Chapter 1

Introduction: Industry 4.0 and Circular Economy: Principles, Terminology, and Measurement Frameworks

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CHAPTER 1

Introduction: Principles, Terminology and Measurement Frameworks

Venkatachalam Anbumozhi

Both advanced and emerging economies of the Association of Southeast Asian Nations (ASEAN) and East Asia recognise that a new industrial revolution built on the principles of cyber-physical systems and automation is inevitable and will shape the future of economic growth. In addition to various national initiatives relating to enhancing industrial productivity, there has been heightened recognition of the importance of Industry 4.0 at the international level. The European Commissions' New Industrialization strategy aims to increase the share of gross value added to 20%, based on industry 4.0 initiatives. Various elements under the ASEAN Economic Community (AEC) Blueprint 2025, from global megatrends, intellectual property, consumer protection, and science and technology, to e-commerce as well as work under the other two pillars of the ASEAN Community and the cross-cutting work on connectivity all serve as building blocks towards an Industry 4.0-ready Community. While there is growing awareness of Industry 4.0 at the sectoral level, a more holistic approach is needed.

On the other hand, emerging ASEAN economies depend on an interrupted flow of natural resources and materials, including metals, minerals, energy carriers, timber, and water etc. Growing demand for manufacturing goods requires a massive increase in the use of these resources, but they are limited, and consumption cannot be unlimited. To maintain competitive and sustainable growth, economies need to produce and consume resources more efficiently, generating little or no waste. In the closed loop of circular economy systems, waste has value because treatment allows the recovery of materials that can be reused as inputs or for the remanufacturing of industrial goods. Various elements under the ASEAN Socio-cultural Community (ASCC) Blueprint 2025, such as the Reduce, Reuse and Recycle (3R) initiative, solid waste management, and smart cities, serve as building blocks for a circular ASEAN. In the circular economy paradigm supported by Industry 4.0, ASEAN production no longer contributes hugely to pollution, and its reduction helps to generate income because part of gross domestic product (GDP) is no longer needed to pay for long-term environmental damage.

1. Enabling Factors of Industry 4.0 and Circular Economy

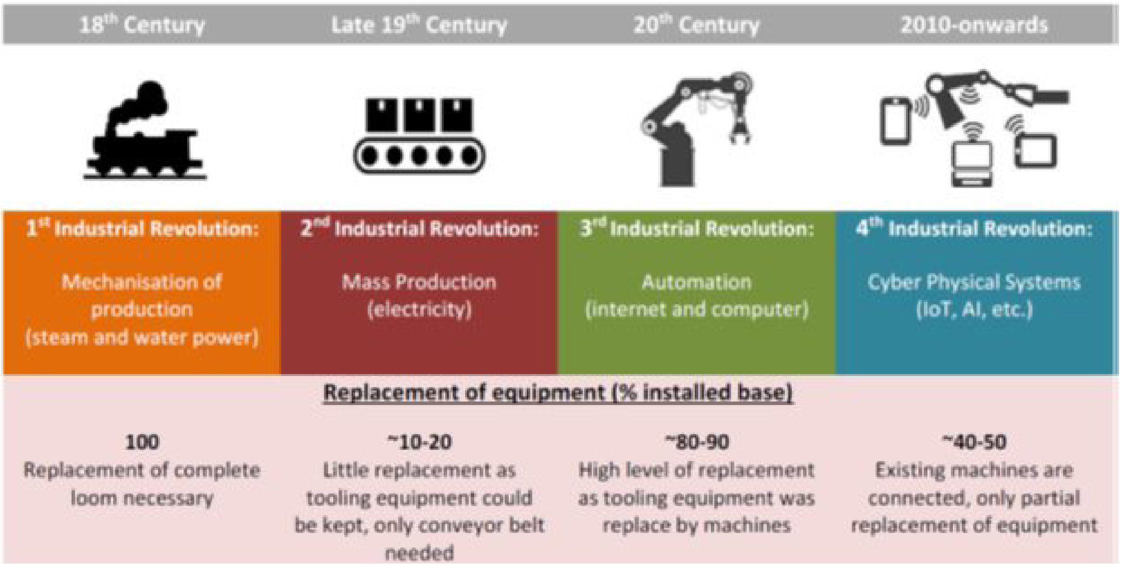
1.1.The concept of Industry 4.0

Technologies change over time and revolutionise production systems, which subsequently influences wider economic systems, social structures and, increasingly, political spheres. Industry 4.0 is preceded by three major industrial revolutions that took place since 1760. Each of these three earlier industrial revolutions had its own characteristics, but all were centred on introducing breakthrough technologies that altered society. Many of the technologies from the earlier industrial revolutions – such as electricity and the internet – remain in use today.

There are slight variations across existing studies in defining the timeline and key characteristics of each industrial revolution. Based on the commonalities between studies, however, the following characterisation and timeline can be drawn, as presented by Figure 1.1. The first industrial revolution in the late 18th century was characterised by the mechanisation of production, driven by steam and water power, while the second industrial revolution in the 19th century was marked by mass production, powered by electricity. The third industrial revolution in the 20th century was mostly about automation with a wider range of technological breakthroughs; computers and the internet appeared as its key features.

With economies of scale being focused in the first industrial revolution, the second and third industrial revolutions enhanced economies of scope and then moved to individual production, respectively (United Nations Industrial Development Organization, 2017). A comparison between the four industrial revolutions also suggests that despite its transformative changes, the fourth industrial revolution requires relatively less replacement of equipment through the upgrading of existing equipment, particularly in the aspects of sensors and connectivity (McKinsey, 2015).

Figure 1.1: Industry 4.0 Concepts



AI = artificial intelligence, IoT = Internet of Things.
Source: Author.

The term 'Industry 4.0' originates from the German government's project, 'Platform Industrie 4.0', to support small and medium enterprises in understanding and exploiting Industry 4.0 strategies and opportunities, particularly in the areas of standardisation and norms, security, legal frameworks, research, and workforce transformation (Box and Lopez-Gonzalez, 2017).

Despite several conceptualisations, there remains a lack of clarity in the definition of the Fourth Industrial Revolution. It is often described as digitisation or full-scale automation (Anbumozhi and Kimura, 2018); 'digitisation of the manufacturing sector' (Wyes, 2018); 'smart, connected manufacturing' (Deloitte 2016); or 'smart manufacturing or factory of the future', focusing on the transformation of the production or manufacturing base (Wilts, Lah, and Galinski, 2018). These various terms do not necessarily have a one-to-one correspondence and are often defined or used in different contexts in various studies. Many also refer to Industry 4.0 as a range of new technologies that combine the physical, digital, and biological worlds (World Economic Forum and Asian Development Bank, 2017). Other commonly used terms that refer to the similar phenomenon of Industry 4.0 include industrial internet, connected enterprise, SMART manufacturing, Manufacturing 4.0, Internet of Everything, and Internet of Things for Manufacturing (Kim and Hong, 2018; Ramanathan, 2018).

As a working definition, this book refers to the definition of Industry 4.0 by Anbumozhi and Kimura (2018), i.e. 'a range of new technologies that combine the physical, digital, and biological worlds'. It is, therefore, clear that for the purpose of assessing the readiness of a country or firm, it is important to look beyond the perspective of manufacturing and production to the broader transformation of sustainability and productivity that is brought about by these new technologies.

The scale, scope, and complexity of the impacts of Industry 4.0 are expected to be significantly different from its predecessors. Though they build upon existing technologies, new technologies brought by Industry 4.0 are evolving at an exponential speed, disrupting almost every industry across the globe, region, and in national economies, with fundamental impacts on entire systems of production, management, and governance (Schwab, 2016; Lah, 2016; Prabhakar, 2018). Industry 4.0 also leads to convergence between industries, such as information, communication, and entertainment, disciplines such as genomics, nanotechnology, robotics, and between biological, physical, and virtual worlds, such as cyber-physical systems.

1.2. The Concept of a Circular Economy

In essence, a circular economy represents a fundamental alternative to the linear take-make-consume-dispose economic model that currently predominates. This linear model is based on the assumption that natural resources are available, abundant, easy to source, and cheap to dispose of, but it is not sustainable, as the world is moving towards, and is in some cases exceeding, its planetary boundaries (Steffen et al., 2015).

The Ellen MacArthur Foundation defines a circular economy as one that is restorative and one that aims to maintain the utility of products, components, and materials and retain their value (Broekaert and Espinel, 2018). It thus minimises the need for new inputs of materials and energy while reducing environmental pressures linked to resource extraction, emissions, and waste. This goes beyond just waste, requiring that natural resources are managed efficiently and sustainably throughout their life cycles. A circular economy therefore provides opportunities to create well-being, growth, and jobs while reducing environmental pressures. The concept can, in principle, be applied to all kinds of natural resources, including biotic and abiotic materials, water, and land (Anbumozhi, 2016).

Eco-design, repair, reuse, refurbishment, remanufacture, product sharing, waste prevention, and waste recycling are all important in a circular economy. At the same time, material losses through landfill and incineration will be reduced, although these may continue to play a much-reduced role in safely removing hazardous substances from the biosphere and recovering energy from non-recyclable waste (Anbumozhi, 2016).

Table 1.1 lists the main characteristics of a circular economy and a number of technical, economic, and social enabling factors required to affect the transition to such an economy. The main characteristics differ for different types of system, for example for food that is consumed, metals that can be recycled, or water used in processing that can be recycled. Similar principles, however, apply, and some key characteristics and enabling factors can be defined. While the list of enabling factors is not exhaustive, it demonstrates the wide range of changes that will be needed to trigger or advance the transition. Central to achieving the necessary systemic changes, however, will be finding synergetic economic and social incentives, for example through financial mechanisms that encourage consumers and producers to hire rather than buy a product, while at the same time stimulating the eco-design of the product (Viswanathan and Anbumozhi, 2018).

Table 1.1: Characteristics and Enabling Factors of a Circular Economy

Key Characteristics of a Circular Economy	Enabling factors
Fewer inputs and greater use of natural resources	*Eco-design and innovation*
• Minimised and optimised exploitation of raw materials while delivering more value from fewer materials	• Products designed for longer life, enabling upgrading, reuse, refurbishment, and remanufacture
• Reduced import dependence on natural resources	• Product design based on the sustainable and minimal use of resources and enabling high-quality recycling of materials at the end of a product's life
• Efficient use of all natural resources	• Substitution of hazardous substances in products and processes, enabling cleaner material cycles
• Minimised overall energy and water use	*Repair, refurbishment, and remanufacture*
Increased share of renewable and recyclable resources and energy	• Repair, refurbishment, and remanufacture given priority, enabling the reuse of products and components
• Non-renewable resources replaced with renewable ones within sustainable levels of supply	*Recycling*
• Increased share of recyclable and recycled materials that can replace the use of virgin materials	• High-quality recycling of as much waste as possible, avoiding down-cycling (converting waste materials or products into new materials or products of lesser quality)
• Closure of material loops	• Use of recycled materials as secondary raw materials
• Sustainably sourced raw materials	• Well-functioning markets for secondary raw materials

Key Characteristics of a Circular Economy	Enabling factors
Reduced emissions	• Avoidance of mixing and contaminating materials
• Reduced emissions throughout the full material cycle through the use of less raw materials and more sustainable sourcing	• Avoidance of mixing and contaminating materials
• Less pollution through clean material cycles	• Cascading use of materials where high-quality recycling is not possible
Fewer material losses and residuals	*Business models*
• Build-up of waste minimised	• Focus on offering product-service systems rather than product ownership
• Incineration and landfill limited to a minimum	• Collaborative consumption
• Dissipative losses of valuable resources minimised	• Collaboration and transparency along the value chain
Keeping the value of products, components, and materials in the economy	• Industrial symbiosis (collaboration between companies whereby the wastes or by-products of one become a resource for another)
• Extended product lifetimes keeping the value of products in use	*Eco-innovation*
• Reuse of components	• Technological innovation
• Value of materials preserved in the economy through high-quality recycling	• Social innovation
	• Data, monitoring, and indicators

Source: Author.

Creating a circular economy requires fundamental changes throughout the value chain, from product design and technology to new business models, new ways of preserving natural resources (extending product lifetimes) and turning waste into a resource (recycling), new modes of consumer behaviour, new norms and practices, and education and finance (Hongo, 2016; Lah, 2016). Integration between policy levels and policy domains, as well as within and across value chains, is also essential (Anbumozhi et al., 2016). Action will be needed at all levels, from the regional level to the local level, and by all stakeholders, including governments and businesses (Ramanathan, 2016).

1.3. Empowering Industry 4.0 for the Circular Economy

Much positive hope has been built up around Industry 4.0 and circular economy notions over the last few years, creating awareness of the issue amongst policymakers and company executives and contributing significantly to the rejuvenation of industries in the ASEAN context (AT Kearney, 2016). In this aftermath, industry leaders in advanced economies remain optimistic overall and see the transition to Industry 4.0

and the circular economy as a unique opportunity to gain global competitiveness, consumer confidence, and environmental integrity.

In truth, momentum is already building in ASEAN and East Asia (Soulinthone, 2014; Permani, Sadicon, and Mahyassari, 2017). Almost two decades into the 21st century, ASEAN, along with China and India, has emerged as one of the world's largest consumers of minerals, ores, biomass, and fuels. Over the last 40 years, the use of materials has almost tripled from 26.7 billion tonnes in 1970 to 84.7 billion tonnes in 2017 (UNEP, 2017). Demands for resources and energy continue to expand in line with the region's industrialisation, rapid urbanisation, and accelerated economic growth. Without alternate models of growth and appropriate planning, the consumed materials and resources may ultimately end up as waste and pollution, imparting negative impacts on the economy.

As discussed before, in a circular economic system, resources are to be kept at the highest possible level of functionality at all times. This goes beyond just waste, requiring that natural resources be managed efficiently and sustainably throughout their life cycles. Eco-design, innovation, product sharing, waste prevention, and waste recycling are all important in a circular economy (Blunck, Werthmann, and Anbumozhi, 2018). At the same time, material losses through landfill and incineration will be reduced, although these may continue to play a much-reduced role in safely removing hazardous substances from the biosphere and recovering energy from non-recyclable waste. Several concepts and visualisations of a circular economy exist and can empower ASEAN to create economic and environmental co-benefits as the dependency on extraction and imports declines in parallel with a reduction in emissions (Tian, 2018). Thus, a circular economy generates new opportunities and needs for business. These can be grouped according to the following four archetypes, which each represent a specific business focus as the main entry point for developing a circular business model (OECD, 2003):

- Relationship with customer: providing a service instead of a product
- Product or process: circular product or process design
- Relationship with the value network: building circular value networks
- Sustainable identity: circularity as a unique selling proposition

In most cases, a company will combine elements of each archetype in its business approach. However, looking from an industrial perspective, the circular economy generates technological needs in the fields of manufacturing, processing, identification, and the recycling of materials and products. The main needs are the following:

- Advanced collection, sorting, and recycling technologies
- Efficient material-processing technologies
- Production technologies that support design for circularity
- Interactive platforms for enhanced connectivity

These needs are to be covered by robotics, analytics and artificial intelligence, sensors and connectivity, machine learning, and human-machine interfaces. All these technologies could typically be designated as Industry 4.0. Until now, the frameworks of Industry 4.0 and the circular economy have not been connected in theory, practice, policy initiatives, or research programmes (Anbumozhi and Kimura, 2018).

Nevertheless, the term Industry 4.0 is applied to a group of rapid transformations in the design, manufacture, operation, and service of manufacturing systems. The term originated in Germany, but developments in other Asian countries have resulted in other labels, such as smart factories, the industrial Internet of Things, smart industry, and advanced manufacturing. The European Parliament's briefing, 'Digitalisation for Productivity and Growth', mentions that Industry 4.0 builds upon six new technology developments (Table 1.2) (European Parliament, 2015). Similarly, Chandrasekar (2015) has identified 10 digital, engineering, and hybrid technologies that will enable the transformation of the current linear economy into a circular one.

On the other hand, PWC (2017) presented a framework for Industry 4.0 based on the following three elements:

- Digital business models and customer access
- Digitalisation of product and service offerings
- Digitalisation and integration of vertical and horizontal value chains

If these elements are compared, it is striking that similar concepts emerge. Both the circular economy and Industry 4.0 are based on the following:

- New product and process offerings
- Integration of value chains
- A change in the approach of customers

From this perspective, it becomes clear that Industry 4.0 and the circular economy at least share common levers of change. The circular economy is considered a driver for envisioning a sustainable industry, while Industry 4.0 provides the driver for circular innovation.

Table 1.2: Technological Developments for Industry 4.0 and the Circular Economy

Technological Developments for Industry 4.0	Ten Enabling Technologies for the Circular Economy
•Information and communication technology •Cyber-physical systems •Network communications: Internet of Things (IoT) •Simulation •Advanced data analytics •Robots, augmented reality, and intelligent tools for the support of human workers	•Mobile technology •Machine-to-machine communication •Cloud computing •Social media for business •Big data analytics •Modular desing technology •Advanced recycling technology •Life and material science technology •Trace and return systems •3D printing

Source: European Parliament (2015).

2. Monitoring the Economic and Environmental Benefits of Industry 4.0 and the Circular Economy

As the manufacturing system is undergoing a phenomenal shift with technological advancements and resource efficiency improvements, it is necessary to understand and adopt the opportunities available with Industry 4.0 and the circular economy. New opportunities will arise in different domains.

New opportunities from the interdisciplinary, cross-sector convergence of technologies: The convergence of multiple advanced technologies will create an innovation system along with new opportunities for further innovations. The Internet of Things (IoT) will interconnect almost everything, while cyber-physical systems – the technologies that marry the digital and physical worlds – will lead to smart production with intelligent systems independently communicating with each other with minimal human intervention (UNIDO, 2017).

New opportunities from data availability: The metaphor of 'data is the new currency', though not new, has been increasingly used to depict the vast opportunities from the age of IoT (Chandrasekaran, 2015). These data can lead to the restructuring of organisations and business models, placing efficiency and real-time capability at the heart of operations. The potential benefits are real. Companies that have applied IoT programmes have reported seeing 16% increases in revenue, with many identifying the ability to understand customers better as a key benefit (Thao and Nguen, 2018).

New opportunities from new business models: Disruptive technologies also give opportunities to unleash potential from new business models, including subscription-based models, broker platforms, intellectual property rights-based models, and monetising data models (McKinsey, 2015). Technologies also create a possibility to expand internationally and create new products and offerings (Deloitte, 2016). Businesses also benefit from technological advancements through improved labour productivity and efficiency, risk reduction, reduction in inventories (hence, lower capital costs), advanced quality control, improved understanding of customer demand, reduction in time to market, and improved and more affordable services and aftersales through, for example, remote maintenance (Cholifihani, 2018).

New opportunities from the changing manufacturing landscape in a circular way: The changing landscape of the global manufacturing industry driven by Industry 4.0 is expected to bring multiple impacts. For example, the use of 3D printing will allow for more active roles of customers in design and manufacturing processes and possibly the mass customisation of products and services (UNIDO, 2017). Benefits from the circular economy can also be derived from greater human-machine interaction, allowing workers to perform a given task for a longer period of time and faster (Li and Lin, 2016).

New opportunities for governments: Advanced technologies can also allow governments to improve efficiency in the delivery of public services with the greater involvement of citizens and enhanced responsiveness to their needs. Initiatives on e-governments have increasingly been part of and, in some countries, serve as the foundation for public sector transformation in responding to the Fourth Industrial Revolution (Jin, 2016; Ramanathan, 2018).

New opportunities for achieving sustainable development: According to the UN's Global Development Report – 2016 Edition, emerging technologies, such as in clusters of biotechnology, digital technology, nanotechnology, neurotechnology and green technology, are crucial for achieving the Sustainable Development Goals 2030 (UNIDO, 2017). Technologies range from self-driving cars, with the potential to increase traffic efficiency, productivity, and reduce traffic congestion and pollution, to decentralised solar systems providing remote communities access to electricity and technologies supporting a circular economy (Anbumozhi and Kojima, 2020).

Beyond the aforementioned opportunities, there are other enormous upsides to the technologies. To fully reap these benefits, however, addressing the enabling conditions is of utmost importance.

3. Challenges in Rolling Out Industry 4.0 and Circular Economy Concepts

New technologies from Industry 4.0 bring about not only new opportunities for the circular economy but also new challenges. At the broad policy level, to attain benefits from the Fourth Industrial Revolution, there are at least three pressing challenges that countries must address: (i) ensuring the benefits are distributed fairly; (ii) managing the negative externalities of the Fourth Industrial Revolution; and (iii) ensuring that the Fourth Industrial Revolution is human-led and human-centred (Schwab and Davis 2018; Anbumozhi and Kimura, 2018). Finally, there is a role for policy in addressing these challenges recognising that improving regulatory agility is a challenge. Discussions on each of these challenges in the context of ASEAN and East Asia are detailed elsewhere (Anbumozhi and Kimura, 2018), and a summary is presented below.

Uneven distribution of benefits: The first and one of the most critical challenges is to address the issue of the distribution of benefits. Benefits from the previous industrial revolutions were and continue to be unevenly distributed (Schwab and Davis, 2018). New technologies can further widen the gap through uneven access to knowledge and technologies and, hence, opportunities from the Fourth Industrial Revolution and Circular Economy (Viswanathan and Anbumozhi, 2018). Gaps exist between and within countries and regions with good electricity and internet infrastructure and those with less developed networks; and between countries with different levels of policy goals, attainments, and availability of skilled labour (Lah, 2016; Prabhakar, 2018). Many developing countries are also struggling to generate and/or attract high-skilled talents and workforce, which are key to further injecting innovation into the system. Within an economy, a key stakeholder group that is prone to the negative impact of Industry 4.0 is the workers. While new technologies can help labour performance, the risk of job replacement is evident. A significant number of jobs – or job tasks – are amenable to automation, while non-routine cognitive jobs (e.g. financial analysis or computer programming) and non-routine manual jobs (e.g. hairdressing) are less likely to be affected (UNEP, 2017). This concern also raises issues on social protection and the need to invest in human capital retraining or upskilling.

Negative externalities: While the economic benefits of previous industrial revolutions were widely acclaimed, there was too little effort to protect vulnerable populations, the natural environment, and future generations (Anbumozhi and Kimura, 2018; Kim and Hong, 2018). Industry 4.0 holds the potential not only to minimise negative externalities but also contribute to the resolution of persistent social and environmental issues (Mouri, 2016). At the same time, the circular economy is not without its own negative externality. Cybersecurity is a growing concern and was identified as one of the major risks in the WEF's Global Risks Report 2018. The financial impact of cybersecurity breaches has shown a steep increase with some of the largest costs in 2017 related to ransomware attacks; a notable recent example was the WannaCry attack, which affected 300,000 computers across 150 countries (WEF, 2017). Another possible negative externality is the issue of competition. Where data are the new currency, wealth, power, and resources are accumulated by, and increasingly concentrated in, a limited number of digital giants. Such issues can be even further exacerbated when these powers acquire smaller start-ups before they become potential competitions (UNIDO, 2017). Such accumulation is happening at a faster pace than how regulations can adapt to ensure fair competition, which brings us to the next challenge. In addition to the above broad challenges, each technology has its own characteristics, and, therefore, implications.

The lack of appropriate regulatory frameworks: This is imperative to capitalise on the opportunities or address the challenges brought about by Industry 4.0 and the circular economy. Opportunities can be better seized by ensuring that everyone has access to the technologies and knowledge required and will involve a portfolio of policies from investment and infrastructure to public–private partnerships (Anbumozhi et al., 2016). As for the challenges, these vary from addressing data security, including cyber security, protection, and privacy, and other measures to address ethical and other public concerns, intellectual property concerns relating to artificial intelligence (AI), and competition, to standards and interoperability (Deloitte, 2016).

4. Measuring the Readiness of Industry 4.0 and the Circular Economy

Growing recognition of the imminence of Industry 4.0 and the circular economy has led to the emergence of dedicated policy discourse on the topic, where discussions are centred around the changes that we are currently and will be facing, the new opportunities and challenges. However, questions and concerns have also emerged around how different agents can enhance their preparedness for Industry 4.0 for the circular economy. From the public sector perspective, the interest will be in the adequacy and agility of the policy tools and mechanisms that we have in hand to respond effectively to Industry 4.0. At the firm level, the interest will be in redefining operational strategies, benchmarking innovations, and building human capital (Sugimoto, 2016). The newness of the topic of Industry 4.0 and the circular economy means there are only a few in-depth studies that address the above policy and corporate strategy questions. While the relevant literature is growing, there is often disjointedness between the policy impacts and firm-level analytical work as studies on Industry 4.0 and the circular economy are often undertaken exclusively by institutions that are not part of the policy decision-making circle, whilst the development of policy and initiatives related to Industry 4.0 is not adequately backed and informed by rigorous analytical work. To this end, more strategic appraisal frameworks are needed in the advent of Industry 4.0 and the circular economy.

Countries and companies need to signal to investors and technology providers that they are ready for Industry 4.0 and the circular economy in an integrated way, which requires enabling policy measures and bold innovations at the institutional level. Empirical evidence suggests that enabling political, legal, institutional, and human resources is a key determinant of private sector activation in new frontier areas.

4.1. A Review of the Existing Readiness Assessment Frameworks for Industry 4.0 and the Circular Economy

There are at least seven recent and relevant frameworks that exist, as summarised in Table 1.3. Most frameworks aim at measuring or benchmarking a country's readiness for digital transformation; identifying key elements for improving countries' readiness; facilitating dialogue; and providing supporting evidence for monitoring and future agenda-setting.

Table 1.3: Comparison of Measurement Frameworks for Industry 4.0 Readiness

Framework	Key Dimensions
1. WEF Global Competitiveness Index (2019)	Institutions, infrastructure, macroeconomic environment, higher education, market efficiency, financial market development, technological readiness, business sophistication, market size
2. WIPO Global Innovation Index (2018)	Innovation input-institutions, human capital and research, infrastructure, market sophistication, innovation output
3.WEF Readiness for the Future of Production (2018)	Structure of production, complexity and scale, drivers of production, technology and innovation, human capital, global trade and investment, institutional framework, sustainable resources, demand environment
4. DII Global Industry 4.0 Readiness Index (2018)	Innovation aptitude, demand factors, driving forces, enterprise excellence, basic enablers, technological sophistication, Industry 4.0 enablers
5. KPMG Change Readiness Index (2017)	Enterprise capability, government capability, people, civil society capability
6. Dell Future-Ready Economies (2016)	Human capital, infrastructure, commerce
7. WEF Networked Readiness Index (2016)	Political and regulatory environment, business and innovation environment, infrastructure, affordability, individual usage, business usage, economic impacts, social impacts

DII = Danish Institute of Industry, WEF = World Economic Forum, WIPO = World Intellectual Property Organization.
Source: European Parliament (2015).

Comparison is made across these frameworks in terms of the data coverage and the feasibility and sustainability of the assessments in terms of access to datasets and the technical details of the methodology. The comparison exercise suggests that none of the existing reports covers all ASEAN countries. However, there is value in synthesising the assessment of these existing reports and indices to develop a hybrid ERIA readiness index for Industry 4.0, particularly at the country and company levels to benchmark positions relative to others in the world and to verify the outcomes of necessary interventions.

A comparison between the indices related to countries' readiness for Industry 4.0 is presented in Table 1.4. This exercise does not suggest comparability of the results given their different coverage, scales, scope, focuses, and objectives, but indicates emerging patterns in readiness, innovativeness, and competitiveness relative to each country in the region, and in comparison with their global counterparts.

Table 1.4: Indices for Measuring the Readiness of Industry 4.0

ASEAN Member States	Global Innovation Index			Global Competitiveness Index			Change Readiness Index			Global Industry 4.0 Readiness Index			Network Radiness Index		
	Rank out of 127 countries	Index score	Rank in ASEAN	Rank out of 137 countries	Index score	Rank in ASEAN	Rank out of 136 countries	Index score	Rank in ASEAN	Rank out of 120 countries	Index score	Rank in ASEAN	Rank out of 139 countries	Index score	Rank in ASEAN
Brunei Darussalam	71	32.89	5	46	4.52	5	-	-	-	-	-	-	-	-	-
Cambodia	101	27.05	8	94	3.93	8	85	0.48	7	115	1.5	7	109	3.4	8
Indonesia	87	30.10	7	36	4.68	4	39	0.57	3	41	3.1	4	73	4.0	4
Lao PDR	-	-	-	98	3.91	9	111	0.41	9	-	-	-	104	3.4	7
Malaysia	37	42.72	2	23	5.17	2	37	0.58	2	22	4.4	2	31	4.9	2
Myanmar	-	-	-	-	-	-	106	0.41	8	-	-	-	133	2.7	9
Philippines	73	32.48	6	56	4.35	7	45	0.55	4	44	3	5	77	4.0	5
Singapore	7	58.69	1	3	5.71	1	4	0.80	1	1	6.6	1	1	6.0	1

ASEAN Member States	Global Innovation Index			Global Competitiveness Index			Change Readiness Index			Global Industry 4.0 Readiness Index			Network Radiness Index		
	Rank out of 127 countries	Index score	Rank in ASEAN	Rank out of 137 countries	Index score	Rank in ASEAN	Rank out of 136 countries	Index score	Rank in ASEAN	Rank out of 120 countries	Index score	Rank in ASEAN	Rank out of 139 countries	Index score	Rank in ASEAN
Thailand	51	37.57	4	32	4.72	3	63	0.51	5	38	3.4	3	62	4.2	3
Viet Nam	47	38.34	3	55	4.36	6	81	0.49	6	91	2.1	6	79	3.9	6

ASEAN = Association of Southeast Asian Nations, Lao PDR = Lao People's Democratic Republic.
Source: Compiled by the author.

Comparison is also made regarding the circular economy policy frameworks in terms of sectoral coverage and the indicators of the assessment in Table 1.5. The comparison exercise suggests that wide areas of policies exist in ASEAN and East Asia countries. However, there is also value in synthesising the assessment of these policies and indices to develop a hybrid ERIA readiness index for the circular economy, particularly at the country and company levels to benchmark positions.

Table 1.5: Comparison of Frameworks for Assessments of Readiness for the Circular Economy

Framework	Key Dimensions and Indicators
1. Significant reduction in the quantity of municipal solid waste by encouraging both producers and consumers to reduce waste through resource recycling, greening lifestyles, and sustainable consumption	Specific policies and mechanisms that lead to a reduction of disposable plastic bags, packaging and other single-use consumer products, increased annual government expenditure on consumer awareness-raising, total waste disposed per capita, and total amount of municipal solid waste going to landfills
2. Significant increase in recycling rate of recyclables by introducing policies and measures and by setting up financial mechanisms and institutional frameworks involving relevant stakeholders	New policies and programmes introduced or existing policy/programmes are strengthened; increased number of state-of-the-art recycling facilities for key recyclables; employment in recycling industries

Framework	Key Dimensions and Indicators
3. Encourage businesses, including small and medium-sized enterprises (SMEs), to increase resource efficiency and eco-productivity, create decent works, and improve circular practices through applying standards, clean technologies, and cleaner production	Policy instruments that support resource efficiency and productivity are introduced or strengthened at the national and local levels; policy instruments are introduced aimed at improving labour conditions and standards in employment contracts; increased number of SMEs receiving expert advice, training, and other support from cleaner production centres and centres of excellence for resource efficiency
4. Promote circularity along the supply chain by encouraging industries and associated suppliers and vendors in socially responsible and inclusive development	Number of companies that have introduced circular supply chain management, number of companies that have introduced green accounting/voluntary environmental performance evaluation such as ISO 14000; vocational training activities/programmes on skills for circular jobs.
5. Promote industrial symbiosis, i.e. the recycling of waste from one industry as a resource for another, by providing relevant incentives and support	Increased number of eco-industrial parks and resource recycling zones; policy instruments introduced or strengthened to incentivise industrial symbiosis and the recycling percentage rate of industrial waste from selected sectors
6. Promote full-scale use of agricultural biomass waste and livestock waste through reuse and/or recycling measures to achieve a number of co-benefits, including carbon emission reduction, energy security, and sustainable livelihoods in rural areas	Greater amount of agricultural biomass waste and livestock waste recycled; number of new projects initiated that use agricultural biomass waste and livestock waste as material inputs
7. Improve resource efficiency and resource productivity through increased circular jobs nationwide in all economic sectors	Economy-wide material flow accounting indicators, such as tool material requirement, direct material input and domestic material consumption; energy efficiency schemes, product standards

Source: Compiled by the author.

A comparison between the indices related to the countries' readiness for the circular economy is presented in Table 1.6. This exercise does not suggest the comparability of results for sustainability given their different coverage, scales, scope, focuses, and objectives; but indicates emerging patterns in readiness, innovativeness, and competitiveness relative to each country in the region, and in comparison.

However, the comparison exercise of Industry 4.0 and the circular economy clearly shows the diversity in readiness amongst individual economies in the region. Levels of development appear to be strongly correlated with projected future readiness. Consideration should, therefore, also be given to capturing a country's conscious effort to put in place initiatives and investment in making their economy future-ready, which may not be reflected in their current economic performance alone (Tan and Wu, 2017).

Table 1.6: Selected Indicators for Measuring Sustainability

ASEAN Member States	Proportion of Population Practising Open Defecation (%)		Material Footprint per Capita (tonne)		Forest Area as a Proportion of Total Land Area (%)		Climate Risk Index Score (rank)
	2000	2015	2000	2017	2000	2015	2016
Brunei Darussalam	2.5	2.6	12.60	19.09	75.33	72.11	109.50 (120)
Cambodia	82.7	40.6	1.66	3.57	65.41	53.57	95.17 (111)
Indonesia	32.2	12.4	3.36	6.23	54.87	50.24	46.17 (37)
Lao PDR	62.0	22.1	1.26	7.37	71.60	81.29	109.50 (120)
Malaysia	1.6	0.3	19.19	22.61	65.72	67.55	65.50 (72)
Myanmar	11.2	4.7	0.53	1.50	53.39	44.47	57.17 (53)
Philippines	10.9	5.7	4.00	4.34	23.57	29.96	31.33 (16)
Singapore			51.14	73.04	23.06	23.06	109.50 (120)
Thailand	1.0	0.3	7.75	14.90	33.30	32.10	37.50 (20)
Viet Nam	17.7	3.9	3.42	10.01	37.82	47.64	15.33 (5)

Lao PDR = Lao People's Democratic Republic.
Source: Compiled by the author.

The suboptimal levels of several ASEAN countries regarding the readiness for Industry 4.0 and the circular economy, particularly given the opportunities and risks for the future, highlight the importance of identifying the key challenges facing the economies of the region. Furthermore, an integrated assessment warrants a methodology that can capture the firm-level and policy-level coverage while fitting with regional aspirations for collective actions in the areas of industrial research, innovation, and capacity building.

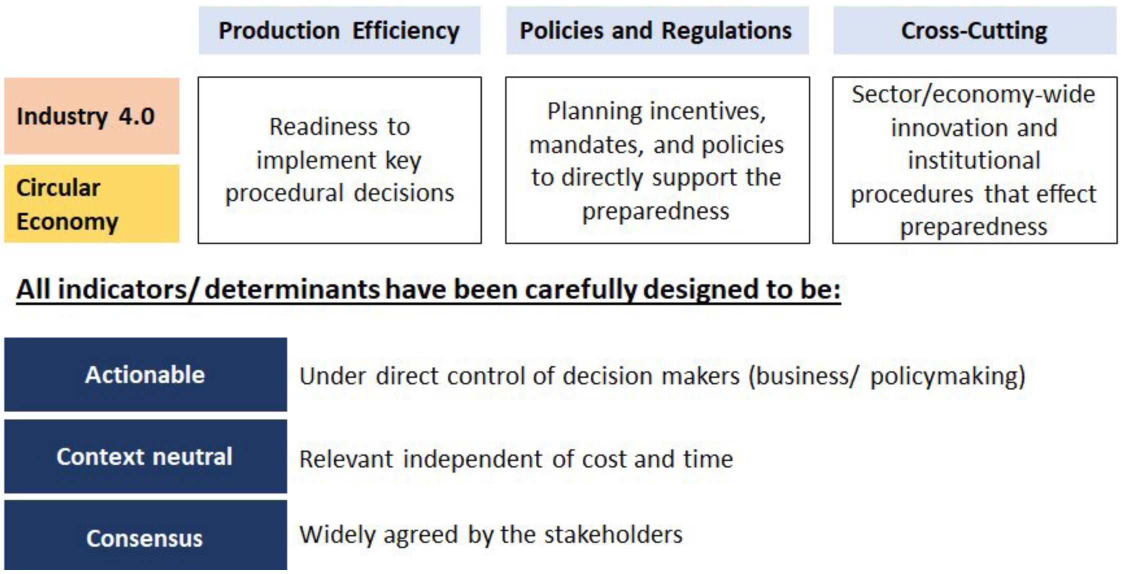
5. ERIA Industry 4.0 for Circular Economy Readiness Assessment Tool

The ERIA Industry 4.0 Readiness Assessment (I4R) for the Circular Economy is a suite of indicators that assesses the firm operational and enabling policy environment for the readiness of Industry 4.0 and the circular economy. I4R is relevant for a wide group of stakeholders. Crucially, it is aimed at policymakers and company managers responsible for identifying priority areas for change. However, seeking feedback from the private sector is an important aspect in the I4R framework development process as the policy and regulatory processes are designed to improve the readiness of firms to adopt new technologies and production processes and make innovations happen at the product level. It is designed as a self-assessment framework, as policymakers and company managers have to design the platform to secure investments and innovations but also in the larger interests of securing productivity and resource efficiency. Implementation of the I4R assessment tool for the circular economy will contribute to domestic and regional-level policy debates and discussions at the corporate level by providing a reference point on actions to facilitate the transformation and inform on the specific interventions needed. ERIA I4R will be a pioneering attempt to measure the readiness of countries and firms for adopting Industry 4.0 and the circular economy in an integrated way.

Underpinned by several levels of data collection at the country, sectoral, and firm levels, the ERIA I4R framework is expected to be updated regularly, thus benchmarking performance on the indicators over time while allowing countries and companies to measure incremental changes, which together will help countries and companies adopt and customise policies and operational measures while comparing themselves with their peers and good performers.

ERIA I4R assesses the readiness at three pillars of factors affecting production efficiency at the firm level; policy and regulations effecting changes at the country level; and the cross-cutting issues of institutions, innovations, and the application of information and communication technology at the sectoral level, thus better articulating the readiness competitively (Figure 1.2). While ERIA I4R builds on the hypothesis that the enabling environment is important for Industry 4.0 and the circular economy to be operationalised in a country or company, other market conditions affect the readiness level, which could rank from 0 to 4. A streamlined dataset, particularly in a panel format with focused criteria for each level, can allow robust identification of how the enabling environment affects innovations, technology integration, and investment flows, controlling for other factors.

Figure 1.2: Organisation of the ERIA Industry 4.0 for Circular Economy Assessment Framework



Source: Author.

The ERIA Industry 4.0 Readiness assessment framework for the circular economy originates from previous ERIA works on Industry 4.0 and the circular economy (Anbumozhi and Kimura, 2016) and global literature surveys on frameworks that evaluate the potential and opportunities, as well as risks and stakeholder consultations process and trial runs.

The assessment framework contributes to new knowledge given that none of the existing assessment frameworks on Industry 4.0 developed at the global level related to Industry 4.0 cover emerging the economies of ASEAN. It makes a specific attempt to customise the methodology to fit with the work under ASEAN at both the sectoral and functional levels.

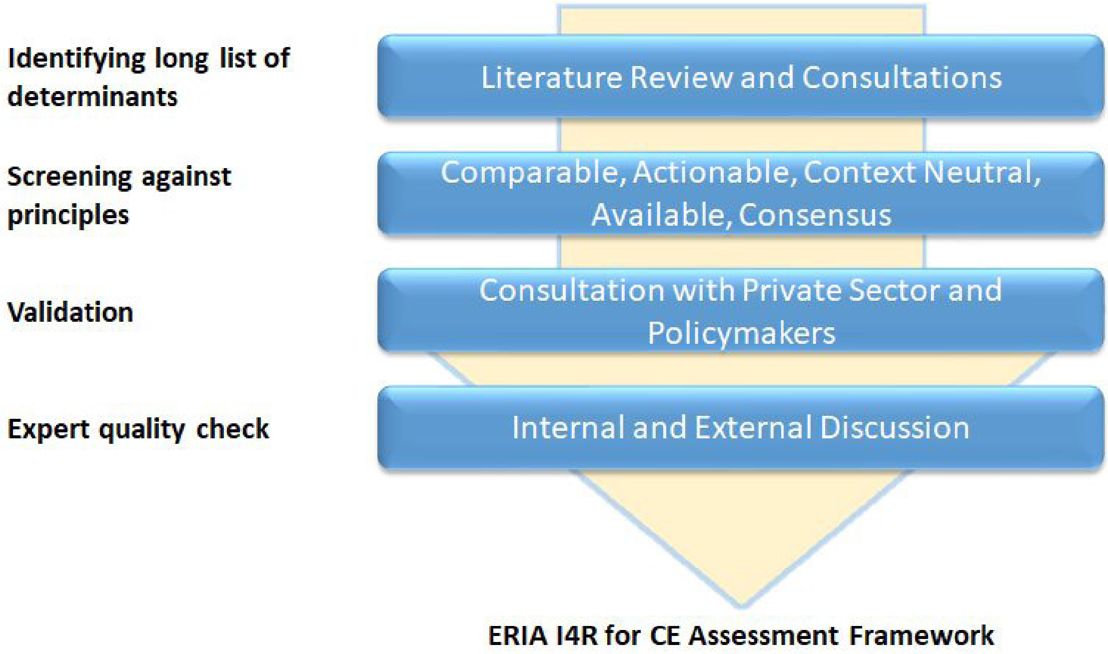
5.1. Development of the ERIA I4R Indicators

The readiness assessment covers the regulatory and institutional framework and reforms, reflecting the current economic base (i.e. education, science, technology and innovation, business and technology promotion, digital transformation, and trade and investment policies) and drivers of production at the firm level (strategy and organisation, plant and equipment, supply chain operation, quality management, resource consumption, product definition, informational technology systems, and human resources), based on which the focus areas are differentiated at four levels separately for Industry 4.0 readiness and circular economy readiness and then combined. The readiness assessment covers institutional and innovation efficiency as cross-cutting factors at the country and firm levels. The readiness level is again assessed on a 0–4 scale, with the assessment criteria to include political environment, economic environment, industrial structure, corporate leadership, business environment, and resources. The role of information and communications technology (ICT) in improving Industry 4.0 readiness for the circular economy is assessed with the factors of cloud manufacturing and use, IT and data security, operational data use, and virtualisation.

The rest of the chapters in the book present the readiness index at the firm, sectoral, and country levels. The in-depth case studies of the automobile, electronics, and textiles sectors in Indonesia and Thailand allow for validation of the methodology and lessons learned from the processes entailed in developing and implementing the suite of indicators across countries and firms that have varying statuses of data availability and information quality. Most importantly, it forms a solid base as a consultation document for the roll-out of Industry 4.0 and circular economy strategies. It also serves as a reference point for the measurement of readiness covering about 50 focus areas with a goal to further refinement.

ERIA I4R was developed in collaboration with the private sector. Figure 1.3 shows the four-step approach governed by a two-tier arrangement: a group of experts across the themes ensured the content, rigour, quality, and relevance of the indicators. In addition, an advisory group of the private sector and policymakers with knowledge of Industry 4.0 and the circular economy were consulted to ensure the indicators are pragmatic and would contribute to the ongoing policy development at the country and regional levels, and the operational agenda of firms selected for the case studies.

Figure 1.3: Methodology for ERIA Industry 4.0 Assessment for the Circular Economy



Source: Author.

A preliminary long list of indicators was initially identified based on a global literature review and on consultations with various stakeholders. A two-stage screening process was then employed to arrive at the first shortlist. In step 1, the four principles of objectivity, comparability, action, and context neutrality were applied to ensure that the indicators would be deployable in almost every country or firm. An attribute that stood out at this stage was one of reconciling various approaches that are considered good practices of circular economy at different points. Therefore, the ERIA I4R framework attempts to be time-neutral and avoids incorporating potential value judgements by the experts on the approach a country or firm is taking at a certain time to promote Industry 4.0 and circular economy outcomes. In step 2, three principles of universal data availability, cost effectiveness of data collection, and the presence of common consensus were then used.

This first shortlist and assessment framework went through multiple stakeholder consultations that informed the final suite of indicators. First, the experts provided advice and quality control in the two rounds of consultation. The private sector experts/advisors helped incorporate close country and sector knowledge on the production process and application potential of both Industry 4.0 and circular economy concepts. Second, the selection of indicators and associated methodological framework was discussed by a peer group of experts. The selection of the indicators also benefited from a private sector survey conducted by ERIA. Although all efforts were made to cover the key factors deciding the I4R, they are not intended as an exhaustive information set. Despite the collection of information and measurements at the policy and firm levels, it is not intended to be perfect set as the enabling conditions vary from factory to factory and country to country.

The assessment further highlights issues explaining variations in levels of readiness. By pilot testing in Indonesia and Thailand, uneven progress has been found in different areas of innovation and technology enablers, such as fixed broadband, 4G, research and development, patents, and cybersecurity. Meanwhile, gaps in human capital between and within factories persist and are considerably wide. On regulatory frameworks, improvements can be pursued through the putting in place and strengthening of the necessary regulations on key areas, such as e-commerce and further enhancement of e-government initiatives, while continuing improvement in the overall quality of the regulatory frameworks. Meanwhile, on supply chain connectivity and infrastructure, while areas for further improvement are country/sector-specific, there is a strong need to expand the region's financing architecture, which serves as a foundation for the further development of next-generation technologies. On the integration of Industry 4.0 and the circular economy, the assessment reinforces the importance of taking into consideration implications of technological advancements, as well as highlights the potential of technologies to serve as effective means to address productivity and resource efficiency issues

5.2. Limitations of the ERIA Industry 4.0 Assessment Framework for the Circular Economy

ERIA I4R is confined to the current set of indicators, and there are some limitations. While the exercises have developed the indicators over several rounds of revisions and consultations, this study has also been exposed to new information on Industry 4.0 and the circular economy, which has implications on the current availability, credibility, and validity of the indicators.

In ERIA I4R, indicators on procedural efficiency attempt to measure the effectiveness of policy and corporate strategy implementation. However, this still presents the limitation of the complete set of indicators in revealing the effectiveness of all policies and strategies. One example could be the exclusion of the effectiveness of institutions, as it is problematic to measure in a way that is comparable across countries and companies. Government and private sector staff numbers and budgets, for instance, are hard to pin down in absolute or relative terms and in ways that have significance in every country. Further, even where such information is measurable, channels of reporting may limit how easy it is to aggregate and make it available to the surveyor. Some measures on providing Industry 4.0 and the circular economy have narrow applicability, which, if properly used, can help promote better outcomes. However, there may not be agreement amongst the experts on deciding the level (0–4). Although, ERIA I4R attempts to measure the quality of the policies, strategies, innovation frameworks, and infrastructure connectivity by aggregating sub-indicators and presenting each indicator in a scalar way, the extent to which quality is captured is limited to the current set of sub-indicators. The quality of plans and strategies may vary by several other attributes. This evaluation also means that countries, companies, and technologies can stand idle as emerging good practices of Industry 4.0 and circular economy shift their goal posts, prompting them to work toward a favourable environment.

6. Structure of the Book

Given the above background and taking into consideration the existing work/methodology, the self-assessment of readiness aims to: (i) measure country- and firm-level readiness for a circular economy and Industry 4.0 with selected indicators (ii) complement the assessment with a stock-take of the relevant initiatives at the national and regional levels in ASEAN and East Asia; and (iii) discuss the potential value-added that can be derived from regional platforms to prepare countries and companies for Industry 4.0 and the circular economy.

Taking into account the approaches used in the existing studies, the assessment approach encompasses four stages: scoping and intelligence gathering; findings from the assessment; collation of initiatives in ASEAN; and case study analysis, as summarised in Table 1.7.

Table 1.7: Structure of the Chapters in the Book

Stage	Scoping and intelligence gathering	Key readiness assessment	Collation of initiatives at the ICT sector level	Case studies
Process	Literature review, review of existing assessments	Focus on multicriteria four-level assessment at the macro (policy), meso (cross-cutting) and micro (firm) levels	Link between national and regional activities and innovation	Assessment of readiness at the firm level in Indonesia and Thailand
Outputs	Chapters 1 and 2	Chapters 3, 4, 5, and 10	Chapter 6 and 9	Chapters 7 and 8

Source: Author.

The rest of the book is organised in eight chapters. Chapter 1 focuses on the first stage, i.e. scoping and intelligence gathering. Based on a literature search, the discussions above provide a better understanding of the characteristics of and technologies brought by Industry 4.0. Universal indicators and tools for measuring the economy-wide impacts of I4R are discussed in Chapter 2. Thematic elaborations on Industry 4.0 readiness with a circular economy focus are discussed in Chapter 3. Chapter 4 articulates the proposed readiness framework at the policy level with a reality check on ASEAN. Chapter 5 measures the cross-cutting factors influencing institutional innovation efficiency for I4R. Chapter 6 features ICT policy analysis conducted in the third stage, i.e. the collation of initiatives in ASEAN. Chapters 7 and 8 are country case studies of Indonesia and Thailand. Chapter 9 outlines national and regional initiatives in the face of Industry 4.0 and the circular economy. Chapter 10 briefly introduces ERIA's Industry 4.0 and Circular Economy Readiness Self-Assessment Tool, the technical details of which are available at http://i4r-eria.org/

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