Q56

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1. Introduction

In recent decades, the global economy has undergone two significant transitions. The first is the accelerated pace and scale of digitalisation, underpinned by the Fourth Industrial Revolution (4.0), which has driven transformative technological advancements such as artificial intelligence (AI), the Internet of Things (IoT), robotics, and blockchain, making systems more interconnected, automated, and intelligent [1]. The second is the green transition, a response to the growing urgency of climate change, shaped by government regulations, societal pressures, and targeted policy support [2-3]. The literature has broadly examined these transitions individually, although awareness is growing that the two are closely intertwined. For example, the EU considers the twin green and digital transitions a precondition for transforming the European economy [4-5]. These two processes are seldom compatible or complementary, although they are often presented as such. As the literature suggests, the relationship between digitalisation and green transition does not automatically generate complementarities or synergies. Digitalisation can both support and hinder the green transition [6]. It holds promise for sustainable solutions, such as smart grids [7], circular economy practices [8], and precision agriculture [9]. At the same time, it poses risks of increased e-waste and energy consumption if sustainability is not prioritised from the outset [10].

As noted by Makitie et al. (2023) and Muñoz de Bustillo (2024), there is limited conceptual clarity around the content and dynamics of twin transition. Müller et al. (2024) highlight that research on digitalisation and sustainability predominantly occurs in isolation, lacking shared definitions of "green" and "digital" transitions. While there is general agreement that digitalisation affects greening both directly and indirectly, clarity on identifying and structuring these effects is lacking. Direct effects often focus narrowly on electricity use and emissions, overlooking broader impacts, such as material or water footprints (Roussilhe et al., 2023). Indirect effects vary by framework. For instance, Hilty et al. (2006) distinguish between first-order effects (e.g. e-waste), second order (e.g. efficiency gains), and third-order effects (e.g. rebound effects). Piscicelli (2023) finds that existing studies often highlight firm-level benefits in specific sectors, typically identifying positive second-order effects from improved circular processes through digital technologies.

This paper examines the metrics used to assess digitalisation and green transition. It emphasises the importance of capturing their mutual interplay. Accurate, theory-informed indicators are crucial for evidence-based policy and strategy, as metrics shape both

understanding and action. There has been no systematic review of the metrics used in academic and policy literature to assess the twin transitions of digitalisation and greening [11]. Without standardised metrics across technologies, locations, and time, it is impossible to track twin transformations. Effective implementation also depends on long-term planning and governance [12]. While digital technologies benefit from spillovers and rapid diffusion [13], green technologies often require targeted policies, subsidies, and compliance mechanisms [14–15]. Comparative and context-sensitive metrics are crucial for guiding progress and addressing sectoral and regional disparities.

In this paper, we conceptualise digitalisation as the transformation of business models, operational processes, and broader socio-economic structures through the deployment of digital technologies and data, with the aim of enhancing efficiency, innovation, and value creation. We understand the green transition as a systemic process that reshapes economic, social, and technological systems to promote sustainability, reduce environmental harm, and improve resource efficiency. These working definitions are consistent with major international policy agendas, including the UN Sustainable Development Goals, the OECD Green Growth Strategy, and the EU Green Deal.

Our study adopts a theory-based literature review approach, which seeks not only to summarise empirical evidence but to build conceptual clarity and propose a structured analytical framework [16]. By doing so, we contribute to a more coherent understanding of how digital and green transitions are measured, individually and jointly.

More specifically, this paper makes the following contributions. First, we provide a comprehensive overview of how digitalisation and green transition are operationalised in academic and policy literature, review existing metrics across different transition stages (inputs, processes, and outcomes), and offer recommendations for future research. Second, we organise indicators to enhance understanding of the various dimensions of digitalisation and green transition in their interaction. Third, we propose several complexity indicators to guide evidence-based policy and business strategies for the twin transition.

The paper is structured as follows. Section 2 explains the methodology for collecting evidence on metrics. Section 3 defines key concepts and reviews studies that use various digitalisation and greening metrics, classified by input, process, or outcome indicators. Section 4 presents stylised facts from the literature. Section 5 proposes new metrics, discusses potential data sources, and

highlights methodological and cost-related challenges. Section 6 concludes with a new interpretative framework for twin transition metrics.

2. Methodology

This review comprehensively explains how digitalisation and greening are proxied in relevant studies, summarising key metrics for these two transitions. Metrics translate concepts like digital adoption or greening into measurable terms.

The literature review encompasses studies published between 2008 and 2024, with the majority from the past six years, specifically from 2019 to 2024. The literature search relies on widely used international bibliometric databases: Scopus, JSTOR, ScienceDirect, Business Source Complete (EBSCO), and Web of Science [17–18]. These features research on digital and green topics in economics, management, finance, environmental economics, and other interdisciplinary fields, published in reputable peer-reviewed journals.

To enhance transparency and replicability, this review adopts a PRISMA-inspired reporting structure, adapted to the objectives of a theory-driven systematic literature review [19]. Given its conceptual focus, the analysis centres on the classification and interpretation of metrics rather than quantitative synthesis. Accordingly, we follow the core PRISMA logic by explicitly documenting the identification, screening, eligibility, and inclusion stages of the literature selection process. This approach allows readers to verify the scope of the search, assess potential sources of bias, and replicate the review strategy if needed.

In generating a database of relevant literature, we followed the identification strategy summarised in Figure 1. Initially, separate keyword searches were conducted for studies specifically related to the digital and green transitions. For the digital transition, the keyword-based search strategy was designed to capture multiple, interrelated dimensions of digital transition. Specifically, it covered: (i) the overarching digitalisation layer, capturing generic and composite conceptualisations of digital change (e.g. “digitalisation”, “digital economy”, “digital transformation”); (ii) the technological layer, focusing on the adoption and diffusion of digital and information and communication technology (ICT)-based technologies (e.g. “digital technologies”, “ICT adoption”, “ICT use”, “Artificial Intelligence”, “Robot”, “automation”, “Industry 4.0”); (iii) the infrastructure layer, reflecting the physical and network foundations of digitalisation (e.g. “digital infrastructure”); (iv) the

organisational and capability layer, capturing the abilities to deploy, integrate, and leverage digital tools (e.g. “digital capability”, “digital affordance”); and (v) the innovation layer, addressing digital-driven innovation processes and outcomes within the digital economy (e.g. “digital innovation”).

For the green transition, the keywords used for searching included the following dimensions: (i) the overarching green transition layer, encompassing generic and composite conceptualisations of environmental transformation (e.g. “green transition”, “environmental transition”, “greening”, “sustainability”); (ii) the energy and low-carbon transition layer, capturing studies focused on decarbonisation pathways and energy system transformation (e.g. “renewable energy”, “low-carbon economy”, “carbon reduction”); (iii) the green production and practices layer, addressing changes in production processes and operational practices aimed at reducing environmental impacts (e.g. “green production”, “sustainable practices”, “environmental practices”, “green initiatives”); (iv) the environmental management and governance layer, focusing on organisational strategies, managerial practices, and investment decisions related to environmental objectives (“environmental management”, “sustainable investment”); and (v) the green and environmental innovation layer, capturing innovation-driven approaches to sustainability (e.g. “green innovation”, “environmental innovation”, “eco-innovation”).

Subsequently, Boolean operators (AND, OR) were applied to combine and refine these searches systematically. For instance, the operator AND was used to combine key themes and capture literature that simultaneously addressed both digitalisation and greening metrics. The operator OR was used to include synonyms, such as “sustainability” OR “environmental transition”. Additionally, wildcard symbols were employed to account for variations in terminology (e.g., “sustain*” to capture both “sustainability” and “sustainable”). This systematic and iterative approach have ensured comprehensive coverage and facilitated the accurate identification of relevant articles across the selected bibliometric databases.

At the screening stage, records were screened based on titles and abstracts. We applied a set of broad inclusion criteria to identify studies potentially relevant to the review, as shown in Figure 1. First, we prioritised peer-reviewed journal articles published in reputable outlets (e.g., ScienceDirect, Scopus, JSTOR, Web of Science, EBSCO) to ensure academic rigour. Second, we retained empirical studies that explicitly addressed digital transformation and/or green transition at the firm, sectoral, or national level. Third, we excluded purely conceptual, descriptive, or policy-discussion papers using the

following exclusion criteria to retain only studies that used measurable or operationalised indicators.

Exclusion criteria were then applied to systematically filter out purely theoretical or review papers lacking empirical validation (unless explicitly focused on metric development), studies limited to non-industrial contexts (e.g. education, entertainment, or tourism), and grey literature, such as policy briefs, reports, and working papers, unless peer-reviewed publications prominently cited them. This structured filtering process ensured that the selected literature provided robust empirical insights that aligned closely with the review's objectives.

Indicators such as the Green Complexity Index or Digital Trade Index were not included because they measure structural economic specialisation rather than interaction effects between digitalisation and greening processes.

For a comprehensive understanding of the extant literature, our analysis categorises contributions along two primary dimensions. First, we apply a functional classification, distinguishing whether a study focuses on the input, process, or outcome dimensions of digitalisation and/or greening. This classification provides the analytical foundation for constructing our framework. By mapping existing indicators onto an input-process-outcome logic, we identify systematic imbalances (e.g., the dominance of input indicators), conceptual gaps (particularly at the intersection of digital and green processes), and missing linkages across transformation stages. This functional structuring enables us to move from a fragmented inventory of measures toward an integrated, theory-driven framework that aligns component-level indicators with interoperability and system-level dynamics.

As a secondary dimension, we classify studies by level of analysis (firms, sector or country). However, since many indicators operate across levels and share methodological similarities, this dimension is analytically less informative for framework development than the functional input-process-output structure.⁵ We also exclude meta-analysis papers⁶. Our final sample comprises 109 papers.

Although our selection strategy aimed to ensure broad global coverage without geographic restrictions, we observed a notable

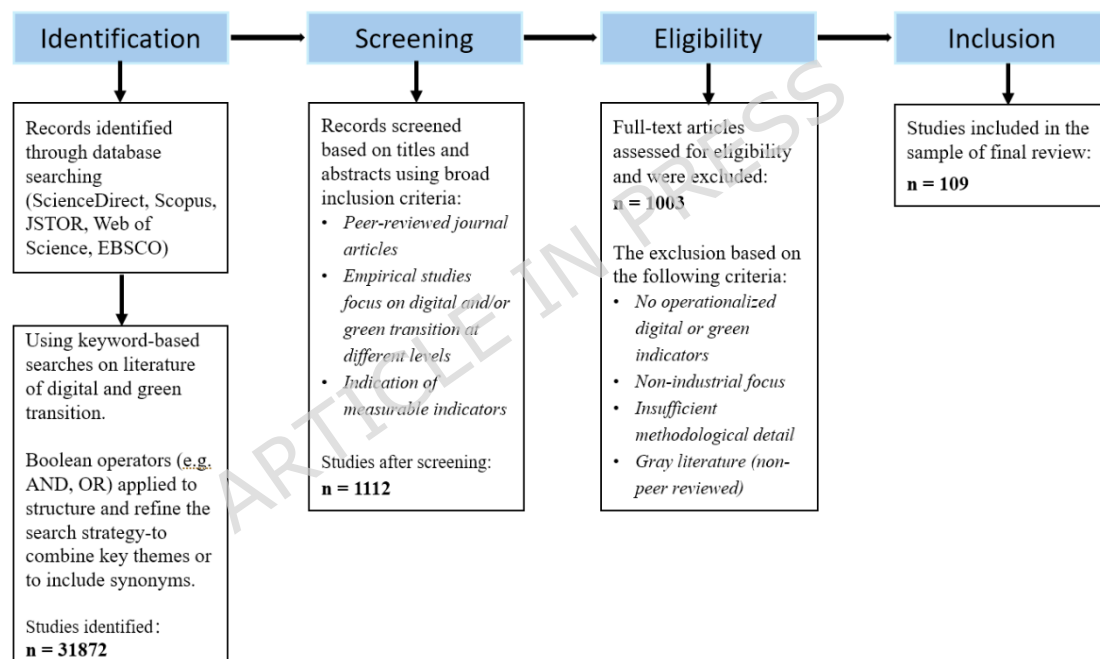
⁵ Additionally, firm-level metrics specifically often rely on non-standardised survey data, which vary in design and lack longitudinal consistency, making cross-country comparison and time-based tracking difficult. These metrics are also prone to biases and lack globally harmonised definitions.

⁶ Meta-analyses were excluded, as our aim was to systematise and assess the conceptual and methodological foundations of twin transition metrics rather than aggregate statistical effect sizes. This approach is consistent with prior theory-oriented reviews (for overview of this literature, see Paré et al., 2015).

concentration of studies on China. Specifically, 34 papers in our final sample examine the Chinese context. This was not a predetermined focus, but rather an emergent pattern within the literature retrieved through our global search strategy.

This considerable presence likely reflects China's influential industrial policies and proactive role in promoting digital and green transitions across multiple sectors. It also underscores China's importance in exemplifying the "twin transition" dynamic in the context of emerging economies, as well as its widely recognised achievements in environmental sustainability and carbon neutrality in recent years. Therefore, due to the substantial representation and contextual specificity of these China-focused studies, we highlight them as a distinct subset in our analysis.

Figure 1: PRISMA-aligned literature identification and screening process



3. Mapping existing metrics: Input-Process-Outcome Perspective

Building on the conceptual definitions outlined in the introduction, this section reviews how digital and green transitions are operationalised in the empirical literature.

We classify indicators by function—input, process, and outcome. Input indicators reflect resources committed, such as ICT infrastructure, green investments, or related employment. Process metrics track actions, such as managerial practices and technology adoption. Outcome indicators capture the results, such as carbon

intensity or productivity growth. Some scholars also refer to output metrics, treating them similarly to outcome measures. Output metrics capture direct services or products (e.g., share of digital service delivery), while outcome metrics reflect broader impacts (e.g., market share achieved via digital channels). Given the overlap, we treat them jointly here.

We also distinguish between individual and composite indicators. Composite indicators, designed to provide a comprehensive assessment of digitalisation or greening transitions, often integrate multiple dimensions. Thus, in the case of composite indicators, distinguishing between input, process, and outcome indicators is difficult, as they may contain all three. Although this integration can complicate clear categorisation, it remains possible and analytically useful to identify and justify components within composite metrics according to their primary functional roles.

3.1. Input category indicators

3.1.1 Digitalisation

In the reviewed literature, firm-level indicators of digitalisation are most commonly derived from large international surveys, notably the World Bank Enterprise Survey (WBES), the European Bank for Reconstruction and Development Business Enterprise Performance Survey (EBRD-BEEPS) and the Community Innovation Survey (CIS). These datasets are frequently used because they include dedicated modules that capture multiple dimensions of digital adoption, typically measured using Likert-scale responses or dichotomous variables. Some studies further apply dimensionality-reduction techniques, such as Principal Component Analysis (PCA), to aggregate these variables into composite measures of digitalisation (e.g., Abidi et al., 2023).

DeStefano et al. (2017) utilised the Ci Technology database to distinguish between hardware (computing and telecom equipment) and software, thereby capturing more detailed ICT usage to provide a finer-grained view of enterprise ICT adoption.

In addition to large-scale international datasets, the literature also proposes alternative measurement strategies. Thus, some studies rely on custom-designed surveys to capture firms' digital orientation by counting the business areas in which they have invested in digitalisation [20-22]. Others operationalise digitalisation from a human capital perspective. For example, Babina et al. (2024) developed a measure of firms' investments in AI-skilled labour, using Burning Glass job postings to capture demand for AI

talent and to identify AI-skilled employees as a proxy for AI technology investments.

The Digital Maturity Assessment (DMA) of enterprises, recently launched by the European Commission (still in pilot stage), provides a detailed overview of a firm's digitalisation. It serves as a paradigmatic tool for designing enterprise digitalisation questionnaires, systematically categorising six dimensions that are also extended to capture the instrumental role of digitalisation in facilitating the green transition: Digital Business Strategy, Digital Readiness, Human-Centric Digitalisation, Data Management and Connectedness, Automation and Artificial Intelligence, and Green Digitalisation.

While survey data are commonly used to measure enterprise digitalisation in academia [23-24], questionnaires have limitations. First, custom-designed surveys often suffer low response rates, limited representativeness, and generalisability. They typically focus on a single country, hindering cross-country comparisons. Second, firm responses may be biased by social desirability or by 'digital washing', in which digital capabilities are overstated. Third, few public institutions provide global microdata on firms' digitalisation. Fourth, most global firm-level databases, such as BEEPS, offer primarily cross-sectional data [25]. The lack of longitudinal data limits the development of robust firm-level metrics.

There exist approaches that disaggregate sector-level digitalisation metrics into firm-level metrics using revenue-weighted or capital-per-capita weights. Mucha and Seppälä (2021) estimate firm-level digital intensity scores by allocating firm revenues across industries and applying sector-level digital weights, assuming that digital intensity aligns with industry characteristics such as profitability or size. This helps address data limitations and mitigate endogeneity, but overlooks firm-specific variation and cannot isolate firm-industry interaction effects.

Eurostat's Digital Intensity Index (DII) is another metric derived from the EU survey on ICT usage and e-commerce in enterprises [26]. It scores firms from 0 to 12 across 12 digital technologies, grouping them into four digital intensity levels. Ten of the twelve indicators can be considered input categories (excluding e-commerce). However, firm-level data are publicly available only in aggregated form at the sectoral (NACE Rev. 2) or regional (NUTS 2) levels. While Eurostat provides detailed sector-level digitalisation data over time, inconsistencies across survey waves, particularly with the inclusion of advanced technologies such as AI and robotics, which were added only after 2018, limit the construction of high-quality, long-term panel data.

The EU KLEMS dataset provides industry-level indicators of tangible and intangible assets, as well as digital technology investments, across EU member states. For instance, Bruno et al. (2024) use the 'share of computer software and databases in net capital stock' to proxy sector digital capability. Other studies combine ICT capital indicators into indexes of sectoral digitalisation, often referred to as 'digital capability', 'digital deepening', or 'digital intensity' [27-30].

When constructing composite measures of sectoral digitalisation based on multiple variables, Principal Component Analysis (PCA) and Factor Analysis are widely used as dimensionality reduction techniques [13, 27, 31-33]. Another approach utilises weighted composite indices, employing either equal weighting [34] or entropy-based weighting [35-37].

An alternative approach to measuring sector-level digitalisation is to adopt an input-output framework, which differs somewhat from relying solely on input-based metrics discussed above. It uses intercountry input-output (ICIO) tables to proxy digitalisation through digital intermediate inputs. This method, grounded in Koopman et al. (2014), captures both direct and indirect digital input flows across sectors via the Leontief inverse matrix. Researchers estimate sectoral digital input by summing the total consumption coefficients for each digital sector. Rui and Li (2023) propose a relative digital input index, which expresses digital inputs as a share of total intermediate inputs, thereby adjusting for sector size.

Data for this approach are accessible through the OECD ICIO, ADB MRIOTs, WIOD, and TiVA databases, enabling longitudinal analysis over 15 years. However, this method misses in-house digitalisation. For example, the automobile industry consumes and develops digital technologies. To address this gap, Calvino et al. (2018) propose a sectoral digitalisation taxonomy that combines ICT inputs, ICT capital stock, human capital, and market behaviour. This highlights the need for metrics that account for industry heterogeneity, distinguishing between technology producers and intensive users, which is a crucial direction for future research and policy.

Finally, moving to the next level of analysis, most regional or country-level metrics use composite indexes that include various input-type sub-indicators to measure digitalisation [38] comprehensively. For instance, the Digital Economy and Society Index (DESI) by the European Commission tracks digital competitiveness across four dimensions in EU27 countries: Connectivity, Human capital, Integration of digital technologies, and Digital public services [4].

The Networked Readiness Index (NRI), published by the World Economic Forum (WEF), evaluates countries' ability to harness digital technologies for economic growth and prosperity. Its four dimensions [39] include: 1) digital technology development environment; 2) digital usage by individuals, businesses, and government; 3) ICT readiness; 4) economic and social impact. The second and third dimensions include many input-based indicators.

The ICT Development Index (IDI), created by the International Telecommunication Union (ITU) (ITU, 2023), measures ICT development across 176 countries. First published in 2009 and resumed in 2022, it now focuses on two pillars: Universal Connectivity and Meaningful Connectivity, both of which align with input-based metrics.

3.1.2. Green Transition

The first main input-type "Green Transition" metrics refer to green investments, which are large-scale investments in green technologies, equipment and human capital. Examples include adopting cleaner technologies to cut emissions, promoting recycling, and hiring for green-related roles to lower carbon footprints and achieve net-zero goals [40-42].

In the reviewed studies, firm-level green investment indicators are frequently derived from enterprise survey data, particularly the WB-EIB-EBRD Enterprise Survey [40-41] and Flash Eurobarometer [43]. Across these contributions, green investment is most commonly operationalised as a binary variable (0/1), indicating whether a firm has invested in environmentally friendly technologies (such as upgraded machinery, equipment, or vehicles) [40-41], or interval-based ones, measuring the scale of investment (e.g. share of turnover) [44-45]. Shrivastava and Tamvada (2019) also use the number of full-time employees in green roles to assess investment in human capital.

At the sector and country levels, studies use indicators such as investment in energy-saving measures for environmental purposes [46] and government environmental expenditure as a percentage of GDP [47] to reflect sectoral efforts toward sustainable development.

A second input-type "Green Transition" metric focuses on electricity use and energy consumption [48-49]. Renewable energy adoption also serves as a key input-based indicator, reflecting a firm's shift toward sustainable sources [20, 36, 50-51]. Some country-level composite indexes incorporate these metrics. For example, Bruno et al. (2023) include the term "greening" in a three-dimensional technology-upgrading framework (intensity, breadth,

and technology exchange), in which the breadth dimension aggregates six equally weighted environmental indicators. Two of these -renewable energy and fertiliser consumption - are input-type metrics.

Table 1 summarises both 'digitalisation' and 'green transition' input-based indicators, more commonly used in empirical studies on digitalisation and greening.

Table 1 Input-type metrics

Indicator	Source(s)	Authors
Digital transition		
1. Access to digital infrastructure (tangible ICT equipment) and digital connectivity		
Households (HHs) with access to internet at home, %; Fixed broadband Internet subscribers/access to high-speed internet (per 100 people); International Bandwidth (in Mbits)	Eurostat; World Bank, ITU	Greenan and Napolitano (2024); Shahbaz et al. (2022); Bruno et al. (2023); Yi et al. (2024)
DSL or other fixed broadband access; access to high-speed broadband (>30Mbits, or >100 Mbits), % of enterprise	Eurostat	Greenan and Napolitano (2024); Gal et al. (2019); Ruiz-Rodríguez et al. (2018);
Individuals using the Internet (% of population); Individuals using a computer (% of population)	World Bank, ITU	Shahbaz et al. (2022); Yi et al. (2024)
Mobile broadband connection (3G modem or 3G handset); Mobile cellular subscriptions (per 100 people)	Eurostat; World Bank, ITU	Greenan and Napolitano (2024); Ruiz-Rodríguez et al. (2018); Shahbaz et al. (2022); Yi et al. (2024)
% Enterprises where more than 50% of employees used computers to access the internet for business purposes	Eurostat	Castelo-Branco et al. (2019)
Enterprises give portable devices for a mobile connection to the internet to their employees;	Eurostat	Castelo-Branco et al. (2019); Ruiz-Rodríguez et al. (2018); Hayriye & Fatma (2020)
Employees use interconnected devices or systems; Enterprises use PCs, servers, extensions and network lines;	Eurostat; CiTDB database	Brodny & Tutak (2022); DeStefano et al. (2017)
Secure Internet servers (per 1 million people);	World Bank, ITU	Bruno et al. (2023)
Share of Computing Equipment (tangible IT capital) in Capital stock net, %	EU KLEMS	Bruno et al. (2021)
Share of Computing Equipment in Gross Fixed Capital Formation, %	EU KLEMS	Bruno et al. (2024); Ferschli et al. (2021); Calvino et al. (2018)

2. Adoption of E-business software (intangible ICT capital)		
Share of computer software and databases in the capital stock net; Share of the volume of Computer software and databases in the volume of total Gross Fixed Capital Formation	EU KLEMS	Bruno et al. (2021); Bruno et al. (2024); Ferschli et al. (2021); Acharya (2016); Calvino et al. (2018)
Have enterprise resource planning (ERP) or customer relationship management (CRM) software package, % of the enterprise; Have database management applications; innovation software; and security and groupware software.	Eurostat	Greenan and Napolitano (2024); Gal et al. (2019); Castelo-Branco et al. (2019); Brodny & Tutak (2022);
Whether enterprises have database management applications, innovation software, and security and groupware software	CiTDB database	DeStefano et al. (2017)
3. Adoption of basic digital technologies (DTs)		
3.1 Web and social media technologies:		
% Enterprises having a website or homepage, whether or not the company has its website (dichotomous variable)	Eurostat	Greenan and Napolitano (2024); Brodny & Tutak (2022); Ruiz-Rodríguez et al. (2018)
Whether or not the company has its website (dichotomous variable)	BEEPS	Abidi et al. (2023)
Use social networks (e.g., Facebook, LinkedIn, Xing, Viadeo, and Yammer)	Eurostat	Greenan and Napolitano (2024); Ruiz-Rodríguez et al. (2018);
Internet use participating in social networks, % enterprise	Eurostat	Belitski et al. (2023)
3.2 Digital breadth (business/functional areas adopting DTs)		
Counts of functional areas where firms have invested in DTs: such as advertising, selling, purchasing, manufacturing, distribution, information systems, human resource management, finance, strategic thinking, management information, and other areas	Author's survey data; Firm's annual report	Ardito et al. (2021); Nasiri et al. (2022); Commander et al. (2011)
4. Adoption of advanced ICTs		
High Cloud Computing services (accounting software applications and computing power); Medium/simple CC services (e-mail, office software, storage of files, and hosting of the enterprise's database)	Eurostat	Gal et al. (2019); Greenan and Napolitano (2024); Castelo-Branco et al. (2019)
Enterprises employ robots (industrial/service)	Eurostat	Brodny & Tutak (2022)

5. Human capital		
% Enterprises that employ ICT specialists	Eurostat	Ruiz-Rodríguez et al. (2018)
Investments in AI-skilled human capital	Burning Glass database; Cognism database	Babina et al. (2024)
6. Digital input index (based on the input-output table)		
Total consumption coefficient on digital sectors; relative digital input index	OECD ICIO database	Rui and Li (2023)
Green Transition		
Green investment:		
1 if the firm invests in machinery, equipment or vehicle upgrades that embody green technologies; 0 otherwise	EBRD-EIB-WB Enterprise Survey	De Haas et al. (2024); Atif et al. (2020)
Sustainable investment scaled by sales turnover (or total assets); Total investments into Circular Economy as a percentage of turnover over the last 3 years	Flash Eurobarometer survey 342, 441; Bloomberg	Hoogendoorn et al. (2015); Demirel & Danisman (2019); Atif et al. (2020)
Human capital investment: How many of the full-time employees of the firm work in green jobs some or all the time	Flash Eurobarometer survey	Shrivastava & Tamvada (2019)
Investment in reducing energy consumption with an environmental purpose;	The Environmental Protection Activities Survey by the Spanish Institute of Statistics, (INE)	García-Quevedo & Jové-Llopis (2021)
The rate of the government expenditure on environment to the national GDP, %	China Statistic Yearbook	Peng et al. (2022)
Energy and resource consumption (input)		
Energy consumption in the sector; Energy consumption in the household	International Energy Agency (IEA); China Energy Statistical Yearbook	Yan et al. (2022); Mendiluce et al. (2010)
Renewable energy use	Personal survey data	Farza et al. (2021); Yacob & Wong (2019);

		Ardito et al. (2021)
Renewable energy consumption; Renewable energy generation	BP (UK)	Shahbaz et al. (2022)
Renewable energy consumption (% of total final energy consumption)	Word Bank, WDI	Yi et al. (2024); Bruno et al. (2023)
The ratio of industrial-added value to the energy consumption of the corresponding industry	China Energy Statistic, China Industrial Statistic, and China Environment Statistic Yearbooks	Wang & Yan (2022)
Fertiliser Consumption (Kilograms per hectare of arable land)	Word Bank, WDI	Bruno et al. (2023)

3.2. Process Category Indicators

3.2.1. Digitalisation

Beyond measuring adoption, firm-level studies examine digital strategies, management practices, and managerial attitudes, commonly seen as processes linking digital inputs to outcomes.

Various studies use surveys to capture organisational behaviours indicative of digital management initiatives [23–24, 52]. In these studies, respondents rate statements like "Digitalisation aligns with business objectives" on a "Likert" scale, with higher scores indicating stronger digital management practices.

A complementary approach to survey-based measures of firm-level digitalisation is text analysis of annual reports. This measure quantifies digital engagement by counting the frequency of digital keywords extracted from sections of company reports, such as "Management Discussion and Analysis", using Python crawlers [53–54]. Researchers build keyword dictionaries from academic literature and policy documents, then standardise the keyword counts to create digitalisation metrics [55–57].

Some studies assess firms' digital focus by weighting digital keyword frequencies relative to the total number of words in annual reports, enabling cross-company comparisons [58]. This helps distinguish firms that merely mention digitalisation from those emphasising digital initiatives. Others categorise keywords into dimensions and use models, such as projection pursuit, to score digital transformation [59]. However, keyword frequency alone

overlooks qualitative aspects such as implementation and integration [21]. Additionally, text analysis is prone to strategic overstatements (digital washing) and is best complemented by financial data on digital project investments to gauge genuine engagement.

Other studies use E-business software indicators, considered input but focused on business processes, supplier and customer relations [32], and data transactions [24], thus included as process-type indicators.

Eurostat provides sector and country-level process-based indicators that are widely used in empirical studies. For example, in advanced ICT adoption, indicators such as the percentage of enterprises analysing Big Data or using data from smart devices reflect the integration of digital technologies [32, 35]. Ruiz-Rodríguez et al. (2018) use the share of firms offering ICT training to capture efforts to upskill the workforce.

Eurostat also tracks e-commerce, including indicators such as the share of enterprises with online sales exceeding 1% of turnover and the share of firms issuing e-invoices suitable for automated processing [60–61]. These metrics show a shift from basic digital adoption to more strategic integration aligned with business goals.

3.2.2. Green Transition

Process-based greening metrics focus on firms' internal strategies to address ecological issues. While section 3.1.2 outlined green investment as input-type metrics, process-type indicators reflect how these investments support green operations or resource efficiency.

Studies often examine processes associated with achieving energy efficiency [46], including investments in renewable energy [44–45], investments targeting to minimise material use, waste recycling, pollution control and heating & cooling improvements [20, 40, 51, 62]. In addition, some studies measure corporate social responsibility (CSR) using survey data on whether firms purchase financial products that incorporate social and environmental considerations [63].

Another dimension is green finance, which supports green transformation through tools such as bonds, funds, and credit [64]. Event-study designs frequently rely on dummy variables to capture the outcome of policy shock. For example, researchers use binary indicators to identify whether a firm has issued a green bond [65] or whether a specific environmental policy, such as China's Green Credit Policy, has been implemented [66]. Environmental violations

are also monitored using binary indicators for regulatory fines [67-68].

Additional process metrics include proxy indicators of managerial commitment and green governance. These use surveys to capture firms' green attitudes and strategic objectives, adherence to green certifications, and environmental management systems (EMS) maturity [40, 43, 50-51, 69-70]. Recent developments, such as China's Certified Emission Reduction (CCER) and Green Energy Certificates, provide additional metrics for assessing green transitions [71].

Lastly, green entrepreneurship reflects innovation-led responses to climate challenges. Cojoianu et al. (2020) measure it via new VC-backed green venture entries per region. Table 2 summarises the reviewed process-based indicators.

Table 2 Process-type metrics

Indicator	Source	Authors
Digital transition		
1. Digital management initiatives		
1.1 Digital orientation		
Committed to using digital technologies in developing our new solutions; Firm's solutions have superior digital technology (five-point or 7- point Likert scale)	Author's survey data	Nwankpa & Roumani (2016); Khin & Ho (2018)
New digital technology is readily accepted in our organisation; We always look out for opportunities to use digital technology in our innovation (five-point or 7- point Likert scale)	Author's survey data	Tsou & Chen (2023); Nwankpa & Roumani (2016); Khin & Ho (2018)
The firm's digitalisation index by text analysis counts the digital keyword frequency in the Annual report.	Firm's annual report and Authors' calculation	Wu et al. (2022); Nasiri et al. (2022); Gao et al. (2024); Zhao et al. (2021); Xue et al. (2022)
1.2 Digital strategy		
Digital transformation (DT) strategy: 1. accurately anticipated DT; 2. firm's strategic plan identifies value from DT; 3. inform management team about valuable options of digital technology; 4. Our firm is driving new business processes built on technologies (e.g. big data, analytics, cloud) (five-point or 7- point Likert scale)	Author's survey data	Tsou & Chen (2023); Nwankpa & Roumani (2016)
1.3 Digital maturity		
Ongoing process of adjusting to a transforming digital environment: based on content analysis of the initiatives described in annual reports	Firm's annual report and Authors'	Nasiri et al. (2022)

	calculation	
Weighted digital word frequencies relative to total words in annual reports	Firm's annual report and Authors' calculation	Liu et al. (2023)
Using models like projection pursuit to calculate digital transformation scores based on digital key words	Firm's annual report and Authors' calculation	Zhuo & Chen (2023)
2. E-business software (intangible ICT capital)		
Enterprises whose business processes are automatically linked to those of their suppliers or customers	Eurostat	Castelo-Branco et al. (2019)
Information exchange and transactions (five-point Likert): 1. processed transaction information in a short time; 2. a well-developed transaction processing network; 3. standardisation and scalability of digital technologies	Author's survey data	Tsou & Chen (2023)
3. Adoption of advanced ICTs		
% Enterprises analysing Big Data from any data source; % Enterprises analyse own big data from enterprise's smart devices or sensors	Eurostat	Castelo-Branco et al. (2019); Brodny & Tutak (2022)
% Enterprises using the AI technologies; Internet of Things (IoT); ICT security measure in daily operation	Eurostat	Castelo-Branco et al. (2019); Brodny & Tutak (2022)
4. Human capital		
Enterprises that provide training to develop/upgrade ICT skills	Eurostat	Ruiz-Rodríguez et al. (2018)
6. E-commerce		
Enterprises with e-commerce sales (online selling) of at least 1% turnover	Eurostat	Belitski et al. (2023); Benecchi et al. (2023)
Internet use - selling goods or services, % of population	Eurostat	Belitski et al. (2023); Benecchi et al. (2023)
Enterprises sending e-Invoices B2BG, suitable for automated processing	Eurostat	Belitski et al. (2023); Ruiz-Rodríguez et al. (2018)
Using online banking (% of population)	Eurostat	Benecchi et al. (2023)
Green transition		
1. Green investment:		
Firm's investments in resource efficiency as a percentage of annual turnover;	Flash Eurobarometer survey 342, 441;	Hoogendoorn et al. (2015); Demirel & Danisman (2019)

	Bloomberg	
Firm's investments in energy efficiency with an environmental purpose	Spanish Institute of Statistics (INE)	García-Quevedo & Jové-Llopis (2021)
1 if firm invest in: heating & cooling improvements; climate-friendly energy generation on site; waste minimisation & recycling; waste, energy or water management; air pollution or pollution control measures; improvements to lighting system; 0 otherwise 1 if the firm's strategic objectives encompass environmental or climate change issues; the firm has established a managerial position responsible for environmental or climate change matters; 0 otherwise.	EBRD-EIB-WBG Enterprise Survey; Flash Eurobarometer survey; or Personal own survey data	De Haas et al. (2024); Shui et al. (2025); Yacob & Wong (2019); Ardito et al. (2021); Bendell (2017)
Socially Responsible Investing: 1. Have you bought a socially responsible financial product? 2. Why have you chosen, or would choose, a financial product that includes social and environmental variables?	Personal survey data	Escrig-Olmedo et al., 2013
2. Green finance:		
Measured as a binary variable with 1 denoting the date when the firm issued green bonds;	Climate Bond Initiative and Bloomberg green bonds;	Tang and Zhang (2020)
A binary variable denoting environmental violations of publicly listed companies in capital markets	The Municipal Ecology and Environmental Bureau of each province in China	Zou et al., (2015); Ma et al., (2022)
A binary variable denoting implemented green finance policies like China's Green Credit Policy	Government report issued by the Ministry of Environmental Protection	Zhang et al. (2021)
3. Green management (score based on Likert scaling from survey):		

Green Management Score based on the following areas: 1. Strategic objectives related to the environment, climate change, or environmental policies 2. Employ a manager with an explicit mandate to deal with green issues; 3. have environmental targets 4. pollution monitoring 5. provide environmental training for employees 6. offers incentives to encourage environmentally responsible 7. Environmental partnerships 8. Requires all suppliers to meet certain environmental criteria 9. Managerial attitude	EBRD-EIB-WBG Enterprise Survey; or Personal survey data	Farza et al. (2021); Cordano et al. (2010); Yacob & Wong (2019); De Haas et al. (2024)
Environmental management system certifications: like ISO 14000, ISO 14001, ISO14064, ISO16000 or others	Flash Eurobarometer survey; Author's survey, or from the firm's website	Farza et al. (2021); Shrivastava & Tamvada (2019); Qi et al. (2021)
China's Certified Emission Reduction (CCER) and Green Energy Certificates	Administration of the People's Republic of China (CNCA).	Zhao et al. (2023)
Beyond complying with environmental legislation Number of Green Strategies beyond compliance with legislation	Flash Eurobarometer survey	Shrivastava & Tamvada (2019)
4. Green Entrepreneurship		
Entry count of new VC-backed or VC-seeking green (environmental) ventures per region per year	Crunchbase dataset (U.S.)	Cojoianu et al. (2020)
Green startup funding from the date of founding till the date of their IPO (reflect the growth potential of green venture)	Crunchbase dataset (U.S.)	Cojoianu et al. (2020)

3.3. Outcome Category Indicators

3.3.1. Digitalisation

Outcome-based metrics for firm digitalisation typically use patent data on digital technologies. Although patents should be considered intermediate outcomes that may lead to innovation, they are also used as proxies for the outcomes of already-acquired green technology capabilities. This emerging area builds on the well-established link between patents and innovation [72-73].

While patent data have traditionally measured innovation in larger firms, given the high costs for SMEs and startups to engage

fully in R&D [74-75], recent research highlights the role of AI in advancing radical innovation across firms of different sizes [76]. Grashof and Kopka (2023) combine firm-level data from the ORBIS database with patent data from PATSTAT to analyse AI's impact on innovation. Enriching the battery of firm-level innovation indicators, tools such as Natural Language Processing (NLP), semantic analysis, and neural networks enhance the analysis of patent data, with more significant potential when combined with other digital data sources, such as enterprise websites and reports [77].

3.3.2. Green Transition

A key focus of environmental performance metrics is the direct ecological impact (i.e. pollution) of a firm's operations. On the output side, emissions such as CO₂, NO_x, and SO_x (measured in kilograms) are critical indicators of a firm's carbon footprint [40]. Carbon intensity, defined as greenhouse gas (GHG) emissions (in tons) per unit of sales, further reflects emissions management efficiency [78-79]. Other relevant metrics include the share of green products or services in firm revenue, used to assess supply-side contributions to sustainability [43-44]. These indicators often rely on survey data that capture the integration of environmental practices into commercial offerings.

At the sector level, outcome-based indicators can be disaggregated using an input-output approach (see Table 3). These include wastewater and greenhouse gas emissions. For example, Ma et al. (2023) use a multiregional input-output model to analyse CO₂ emissions in digital exports by sector. Some studies, such as Peng et al. (2022), construct composite indexes (e.g., a green transition index for Chinese manufacturing) using entropy methods. The World Bank's WDI also offers widely used country-level indicators such as absolute CO₂ emissions and emissions per capita [80], as reflected in the "greening" sub-index by Bruno et al. (2023). To address the ecological limitations of traditional country-level development indicators, Hickel (2020) introduced the Sustainable Development Index (SDI), which modifies the Human Development Index (HDI) by capping per capita income and dividing it by outcome-type indicators, including CO₂ emissions and material footprint, which exceed planetary boundaries.

Table 3 Outcome-type metrics

Indicator	Source	Authors
Digital transition		
Digital innovation		

AI patent count: AI application patents; AI technique patents	PATSTAT, WIOP	Grashof & Kopka (2023)
ICT patent counts	OECD Statistics database	Yi et al. (2024)
ICT goods import (% of total imports); ICT goods export (% of total exports)	World Bank, WDI	Shahbaz et al. (2022); Yi et al. (2024)
Green transition		
1.1 Green products and service		
A binary variable equals one if a firm offers green goods and services, and as a percentage of the firm's most recent annual turnover)	Flash Eurobarometer survey 342	Hoogendoorn et al. (2015); Shrivastava & Tamvada (2019)
1.2 Green innovation		
Green technological innovation: implementing re-planning of water usage; re-planning (or in the process) energy; renewable energy; recycling & and reusing; redesigning (or in the process) products and services	Flash Eurobarometer Survey 441; Personal own survey data; patent data	Demirel & Danisman (2019); Bendell (2017); Li et al. (2018)
Eco-innovation: The number of eco-innovations types a company adopts is counted using an ordinal variable.	Content analysis of related information disclosed by company websites, annual reports, and sustainability reports	Latupeirissa & Adhariani (2020); Luo et al. (2012)
A categorical variable is constructed to represent the different types of eco-innovation (e.g. Green product innovation and green process innovation)	Personal survey data	Dong et al. (2014); Chen et al., 2006
The number of eco-innovations	Eurostat; OECD Statistics database	Przychodzen & Przychodzen (2015)
Green patents application	State Intellectual Property Office (SIPO) of China	Song et al., (2024); Lian et al., (2022); He et al., (2021); Liu et al. (2019)

Green innovation is measured by the ratio of the industry j 's green patent counts in country i in year t to that in the US	Harvard Business School Patent Inventor Database	Yuan et al. (2021)
US The proportion of green innovation is constructed by the ratio of green patent counts to total patent counts.	Harvard Business School Patent Inventor Database	Yuan et al. (2021)
The green patent rate	China Statistic Yearbook	Peng et al. (2022)
Regional green patent applications	OECD REGPAT database	Cojoianu et al. (2020)
Renewable energy patents per capita to adjust for country size, including solar energy technology, wind energy technology, biomass energy technology, and geothermal energy technology.	International Renewable Energy Agency, IEA	Yi et al. (2024)
Green specialisation: the ratio of green patents to all patents in that region over the ratio of patents to all regions.	OECD REGPAT patent database	Santoalha and Boschma (2021); Cicerone et al. (2023); Orsatti et al. (2024); Grashof & Basilico, 2024)
2. Energy and Carbon intensity		
Energy intensity: the ratio of total urban electricity consumption to real GDP	China Statistical Yearbook	Wang et al. (2022)
Energy intensity: the total cost of electricity and fuel normalised by sales	EBRD-EIB-WB Enterprise Survey	De Haas et al. (2024)
The Energy Intensity level of Primary energy	World Bank, WDI	Yi et al. (2024); Bruno et al. (2023)
Carbon intensity: is measured by the ratio of a company's carbon usage in absolute terms to a related business metric-such as firm's sales (in US\$)	GHG protocol; WBCSD, WRI, 2004	Hoffmann & Busch (2008)
Material footprint exceeds per-capita	UN International Resource Panel Global	Hickel, J. (2020)

	Material Flows database	
3. Pollution emission (output)		
CO ₂ emissions from fuel combustion adopts the multiregional input-output model to decompose the CO ₂ emissions into a consistent industry classification with the ADB-MRIO tables.	IEA (covers more than 60 countries)	Ma et al. (2023)
Greenhouse gas emissions (in the sector)	OECD database	Yan et al. (2022)
CO ₂ / Sulphur dioxide emissions; Gross production per volume of wastewater discharge; Gross production per volume of solid waste discharge; smoke (dust)	China Energy Statistic, China Industrial Statistic, and China Environment Statistic Yearbooks	Peng et al. (2022); Wang & Yan (2022); Meng & Zhao (2022)
Total CO ₂ emissions (kt); CO ₂ emissions (mt) per capita (country level);	Word Bank, World Development Index, WDI; China Environmental Statistical Yearbook; Eora MRIO database, with PRIMAP	Avenyo & Tregenna (2022); Bruno et al. (2023); Li et al. (2022); Wang et al. (2023); Hickel, J. (2020)
Total Greenhouse gas emission; Nitrous oxide emission (% change from 1990); Sulphur dioxide emissions; Smoke (dust) emissions; Industrial wastewater (country level)	Word Bank, WDI; China Environmental Statistical Yearbook	Avenyo & Tregenna (2022); Bruno et al. (2023); Li et al. (2022); Wang et al. (2023)
The total quantity of CO ₂ emissions/NO _x emissions/SO _x emissions released by the facility into the air in kg;	European Pollutant Release and Transfer Register, E-PRTR v18	De Haas et al. (2024)
Firm's carbon intensity: the ratio between the total GHG emissions (in tons) and a firm's sales (in US\$)	GHG protocol, WBCSD and	Hoffmann & Busch (2008)

	WRI, 2004	
4. Green total factor productivity (GTFP) or Environmental & energy efficiency		
Calculate carbon and energy efficiency by using Shepherd distance function and fix-effect Stochastic Frontier Analysis (SFA) method.	OECD database	Yan et al. (2022)
Using the non-radial directional distance function and the meta-frontier method	China Statistic Yearbook	Meng & Zhao (2022)
Using the slacks-based measure (SBM) model with Malmquist-Luenberger (GML) method to calculate GTFP	China Statistic Yearbook	Wang & Yan (2022)
Green economy efficiency index: by DEA method (by a non-radial and non-angle SBM -slacks-based measure- model)	China Energy Statistical Yearbook and China City Statistical Yearbook	Li et al. (2022)
GTFP: by using slacks-based measure (SBM) model with the Global Malmquist-Luenberger (GML) method to measure GTFP	China Statistic Yearbook	Wang et al. (2023)

Other outcome-based green metrics focus on innovation and energy productivity.

Green innovation, also referred to as eco- or environmental innovation, is a widely used outcome metric, encompassing new products, processes, or organisational practices that reduce ecological harm [81–83]. These innovations are often categorised as end-of-pipe, process, product, or organisational types [84]. Indicators may be categorical, indicating the types of innovations adopted [85], or continuous, reflecting the number of innovations implemented [86].

Patent data offer another quantifiable metric for green innovation [87–89], with green patents serving as proxies for a firm's technological commitment. At the industry level, patent ratios can signal sectoral transformation [90], while Yi et al. (2024) assess renewable energy innovation (e.g. solar, wind, biomass, geothermal), using per capita green patent counts.

Furthermore, green specialisation assesses comparative advantage in green technology by comparing a region's share of green patents with those of other regions [91–94]. Regional innovation networks have also been mapped using geographic weighting and patent information; for example, Liu et al. (2021) apply a gravity model to analyse inter-provincial green innovation in

China.

A final strand centres on green total factor productivity (GTFP), a key indicator of green economic performance. GTFP reflects the integration of economic output with environmental efficiency, typically assessed using Data Envelopment Analysis (DEA) or Stochastic Frontier Analysis (SFA) [48, 95–98].

In summary, outcome-based metrics offer diverse approaches to measuring greening, encompassing emissions reduction, energy efficiency, green patents, and sectoral innovation. However, heavy reliance on patent data risks overlooking informal or unregistered forms of eco-innovation.

4. Building Blocks for a Conceptual Framework of Twin Transition Metrics

The reviewed indicators span multiple levels of analysis, including firm-level (micro), sectoral (meso), and national or cross-country (macro) metrics. However, the primary focus of this study is not scale differentiation per se, but the interaction structure between digitalisation and greening. Therefore, indicators are analysed according to their functional role (input, process, output, interoperability), rather than their level of aggregation.

Drawing from the literature review, we identify a set of key dimensions that serve as foundational components for developing a conceptual framework of metrics for the twin transition. We structure them as interrelated building blocks that expose gaps, tensions, and complementarities across different layers of measurement, from input-based indicators to systemic interactions.

(1) *Indicator Typology Dimension.* Distinguishing clearly between input, process, and outcome indicators across digital and green domains, a review of twin transition literature shows that input indicators are the most developed group for both digitalisation and greening in terms of quantity and coverage. In contrast, process and outcome indicators are less advanced, particularly for greening, where process metrics, such as green management strategies, remain qualitative and context specific. Nonetheless, there is a clear evolution from basic infrastructure metrics to more sophisticated outcome-based indicators.

(2) *Integration Gap Dimension.* While digital and green indicators are well developed independently, few metrics capture their intersection, suggesting a theoretical ‘boundary failure’. Both areas emphasise patents and efficiency, but integrated indicators measuring dual impacts remain limited. Digitalisation can support

greening, yet metrics for combined effects are underdeveloped. For example, few indicators assess digitalisation's environmental impact (e.g. ICT carbon footprint). Input- and process-based indicators for integrated efforts, such as digital strategies targeting greening, are sparse or still in the pilot stage (e.g., EU DMA survey).

(3) *Data Heterogeneity Dimension*. A review highlights methodological challenges in operationalising measurement across diverse sources, including surveys, administrative data, and direct monitoring.

(4) *Geographical Asymmetry Dimension*. The availability and sophistication of indicators vary significantly across geographical areas, with more comprehensive data available for EU countries through Eurostat. At the same time, China dominates academic publications on the twin transition. While this illustrates China's prominence in the literature, it also highlights a gap in studies that examine the twin transition across a broader range of national and regional contexts.

(5) *Duality Misalignment Dimension*. The disconnection between the digital and green domains reflects a broader systemic oversight in theoretical frameworks and policy approaches. Current metrics treat greening and digitalisation as separate processes, overlooking potential complementarities and trade-offs. The enabling role of digital tools in green transitions, or how green investments might spur digital innovation, remains underexplored. This stems from two factors. First, the complexity of their interaction — capturing synergies requires a deeper understanding of these mutually dependent yet technologically and socially distinct processes. Second, there is a lack of policy alignment. Despite rhetorical commitments, stakeholders operate in separate policy arenas and have yet to apply sufficient pressure to prioritise the digital-greening nexus.

(6) *Aggregation Limitation Dimension*. The review shows that indicators tracking greening and digitalisation are primarily individual-level indicators, highlighting the need for composite indicators to capture system-level interdependencies. Complex or multidimensional indicators are still rare. Exceptions include the EU Digital Economy Index and the Green Total Factor Productivity (Green TFP). Although indispensable, individual indicators are inherently biased, as they treat sustainability issues such as biodiversity loss, climate change, and water scarcity in isolation. As a result, trade-offs in decision-making are often ignored [99]. Most indicators focus separately on inputs or outcomes rather than linking inputs, outcomes, and processes. Composite indicators, by definition, should capture system-level dynamics of isolated parts. Yet,

environmental efficiency scores and digital transformation indices still conceptually treat digitalisation and greening as separate, unrelated categories.

(7) *Transformational Blind Spot Dimension*. Our evidence suggests that current approaches linking digitalisation and greening are too static or sectoral to capture dynamic transformation processes. Measuring the direct contribution of digitalisation to greening, whether positive or negative, is the next frontier. However, this represents a narrow approach to the twin transition, as it overlooks their roles as system transformation processes with various direct and indirect linkages.

These dimensions form the conceptual base for the framework proposed in the next section, aiming to integrate measurement logics and reconcile trade-offs and complementarities inherent to the twin transition.

5. A Conceptual Framework for Integrated Metrics of the Twin Transition

To move from fragmented measures to a theory-driven approach, we propose a three-tiered conceptual framework for metrics that captures the complex and interdependent nature of the twin transition. This framework rests on layered indicator types, including component-level, interoperability-focused, and system-level indicators, organised around an input-process-outcome logic.

Our model recognises that digitalisation and greening interact as general-purpose transformation logics with their ecosystems, yet their overlap remains poorly captured by existing metrics. A more integrated framework can guide indicator development, inform policy coherence, and advance research on the twin transition.

5.1 Component-Level Indicators: Dual Logics of Green Digitalisation and Greening of Digitalisation

In line with emerging literature on the digital-green nexus, we distinguish between two strategic orientations:

- i. *Green digitalisation (digitalisation for sustainability)*, referring to the use of digital technologies to achieve environmental objectives. It leverages digital technologies, including AI, IoT, blockchain, and big data, to support environmental sustainability by optimising energy use, reducing waste, and mitigating climate change.
- ii. *Greening of digitalisation (sustainable digitalisation)*, referring to reducing the environmental footprint of digital technologies

themselves, focusing on making infrastructure, devices, and operations more energy-efficient and sustainable.

Table 4 synthesizes the analytical distinction between impact-side and footprint-side dimensions of the digital-green nexus, clarifying how current indicator systems conflate these two measurement logics.

Table 4: 'Green Digitalisation' (*digitalisation for sustainability*) vs. 'Greening of Digitalisation' (*sustainable digitalisation*)

Dimension	Analytical Logic	Core Indicators (Illustrative)	Policy Implication
Green Digitalisation (<i>digitalisation for sustainability</i>)	Digital technologies as enabling instruments for environmental transition (impact-side effects).	Avoided emissions enabled by digital solutions; energy savings from smart systems; renewable energy integration managed digitally; diffusion rate of green digital solutions.	Requires sectoral transformation metrics
Greening of Digitalisation (<i>sustainable digitalisation</i>)	Reduction of environmental footprint of digital infrastructure and devices (footprint-side effects).	Data-centre efficiency (PUE/WUE); carbon intensity of digital infrastructure; rare earth material intensity per device; e-waste generation and recyclability rates; algorithm energy intensity (kWh/task).	Requires efficiency & lifecycle regulation

While helpful, these indicators are siloed, often restricted to sector-specific use cases or input-based proxies. To advance, metrics should capture:

- Joint metrics (e.g. energy efficiency enabled by digital tools)
- Infrastructure circularity (e.g. device recyclability rates),
- Algorithm-level sustainability (e.g. energy per inference task).

This component layer establishes the foundation for evaluating specific interventions and their immediate effects.

5.2. Interoperability Indicators: Capturing Complementarities and Trade-offs

The second layer addresses cross-cutting effects between digitalisation and green transition. Complementarities arise when digital innovation enables environmental improvements (e.g., IoT in energy management). At the same time, trade-offs arise from the resource-intensive nature of digital systems (e.g., rare metals and data centre emissions).

'Green Transition' does not rely on a single core technology but combines multiple innovations driving the sustainability transition [12, 100]. It addresses diverse challenges, each requiring tailored solutions. For example, solar panels address energy decarbonisation, while biodegradable plastics tackle waste. Greening technologies are sector-specific, with different needs met by electric vehicles, carbon capture, energy storage, or precision farming. Moreover, greening involves systemic changes, such as circular economies and renewable energy grids, which depend on integrating various technologies.

While some argue that the diversity of green technologies hinders self-reinforcing dynamics [12], we view green transition as a directional transformation regime. Rather than constituting a single general-purpose technology, 'greening' represents a directional transformation regime that coordinates and reorients a heterogeneous family of technologies around shared performance principles, primarily decarbonisation, resource efficiency, and circularity. Despite lacking a single-core technology, green technologies share foundational principles: decarbonisation, resource efficiency, and sustainability. They also face common challenges, such as interoperability, which requires integration

across various systems. AI and IoT enable smart grids and precision agriculture, while battery technologies span energy systems, mobility, and households. Moreover, they create spillover effects (e.g. energy-efficient buildings inform urban planning, and green hydrogen developed for industry benefit transportation).

Although green transition does not revolve around a single core technology, it operates as a directional transformation regime that imposes shared performance criteria, such as decarbonisation, efficiency, and lifecycle accountability, across sectors. These shared criteria generate demand for monitoring, optimisation, coordination, and traceability, thereby increasing reliance on digital infrastructures (e.g., IoT, AI, digital twins, data platforms). In this sense, greening does not merely coexist with digitalisation; it actively shapes its trajectory by inducing convergence around interoperable digital architectures that enable system-wide integration (e.g., smart grids, mobility platforms, circular supply-chain tracking). We therefore conceptualise the green transition not as a single technological trajectory, but as a system-level coordination process that restructures multiple technological domains.

However, to trace this process, we need more than stand-alone indicators, as outlined in section 5.1. Systemic composite indicators capturing inputs, processes, outcomes, and linkages are essential. Beyond the input/output logic of the production function, we must develop metrics that reflect real-world interconnections and interdependencies.⁷

In line with Paré et al.'s (2015) typology of theory-based literature reviews, this section proposes an organising framework to guide both measurement development and theoretical inquiry. Based on the classification of 109 reviewed studies, we observe that most indicators follow a linear Input–Process–Output (IPO) logic, while only a minority address cross-domain complementarities, trade-offs, or systemic feedbacks. Building on this empirical mapping, we develop an organising framework that both reflects the dominant structure of existing measurement approaches and extends it by incorporating second-order interactions and systemic effects. The framework therefore serves a dual role: it synthesises the current state of measurement practice and provides a conceptual guide for future indicator development.

Figure 2 presents this three-layer structure. The base layer follows an Input–Process–Output logic. Superimposed on this are

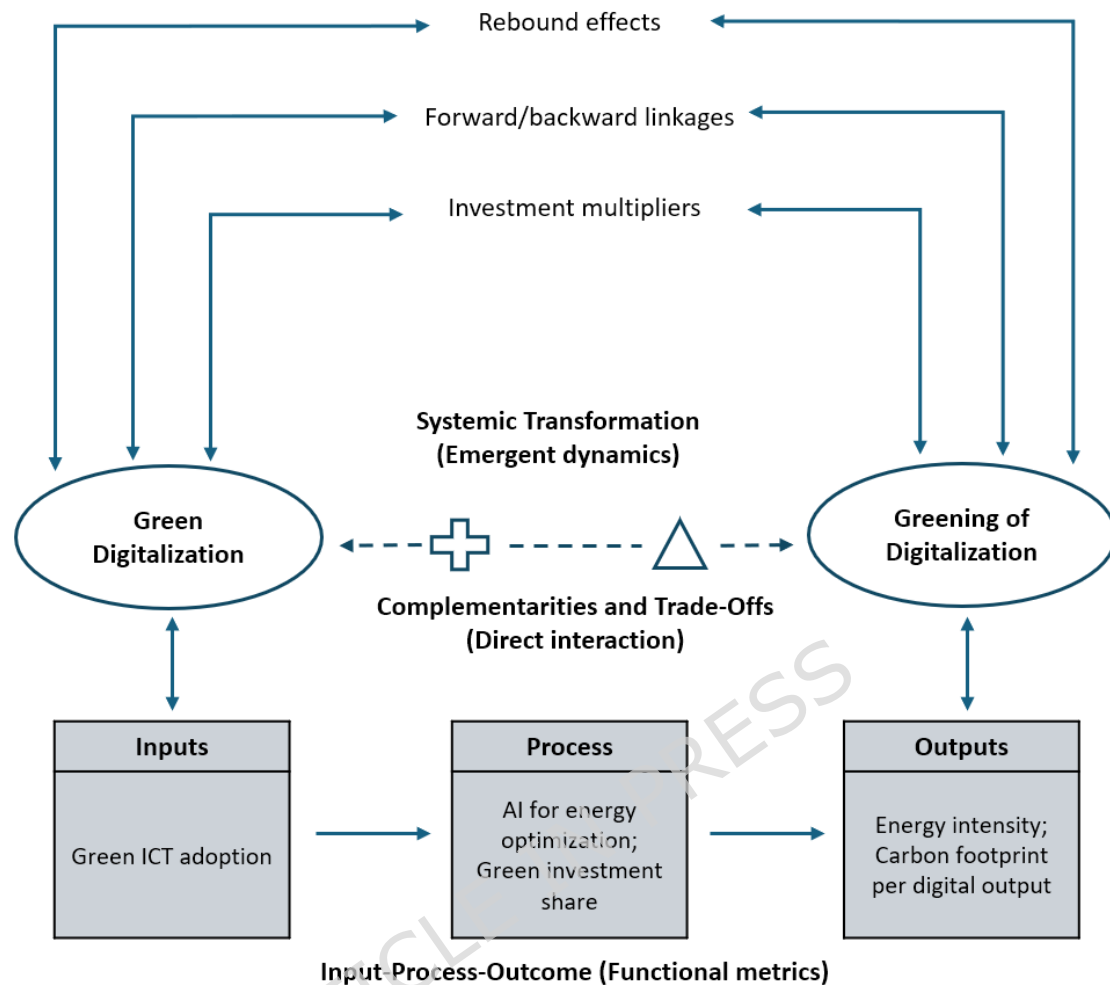
⁷ An example could be the Zonothope (Dosi et al. 2016; 2021).

second-order interactions capturing complementarities (+), trade-offs (-), and rebound effects (Δ) between digitalisation and greening. These interactions are further embedded in a broader systemic layer characterised by feedback loops, spillovers, and multiplier effects that cannot be reduced to linear production-function metrics but are essential to understanding the full dynamics of the twin transition.

In this sense, the framework is not merely descriptive but heuristic: it identifies structural limitations in current indicator systems and proposes a direction for more integrated measurement architectures.

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Figure 2: The overview of the twin transition metrics framework



Composite indicators operationalise this framework by combining economic, environmental, technological, and organisational dimensions. For example, digital-green interaction may be modelled as a composite index structured along IPO components:

- **Input:** investment in digital and green technologies; R&D expenditure in ICT and green innovation.
- **Process:** adoption rates of green/digital technologies (e.g. AI for energy efficiency); cross-functional applications (e.g. IoT for resource optimization).
- **Outcome:** reduced carbon intensity per digital output unit; improvements in energy efficiency via digital tools.

This system reflects the digitalisation-greening relationship as an integrated structure. A composite index may use weighted cross-sector adoption rates (process) and efficiency metrics (outcomes),

grounded in plausible (but not necessarily causal) input-output relationships. A step forward is to explicitly include both complementarities and trade-offs (i.e., green digitalisation and digital greening). This requires data on sector-level interactions. For instance, in transportation, we could measure reduced fuel use from AI-optimised logistics (complementarity) against the increased energy use from data processing (trade-off). In manufacturing, this could mean balancing IoT-enabled energy savings with the emissions generated by the production of IoT devices. If sector-specific data are available, these interactions can be captured through aggregate indicators such as the Sustainability Efficiency Score, the Net Emissions Impact of digitalisation, and the Resource Circularity Ratio.

Table 5 illustrates how complementarities and trade-offs can be operationalised through these three sector-specific interoperability indicators, linking digital inputs to green gains and digital footprints.

Table 5: Illustrative Interoperability Indicators in Manufacturing

Digital Input	Complementarity (Green Gain)	Trade-off (Digital Footprint)	Interoperability Indicator
IoT-enabled energy monitoring	Reduced energy consumption in production processes	Emissions from production and operation of IoT devices	Sustainability Efficiency Score = Energy Savings from Digitalisation / Energy Consumed by Digital Systems
AI-enabled process optimisation	Lower carbon intensity of output	Electricity use from data processing and cloud services	Net Emissions Impact = Emissions Avoided - Emissions from Digital Systems
Digital material tracking systems	Improved material efficiency and waste sorting	Rare earth use and e-waste from digital infrastructure	Resource Circularity Ratio = Recycled Materials in Digital Systems / Total Materials Used

These interoperability indicators provide a more accurate picture of the net value of digital-green strategies, informing decisions in complex environments.

5.3 System-Level Metrics: Dynamic Interactions and Feedback

Systemic transformations are rarely linear and require system-level modelling (e.g. network analysis, system mapping, and agent-based models) beyond aggregate metrics. Composite indicators cannot capture feedback loops, dependencies, and emergent behaviours inherent to systemic transformations. Feedback loops, spillovers, and multi-level governance frictions complicate the attribution of impact. For example, efficiency gains may lead to rebound effects (e.g. cheaper energy increasing demand, thereby diminishing the sustainability benefits). Other feedback mechanisms also exist, including backwards and forward linkages, spillovers, and investment multipliers [101]. These are harder to quantify but essential to understanding the economy-wide consequences of technological diffusion.

Though data-intensive and assumption-sensitive, system dynamics models provide tools to visualise relationships and feedback loops through causal loop diagrams and stock-and-flow structures (e.g., carbon accumulation, digital skill diffusion). Such models, including Climate-Energy-Economy (CEE) models, simulate how policies and innovations ripple through environmental and economic systems. Future work could leverage OECD Inter-Country Input-Output Tables to map ICT-related interdependencies in energy-intensive sectors. This would help illuminate cross-sector flows and feedback not visible in current metrics.

Digital innovations can also alter behaviour and redirect investment flows in ways that are often unpredictable, creating both opportunities and risks for green and digital transitions. For example, the rapid adoption of AI and automation may lead firms to prioritise efficiency over sustainability. At the same time, platform-based business models can disrupt traditional industries without necessarily advancing environmental goals. Similarly, digital finance tools, such as cryptocurrencies or algorithmic trading, may shift capital away from green investments or amplify volatility in emerging green markets. These dynamics underscore the importance of actively shaping digital innovation to align with sustainability objectives, rather than assuming alignment will occur naturally.

In summary, metrics for the twin transition face several challenges. First, sectoral diversity makes it hard to develop

universal metrics. Second, there are no globally accepted standards for measuring the twin transition, resulting in fragmented, incomparable metrics. Third, it can be difficult to attribute improvements in sustainability directly to digitalisation. Fourth, the indirect effects are complex, and feedback loops can be multiple and difficult to trace. Fifth, multi-level disconnects hinder alignment between firm-level and macro-level metrics. Sixth, digital and green transitions often involve global supply chains (see Wu 2013 on Taiwan), which limit local impact tracking. Finally, data gaps, especially from small and medium-sized enterprises (SMEs), restrict the measurement of digital-green synergies.

Despite these challenges, the integrated metric systems described above represent a necessary evolution toward capturing the complexity and dynamics of the twin transition.

6. Conclusions

This paper argues that digitalisation and greening have been primarily studied in isolation, which is unsatisfactory as their interplay remains underexplored despite their critical implications for achieving sustainable and inclusive innovation. It highlights the need to address both transitions, aligned with the UN SDGs, and calls for standardised metrics to support integration and cross-country comparability.

Motivated by this gap, we systematically reviewed the literature on twin transition metrics, classifying indicators into input, process, and outcome categories. While digital and green indicators are relatively well-developed individually, few capture their intersection. Most metrics treat them as separate processes, overlooking their complementarities and trade-offs. Complex or multidimensional indicators remain rare and typically focus on either greening or digitalisation in isolation. Overall, integrating metrics for both transitions remains conceptually undeveloped.

Our theory-oriented review advances the literature by moving beyond descriptive synthesis toward the development of a conceptual framework for understanding twin transition metrics [16]. As such, it lays the groundwork for further empirical testing, comparative studies, and refinement of indicators.

Consequently, we propose a framework (section 5.2) that organises existing and emerging metrics into three categories: component-level, interoperability-focused, and system-level indicators, organised across an input-process-outcome logic.

One potential limitation of our review is the geographical skew introduced by the predominance of China-focused studies, which

account for nearly one-third of the final sample. While this reflects China's prominence in the field, it also underscores the need for more research on twin transitions in a broader range of national and regional contexts.

In conclusion, this paper establishes a foundational step toward more systematically studying twin transition metrics. It identifies the critical challenge of the lack of comparable metrics to capture both trends, setting the stage for future research to address this gap. By investigating synergies and trade-offs between digitalisation and greening, this integrated approach can inform evidence-based policy and practice, advancing sustainable development in alignment with global priorities.

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Declarations

Ethical approval

Not applicable. This article does not involve studies with human participants, human data or tissue, or animals; therefore, ethical approval is not required.

Consent to participate

Not applicable. This study did not involve human participants.

Consent to publish

Not applicable. This manuscript does not contain any individual person's data in any form (including images, videos, or identifiable quotations) that would require consent for publication.

Competing interests

The authors declare that they have no competing interests.

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& editing.

Slavo Radosevic: Conceptualization; Methodology; Formal analysis; Writing - original draft; Writing - review & editing; Visualization.

Zhonghe Wang: Methodology; Formal analysis; Investigation; Writing - original draft.

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