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FROM STEAM TO SENTIENT SYSTEMS: A SYSTEMATIC REVIEW OF INDUSTRIAL REVOLUTIONS 1.0 TO 8.0 AND LEAPFROGGING OPPORTUNITIES FOR LESS DEVELOPED ECONOMIES

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ABSTRACT
The history of global industrialization, from the early mechanized textile mills of 18th century Britain to the (predicted) autonomous and bio-digital ecosystems of the mid-21st century, is one of the most significant in human history. In this systematic review eight distinct industrial eras (evolutionary cycles) will be discussed covering technologies, economy and society characteristics. Using published academic literature, multilateral (MD) development reports and empirical case studies, the extent to which poor and poorer LDCs, defined by the World Bank, can take advantage of the asymmetric opportunities imbedded in this long arc of technological change, is evaluated. The review demonstrates that LDEs do not only need to wait for technologically more advanced examples to be picked up by industry, but can take more advanced technologies selectively and diffuse them to the industry without following through the preexisting technological infrastructures and experience an accelerated structural change if the infrastructure is conducive. There are four cross-cutting opportunity domains identified: digital leapfrogging, renewable-energy transitions, Agri-tech modernization and human capital formation. A policy framework of regulatory, institutional and investment priorities for LDE governments and their development partners is the focus of the study's conclusion.

Keywords: *Industrial revolution; Industry 4.0; Industry 5.0; less developed economies; leapfrogging; technology diffusion; digital transformation; sustainable development*

Introduction
Industrialization has always evolved unevenly over time and geography, and each technological advance has brought about a restructuring of comparative advantage, of labor markets, of economic power. The idea of numbering industrial revolutions, cooked up in policy debates by Klaus Schwab's 'Industry 4.0' formulation at World Economic Forum in 2015, has since evolved both backward and forward as more and more paradigms of mechanization have been added and connected to previous and upcoming concepts. Although the majority of the available literature is on the more sophisticated industrialized economies, a new strand of research considers the implications of the above for less developed economies (LDEs).
The perspective on which this study is based is that the present moment is highly atypical: a group of currently industrializing countries may see and take up technologies from several ages of industry at once. Although a small farming enterprise in a rural environment in Kenya has no power it could have access to the satellite forecasting service before she has grid electricity. Collaborative Robotics can

be deployed within the factory without Bangladesh Company having gone through decades of mass production Taylorism. This 'leapfrogging' of developmental time scales is a structural opportunity and the current review aims to systematically trace this path.

The specific intent of this study is: (i) to offer a consolidation of key findings on industrial phases 1.08.0; (ii) to review past experiences of late industrialisers on 'catching up' with technological frontiers; (iii) to provide an overview of the main opportunity domains available to LDEs across emerging industrial paradigms; (iv) to discuss enabling and structural conditions for the successful transition from technological access to sustainable development outcomes by LDEs; and (v) to move forward with policy proposals, including for governments, the multilateral community, and private actors.

The methodological framework is described in Section 2, the historical and conceptual background of Industries 1.0-8.0 in Section 3, the discussion of the theory of leapfrogging and precedent in history in Section 4, the analysis of the barriers and enabling conditions in Section 5, the introduction of a policy framework in Section 6, and the conclusion in Section 8, which includes a research agenda.

Methodology

Review Design

In this study, a systematic review methodology was used and adapted to the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) guidelines for interdisciplinary policy and development research. In view of the prospect and speculations in the higher industrial phases (6.08.0) the authors decided to adopt an interlaced method in which the bibliometric analysis of the peer-reviewed literature and the critical review of the grey literature (World Bank, UNCTAD, UNIDO, the International Labor Organization (ILO), African Development Bank and Asian Development Bank) played a simultaneously complementary role.

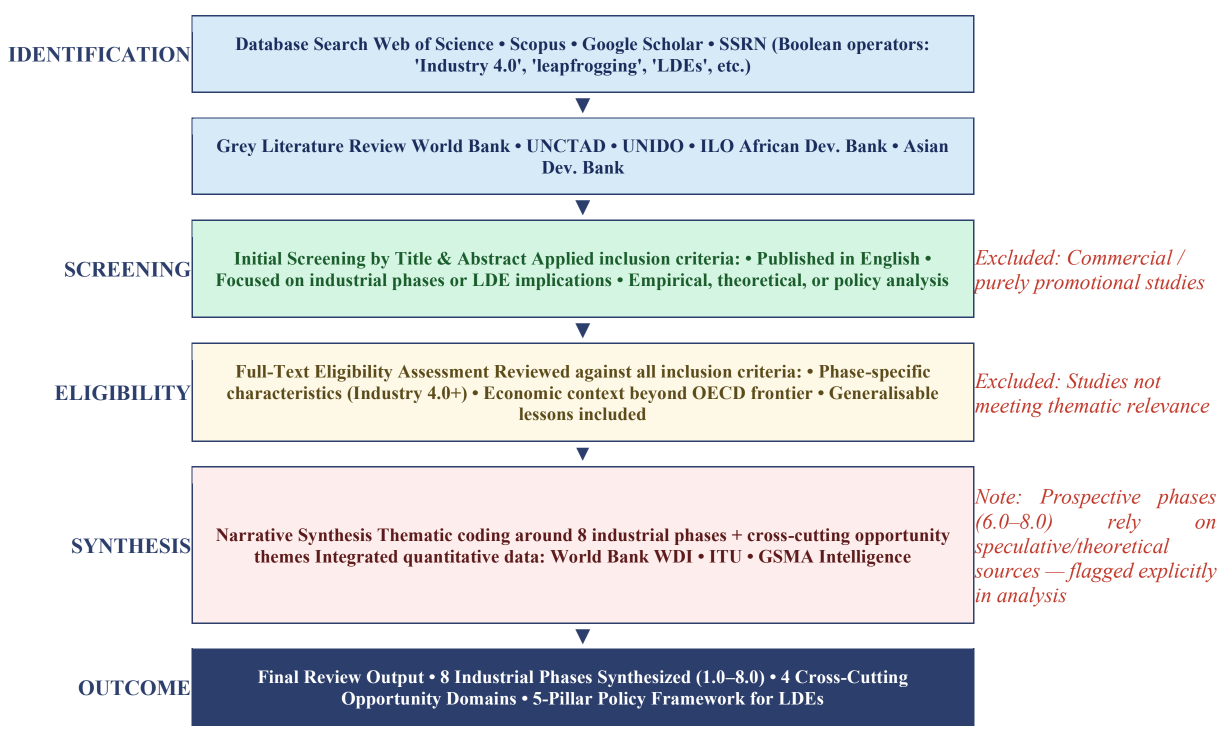

Figure 1: Systematic Review Methodology — PRISMA-Adapted Flow

Search Strategy and Inclusion Criteria

Using Boolean operators, the concepts of two concept families were combined in searches on Web of Science, Scopus, Google Scholar and SSRN: (a) 'industrial revolution', 'Industry 4.0', 'Industry 5.0', 'smart manufacturing', 'digital transformation', 'Society 5.0', 'cyber-physical systems', 'quantum manufacturing', 'bio-digital convergence'; and (b) 'developing economies', 'low-income countries', ' least developed countries', 'technology leapfrogging', 'digital divide', 'late industrialization', 'catching-up development', 'technological diffusion'.

To select the studies, the following inclusion criteria were applied: (i) published in English; (ii) focused on either characteristic of a specific phase of the defined industrial Age (Industry 4.0 and beyond) or (iv) implications to the economy other than OECD frontline; (iii) empirical, theoretical or policy analysis and not purely promotional/commercial. Where studies were derived that illustrate more generalizable lessons, these were included.

Data Synthesis

A narrative synthesis method was utilized and organized around the eight industrial phases and the cross-cutting opportunity themes from the iterative thematic coding. In order to provide the qualitative analysis with some context, quantitative, data sourced from development databases such as the World Bank's World Development Indicators, ITU, and GSMA Intelligence was included. If evidence for the prospective phases (6.0-8.0) is restricted to speculations, or theoretical sources, this is clearly stated and considered for the analysis.

3. The Eight Industrial Phases: A Consolidated Review

Table 1 below provides a synthesized overview of the eight industrial phases. The following sub-sections elaborate the technological, economic, and social characteristics of each.

Table 1: Overview of Industrial Phases 1.0 to 8.0 Key Technologies, Adopters, and Impacts

Revolution	Period	Key Technologies	Early Adopters	Socio-Economic Impact
Industry 1.0	c.17601840	Steam power, mechanical looms, coal mining	UK, Western Europe	Urbanization, wage labor, displacement of artisans
Industry 2.0	c.18701914	Electricity, steel, mass production, railroads	USA, Germany, France	Assembly lines, corporate capitalism, labor unions
Industry 3.0	c.19602000	Electronics, computers, early automation, CNC	OECD nations	White-collar workforce, software sector, globalization
Industry 4.0	c.2010present	IoT, AI/ML, cyber-physical systems, big data, cloud	Global (leader: China, Germany, USA)	Smart factories, platform economy, data sovereignty

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Industry 5.0	Emerging	Human-robot collaboration, cobots, personalization	EU policy framework	Worker-centric production, resilience, sustainability
Industry 6.0	Horizon 2030s	Quantum computing, advanced AI, 6G, AR/VR integration	Research labs globally	Hyper-personalization, quantum advantage in logistics
Industry 7.0	Horizon 2040s	Bio-digital convergence, synthetic biology, neuro-tech	Speculative / early R&D	Human augmentation, bio-manufacturing, ethical debates
Industry 8.0	Horizon 2050+	Autonomous ecosystems, post-scarcity AI, space-based production	Visionary / theoretical	Societal restructuring, universal basic services, redefine work

Industry 1.0: The Age of Steam and Mechanization (c.17601840)

The Industrial revolution began in Britain but was essentially based upon the shift from hand crafted to water powered then steam powered machine produced manufacturing. It was marked through the invention of the spinning jenny (Hargreaves 1764), improvements of the steam engine (James Watt 1769) and the mechanization of textile production in the spinning factory system. The size of the coal industry grew even faster to provide fuel to steam locomotives, and canals then had to be dug and later, railways to transport raw materials and finished products.

In LDEs the social trade-offs of the experience of Industry 1.0 are largely a lesson of the past and a warning: the winners from the initial development of Industry 1.0 in Britain, first and then continental Western Europe and the north of the USA, derived significant first-mover advantages in manufacturing capacity, capital investment and institutional construction and were able to consolidate the global inequality resulting from it over the following centuries. Colonies and periphery economical units were brought into the world of industrialization mainly as producers of commodities, dependency which remained both strong and enduring.

Industry 2.0: Electrification and Mass Production (c.18701914)

Electricity, steel, and streamlined mass production were hallmarks of the second industrial revolution. Qualitative jumps in productive capacity were made possible by Thomas Edison's direct current systems, Nikola Tesla's alternating current and the Bessemer steel process. Frederick Winslow Taylor's scientific management principles and the introduction of moving assembly lines by Henry Ford formally established an economics of scale that had shaped industry into a throughput management system instead of a craft-work. During this time period, telecommunications is coming to a life of its own with the development of the telegraph and telephone.

This was echoed by the preeminence of the USA and Germany over Britain, which demonstrated that first-mover advantage is not guaranteed and that the arduous journey of industrialization through Germany's 'backward' state-supported university-industry link up and USA's infant industries protection successful after all. The most telling example for today's LDEs is that of Japan's Meiji industrialization process (1868 and beyond) which exemplifies a deliberate and state-directed process of acquiring and adapting foreign technologies while preserving political sovereignty.

Industry 3.0: The Digital Revolution (c.19602000)

The third industrial revolution brought in the electronics, information technology and automation. Eventually, production was changed and service delivery was transformed with the advent of programmable logic controllers, computer numerical control (CNC) machining and the eventual personal computer. The advent of the internet, with early commercial usage in the 1990s, ushered in the creation of global information networks and new models for organizations, namely distributed supply chains and offshore service delivery, and more recently platform-based businesses.

LDEs had mixed results from Industry 3.0. Given the example set by export-oriented manufacturing in East and Southeast Asia (ESA-ISA), including South Korea, Taiwan, Singapore and in time China, Vietnam and Thailand, it is obvious that selective technology importing and investment in human capital and infrastructure could be a way for rapid economic transformation. But over this time frame, manufacturing value chains were largely closed to most sub-Saharan African and South Asian economies.

Industry 4.0: The Fourth Industrial Revolution (c.2010present)

Under Industry 4.0, the prevailing paradigm, there are cyber-physical systems, The Industrial Internet of Things (IIoT), Artificial Intelligence, Machine Learning, Advanced Robotics, and Additive Manufacturing (3D) Printing, Cloud Computing, and Big Data Analytics. The common denominator is interconnection: production systems are physically interconnected in real time with digital twins, supply chain systems and of course with platforms which are accessible to the customer, allowing mass customization, predictive maintenance and machine autonomy of making decisions.

The picture is complex and multi-faceted for the LDE for Industry 4.0. In the other, advancing technologies and ability to generate sense, move data and connect things with cost-efficient algorithms at a more rapid pace than ever before, generate unprecedented access to productive capabilities which would have taken decades to accumulate. The other side of that coin is that automation presents a danger to labor cost arbitrage the strategy that have made it possible for the late industrializers to get in on global manufacturing and supply. In five ASEAN countries, the ILO estimated that routine, lower-skill assembly work could be at a high risk of being automated in the next 50 years, pushing up the proportion of wage employment to as high as 56%.

Industry 5.0: Human-Robot Collaboration and Resilience (Emerging)

Industry 5.0 is a shift way warded from the Industry 4.0 concept and it is conceptualized mainly in the framework of EU policy (European Commission, 2021). Industry 5.0 is not about replacing people with machines but three principals: Human centric technology that helps people feel good, not worse; Sustainability industrial systems that fit into the planet; Resilience supply chains that are resilient, as made evident by the interruption caused by Covid-19. An emblematic technology are Collaborative Robots (cobots) that can collaborate with man, instead of replacing him.

LDEs are an important element of the human-centered framing of Industry 5.0: this is because it indicates that the global industrial edge is no longer purely automated, but increasingly more human in nature, with emphasis placed on human skills, judgment and creativity. This offers the opportunity for LDEs to differentiate themselves based on quality, craft and human added value, and not just on labor cost. It also signals that inclusive industrial policy spending is a social positive, but it is also an economic strategy focused on building workers' capacity to work in collaboration with technology.

Industries 6.0, 7.0, and 8.0: Prospective Horizons

Industries 6.0, 7.0, and 8.0 are still to be more or less speciously discussed; but a certain trajectory does seem to be visible in the academic and technology-foresight literature. In Industry 6.0 (expected in the 2030s), quantum computing is expected to play a significant role in optimization and drug discovery; 6G universal connectivity will drive communication in near-zero-latency environments, extended reality (XR) means a new type of interface for remote and immersive work, and advanced AI systems will come to narrow use cases that approach the level of ‘artificial general intelligence'. The speculative literature on Industry 7.0 (2040s) is introduced by describing the convergence of biological systems and digital infrastructure, which is manufacturing using synthetic biology, precision medicine, brain-computer interfaces, and bio fabrication. The release of materials, fuels and pharmaceuticals from manufactured organisms is a paradigm shift that could have huge impact for LDEs engaged in resource-based business models. More specific Industry 8.0 extrapolation (3050s, 4050s and beyond) suggests an era where product systems are fully autonomous, self-organizing and self-optimizing, and may include space-based resources and manufacturing, and where there will be a post-scarcity environment for basic products. Although speculative, early positioning in terms of education, institutional readiness and R&D investments make a difference in deciding whether LDEs are a part of the transitions or stakeholders.

INDUSTRY 1.0 c.1760–1840	**INDUSTRY 2.0** c.1870–1914	**INDUSTRY 3.0** c.1960–2000	**INDUSTRY 4.0** c.2010–Present
Age of Steam	***Electrification & Mass Production***	***Digital Revolution***	***Cyber-Physical Systems***
Key Technologies • Steam power • Mechanical looms • Coal mining	**Key Technologies** • Electricity & steel • Assembly lines • Telegraph / telephone	**Key Technologies** • Computers & CNC • Internet • Global supply chains	**Key Technologies** • IoT / AI / ML • 3D Printing • Cloud & Big Data
Early Adopters UK, Western Europe	**Early Adopters** USA, Germany, France	**Early Adopters** OECD nations	**Early Adopters** China, Germany, USA
LDE Relevance Colonial raw-material extraction; first-mover advantage locked in	**LDE Relevance** Japan Meiji model — state-directed tech acquisition; lesson for LDEs	**LDE Relevance** East/SE Asia: South Korea, Taiwan, Singapore, China catch-up success	**LDE Relevance** Leapfrogging window: M-Pesa, bKash, solar home systems. Risk: automation of low-skill jobs
INDUSTRY 5.0 Emerging (2020s)	**INDUSTRY 6.0** Horizon 2030s	**INDUSTRY 7.0** Horizon 2040s	**INDUSTRY 8.0** Horizon 2050+
Human-Robot Collaboration	***Quantum & Extended Reality***	***Bio-Digital Convergence***	***Autonomous Ecosystems***
Key Technologies • Cobots • Personalization • Resilient supply chains	**Key Technologies** • Quantum computing • 6G connectivity • Advanced AI / AGI	**Key Technologies** • Synthetic biology • Brain-computer interfaces • Bio-fabrication	**Key Technologies** • Post-scarcity AI • Space-based production • Self-organizing systems
Early Adopters EU policy framework	**Early Adopters** Research labs globally	**Early Adopters** Speculative / early R&D	**Early Adopters** Visionary / theoretical
LDE Relevance Human-centered framing opens space for LDE quality/craft differentiation	**LDE Relevance** Early R&D positioning and regulatory readiness are key differentiators	**LDE Relevance** Opportunity for resource-rich LDEs in agri-biotech; GMO governance critical	**LDE Relevance** Institutional readiness and education investments today shape LDE positioning

Figure 2: Industrial Phases Evolution — Industry 1.0 to 8.0 E*ight industrial eras (c.1760–2050+)*

Leapfrogging Theory: Historical Evidence and Conceptual Foundations

Theoretical Framework

Technological leapfrogging is the ability of countries or economies that reach the level of development last in the day to jump over or skip intermediate steps in the technology adoption process and directly adopt the latest available technology and shorten the time lag in the process. The key components of the framework are seminal works by Abramowitz (1986) who identified 'social capability' as the determinant of catch up growth, and by Perez and Soete (1988) who theorized about the windows of opportunity at paradigm shifts in techno-economics. Recent work by Steinmueller (2001), Davids and Frenken (2018) and Meagher (2019) has clarified the concept by differentiation between a process of pure leapfrogging (when an entire earlier technological generation is evaded), a process of stage-skipping (when a technological sequence is more compacted) and a process of path-creating (when novel technological pathways are developed that were not followed by earlier industrializations).

Leapfrogging is the most empiricism-supported in Africa in the case of the mobile telecommunication boom in sub-Saharan Africa. The developing world could move to mobile rates equal to or higher than those of Western Europe in only ten years, with countries such as Kenya, Ghana, Nigeria and Rwanda leading the way with substantially higher mobile market shares due to the absence of legacy, fixed line telephony infrastructure constraints. This "infra-bypassing" capability, in turn, allowed Kenya's mobile money ecosystem one that has no counterpart in advanced economies to emerge through a process of leapfrogging and making a leap in financial services.

Preconditions for Successful Leapfrogging

Emerging from the literature, there are some prerequisites that must be present before successful leapfrogging can be realized and prevent the simple copying of technology that yields no greater overall development benefits. First, the social and institutional capability as Abramovitz (1986) put it, the absorptive capacity of the economy is essential for the transfer of technology to increased productivity, and is shaped by levels of education, research infrastructure, regulatory quality, and institutional credibility. Leapfrogging is better reflected in countries whose education systems had an interactive-done-programmatic investment in both training and secondary and tertiary education.

Second, market size and demand aggregation: innovations that leap over can be commercially successful, if there is enough domestic demand to be consolidated. Digital financial services, for one, succeeded in reaching the critical mass it needed for the East African region, partly attributed to the high number of populations that are not banked, but have shown that they had a need for safe money transfers. Third, regulatory enabling environments: deliberate measures and rules set up to ease barriers to the introduction of innovations, including 'regulatory sandboxes' in FinTech or efficient use of spectrum for mobile broadband. Fourth, development finance and risk absorption: development finance institutions and blended finance mechanisms are key in de-risking pioneer investments, while fourth stage ventures involve high business risk.

Opportunity Mapping for Less Developed Economies

Table 2 presents a systematic mapping of key opportunity domains for LDEs across industrial phases. The following sub-sections analyses each domain in depth.

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Table 2: Opportunity Mapping for Less Developed Economies Across Industrial Phases

Opportunity Domain	Core Technologies	Target LDE Regions	Illustrative Cases
Digital Leapfrogging	Mobile internet, FinTech, e-commerce	Sub-Saharan Africa, South Asia	M-Pesa (Kenya), bKash (Bangladesh)
Agricultural Technology	Precision farming, drone monitoring, AI crop analysis	Africa, SE Asia, Latin America	Hello Tractor (Nigeria), Aerobatics' (SA)
Renewable Energy	Solar micro grids, wind, off-grid IoT	South Asia, Pacific Islands, Africa	Solar Home Systems (Bangladesh)
Health Technology	Telemedicine, AI diagnostics, mHealth apps	Rural India, Africa, Pacific	mHealth platforms across SSA
Education Technology	MOOCs, offline AI tutors, tablet learning	Global South, refugee populations	Kolibri (offline LMS), Atingi
Smart Governance	e-Gov, blockchain land registry, open data	Rwanda, Estonia model-adopters	Rwanda Digital ID, GeoPoll
Industry 4.0 Manufacturing	Low-cost automation, 3D printing, modular factories	Vietnam, Bangladesh, Ethiopia	Ethiopian Industrial Parks
Green Industry	Circular economy, eco-design, bio-materials	Emerging market SEZs	Rwanda plastic-free policy model

Digital Infrastructure and Financial Inclusion

The mobile broadband connectivity is the biggest possible leapfrogging vector for LDEs in the digitally connected world of Industry 4.0. At the time of writing in 2024, over 500 million mobile internet subscribers have entered into sub-Saharan Africa, where penetration rates are about 45%, (a penetration rate that has been arrived at in the region without having the previous generation and more than 50-year-old established fixed-line infrastructure network). This infrastructure independence provides a basis for developing an array of digital services which are otherwise limited by their physical infrastructure needs.

Mobile financial services (MFS) are a primer on its development power. Safaricom's M-Pesa service in Kenya was launched in 2007 and currently handles about half of Kenya's GDP each year and is active in eight countries. Its success has ignited the development of a range of digital payment, insurance, savings and credit products that have seen an impact on financial inclusion for the previously unbanked rural and low-income population. The situation is similar in Bangladesh (bKash), Tanzania (Tigo Pesa), and starting to happen more and more in West Africa. Extending coverage to smallholder farmers to provide working capital on a "let's receive the farmer's harvest" basis, or micro-manufacturers to receive payments from overseas buyers without maintaining correspondent banking accounts is a very exciting frontier use that has great opportunity to increase the industrial presence.

Agricultural Technology Transformation

Most of the LDEs are still agricultural, providing employment to 60-80% of workers in low-income countries, and farming is a significant contributor of export revenue and food security for households. Low-cost mobile connectivity, combined with a range of precision agriculture techniques including precision crop health monitoring through drone crop monitoring, satellite utilization of multispectral images from plants for crop monitoring, AI and machine learning-based yield prediction models, soil sensors, and automated irrigation systems, has the potential to deliver an unprecedented level of agriculture productivity with minimal mechanization investments.

Examples of digital agriculture tools for smallholders in the CGIAR network, the Digital Green platform of the International Food Policy Research Institute (IFPRI) in India and Ethiopia, and Industry 4.0 technology in the form of Hello Tractor's Uber-for-tractors solution in Nigeria demonstrate the relevance of Industry 4.0 concepts in smallholder agricultural contexts. One of the important lessons learned from the cases is that solutions that need the last mile to work (e.g. always connected to the internet, costly hardware, and literate users) do not scale when deployed in LDE agricultural settings. Offline capable applications, SMS interfaces and shared device models significantly increase access.

Synthetic biology and bio fabrication are emerging technologies that could provide transformative opportunities for LDEs with agriculture comparative advantage under the "Industry 6.0 and 7.0" perspectives. Engineered microorganisms that can fix nitrogen, suppress pathogens in crops and boost carbon sequestration in soil could lower input costs, boost output and resilience. Nevertheless, legislation pertaining to agricultural biotechnology continues to be a major hurdle in many LDEs, while public confidence in GMOs needs to be nurtured by communication approaches.

5.3 Renewable Energy and Distributed Power Systems

While access to energy is fundamental in the process of industrialization, an estimated 685 million people worldwide do not have electricity access with most of this population in sub-Saharan Africa and South Asia. Demand for rural electrification has been so comprehensively changed by the dramatic course price reduction of solar photovoltaic (PVs) (down more than 90% from 2010, IRENA) and the improvement of battery storage economics, that distributed solar solutions become economically viable over grid extension with a population of less than 5 kilometers with grid connection.

Bangladeshi Solar Home System (SHS) program through the hands of IDCOL (Infrastructure Development Company Limited) has touched the lives of more than 6.5 million families with the provision of solar home system serving about 20 million people living in rural areas, which is one of the largest off-grid electrification series in the history. This source of energy has enabled study at night, refrigeration of medicines, powering of productive assets (sewing machines, processing equipment) and charging of mobile devices for accessing digital services. Distributed renewable energy doesn't just have a development impact on the power industry it has a ripple effect that's significantly greater.

Turns out that the transition to renewables is also a chance for LDEs to skip the carbon lock-in from the coal- and gas-based industrialization and it's more expensive politically (that is, with regards to international climate finance conditionality) than economically (in view of carbon pricing trends). Employees who are adapting to the new paradigm of proactively developing a positioning strategy in the emerging green hydrogen economy, battery value formation chain (countries that are rich in lithium, cobalt and manganese materials) and solar manufacturing value chain are a new positioning index in the direction of global demand and environmental sustainability.

5.4 Health Technology and Human Capital

Healthcare is a development priority and an economic sector with the potential for LDEs to use Industry 4.0 technologies to overcome infrastructure challenges. In low resource areas, telemedicine platforms, AI diagnostic tools, community health worker mobile applications and digital disease surveillance tools have shown an impact. The iCCM (integrated Community Case Management) program emphasizes the adoption of mobile health tools to bring diagnostics and treatment beyond the reach of the over-stretched formal health system in Ethiopia, to rural community healthcare workers.

In areas with limited access to expert medical doctors, use of AI diagnostics tools such as image recognition for TB screening via chest X-rays, malaria screening via blood smear microscopy, and screening for diabetic retinopathy hold special promise. Accessible on a smartphone, a new AI diagnostic device at the radiologist level is a pay-for-service truly scalable from a previous benchmarking decade that would involve paying decades to specialists and costing hundreds of millions of dollars in order to achieve the same value.

5.5 Education, Skills, and Human Capital Formation

Successful industrialization depends on successful human capital formation, which in turn is a precondition of a successful industrialization. For LDEs, the challenge is twofold: developing their skills to join the Industry 4.0 economies while cultivating the transition towards Industry 4.0 for workers whose existing skills are increasingly under threat of being automated. Massively open online courses (MOOCs) via the web and even offline learning management systems (Kolibri), an AI-based personalized tutoring tool and low-cost tablet-based learning are unprecedentedly creating access to quality educational content.

The evidence about the developmental effects of educational ICT, however, is mixed and there are some caveats. The technology is relevant to the curriculum and of high quality: If the content is not relevant and pedagogically sound, then a limited learning benefit from using the technology will be achieved. The issue of teacher PD is especially important when technology is introduced without adequate support for building teachers' content knowledge and skills, it tends to be underutilized. Last but not least, deliberate attention is needed for the gender differentiated access to educational technology in patriarchal social contexts since the benefits of digital education may systematically miss girls and women if not explicitly considered in the educational programs designs.

The strategic investments in technical and vocational education and training (TVET) programs with the specific technological area of Industry 4.0 related occupations like Data Analytics, Robotics Maintenance, IoT systems and Cybersecurity, provide LDE workers comparative advantage in the international labor market. The Philippines has been developing a diverse, digitally competent workforce over the past few decades, to the point where more than 1.5 million Filipinos now work in the information technology-business process outsourcing (IT-BPO) sector, with total annual revenues expected to be around USD 30 billion, and is now able to sell or export services to the global digital economy to leverage this asset.

Structural Barriers and Enabling Conditions

Infrastructure Deficits

LDEs have great potential to outpace the current infrastructure limitations in mobile connectivity to Industry 4.0, while still facing significant infrastructure gaps that limit its mobility. Digital equipment, sensors, and automation systems have electricity supplies that are unreliable or unavailable for significant portions of the LDE population. The level of Internet bandwidth can also be measured on a Purchasing Power Parity (PPP) basis: In sub-Saharan Africa, the industry has had little competition in terms of national and international fiber infrastructure, with PPP rates being amongst the highest in the world. Software and hardware are interlinked, as is the infrastructure gap, which takes a hardware form because the median cost of a smartphone is still out of reach for the poorest earning quintiles in LDEs, though making these devices in LDEs easier to access.

Options for infrastructure investment in LDEs range from public finance (for economically indispensable but commercially unviable infrastructure) to development finance (for commercially viable but high-risk pioneer investments) to enabling regulation (to help bring private investment into the telecoms, energy and transport sectors). Difficulties of reaching out to the very low income and very remote at the end of the last mile provide a need to consider cross-subsidy tools and to work with innovative delivery models to be sure that urban middle-class consumers don't receive digital dividends.

Institutional and Governance Challenges

Empirical literature has long documented institutional quality as one of the principle factors affecting the sustainability of gains from technological adoption from abroad, covering a host of sub-categories relating to the effectiveness of regulations, the rule of law, property rights and the control of corruption. Successful industrial transformation (in South Korea in the 1960-80s, China in the 1990s-2000s, and Vietnam in the 2000s-2010s) has generally involved liberalization of markets in strategic sectors and robust state capacities to plan economic activities, facilitate investments and to rigorously enforce performance standards on industrial actors. The institutional models that have worked for rapid industrialization are diverse, but the paradigm is to consider an industrial strategy instead of a short-term rent income.

There is a special sensitivity in the area of IP rights with respect to technological catch-up by LDE. Unless LDE firms can adapt and indigenize imported technologies without infringing on strong IP protection as provided in the TRIPS agreement under the WTO, blockage can occur when governments expect companies to do everything possible to build their own technology. If countries expect companies to "do their utmost" to build their own technology, then as provided in the TRIPS agreement, IP protection can prove restrictive of LDE ways for the companies to reverse-engineer, adapt and indigenize imported technology. All TRIPS flexibilities should be put to good use, and lobbying for the re-optimized international IP system for technology to catch up with development is justified, especially for LDCs and PH-related technologies.

Digital Divide and Inequality Risks

One of the frequent issues in the LDE digital transformation literature is how the opportunities of Industry 4.0 technologies can widen inequality instead of narrowing it (inter-nations, intra-nations, and inter-demographic inequalities). The global distribution of AI development power, cloud computing and platform markets, and the technological power of a few countries could result in structural dependency for LDEs that could be digital colonialism in the 21st century. The construction of digital infrastructure by LDE companies on platforms managed by foreign technology companies' causes' loss of data sovereignty, lock-in and creation of value that is shared inequitably with foreign shareholders.

In LDEs, digital inequalities (between urban and rural regions, women and men, the young and the old) exist and risk hollowing out the benefits of digital transformation among the more disadvantaged urban populations, women or young people. However, there is empirical evidence in Sub-Saharan Africa that while mobile money is largely positive, it has failed to truly overcome gender-based financial exclusion because of the association of higher social norms and the documents needed to use mobile money. To achieve inclusivity, policies need to be explicit on these in-country disparities, such as: gender-responsive digital literacy programs, community technology access points, and digital public infrastructure based on open and interoperable standards.

Automation and Labor Market Disruption

The one most politically relevant problem that LDEs may face is the effect of Industry 4.0 on the labor-intensive manufacturing which served as the main driver for structural change up to now. The 'robotics threat' has 2 impacting avenues to counteract LDE manufacturing competitiveness: re-shoring (manufacturing coming back to advanced economies due to automation making up the cost advantage from cheap labor) and automation of LDE factory floors (higher wages makes it economically more viable to automate even at lower productivity levels). The extent of the effects is disputed, with analyses from the World Bank and the OECD suggesting that a significant portion of jobs may be at risk of automation while other studies suggest that, despite changes in jobs' task content, new jobs are likely to be created in response to complementarities between humans and automation (Latif et al., 2026).

A reaction rather than an overreaction or under reaction to this is justified. LDEs need to proactively invest in improving the skill level of manufacturing jobs; improve quality, complexity of export manufacturing. Parallel, the service sector in areas such as health, education, care, hospitality and creative industries provides a large absorption potential of employment that is fairly immune to automation, especially in the framing of Industry 5.0, which has been human-centered.

7. A Policy Framework for Industrial Transformation in Less Developed Economies

Drawing on the preceding analysis, this section articulates a five-pillar policy framework for LDE governments, development finance institutions, and international partners. The framework is intended to be adaptive recognizing the diversity of LDE contexts rather than prescriptive.

Pillar 1: Foundational Digital Infrastructure

Pillar 1 relates to the basic building products of the digital economy. LDE governments would do well to think about broadband connectivity, secure electricity and digital identity as public goods (parallel to the earlier development paradigm of roads and water) and treat it as such, providing resources accordingly. Where economically necessary projects lack commercial viability, public funding should go to them, and the regulations should be built to allow commercial projects to attract private funding. Shared infrastructure types include national wholesale broadband networks (including open access tower infrastructure), which can minimize duplication and reduce access costs. International bandwidth costs for land-locked and island LDEs could be significantly decreased through regional integration (under the African Union, ASEAN, CARICOM and SAARC frameworks) including cross-border fiber connectivity.

Pillar 2: Industrial Policy and Strategic Selectivity

LDEs should strive to understand and create an industrial policy which clearly targets the sectors that offer the biggest potential for productivity upgrading, jobs creation and technological learning. This must transcend short-term and catch phase investment promotion and go in the direction of targeted investment to tap areas that LDE can build on its comparative advantage such as agricultural processing, renewable energy manufacturing, digital services, pharmaceuticals, and the creative industries. Appropriate components of an IDZ or SETZ the worker skill development mandates, strong domestic linkage requirements and technology transfer provisions when well-designed can foster increased industrial capability.

International community (bilateral development agencies, World Bank Group, regional development banks, WTO) should work to change the rules and LDE financing instruments, so as to allow for more "space" for strategic interventions. History shows that effective industrialization in both types of industrialisers has depended on some active, roles for the state which exceed mere level playing field.

Pillar 3: Human Capital and Skills Ecosystems

There is a need to increase investments in education and training, but to also reshape it in terms of skills needed in Industry 4.0 and beyond. Whilst there is an equal consideration of technical skills (programming, data analysis, electronics, systems thinking), there is also an equal consideration of relatively automation-resistant cognitive and social skills (critical thinking, creativity, collaboration and communication). The TVET systems need to be reconfigured with higher degree of propinquity to industry needs including apprenticeship programs and modular credentialing systems and mechanisms for employer co-investment in training. Support should be given to LDEs to build capacity for Research and Innovation for strategic national interests in the STEM disciplines alongside the established tradition of predominance of programs in humanities and social sciences in Universities. Limited research investments can have a bigger impact through regional research networks and through South-South technology cooperation. Diaspora engagement programs (attracting scientists and engineers from LDE-origin institutions from advanced economies to participate in national science and engineering programs) are seen as underutilized resources.

Pillar 4: Regulatory Innovation and Digital Governance

ESR policies need to adapt to technological novelty while maintaining consumer safety and privacy, data rights, and public safety. In FinTech, however, regulatory sandboxes involving time-framed and limited-scope experiments (configurations) have worked well in agriculture, in multiple LDE contexts, and should be adopted for agricultural biotechnology, telemedicine, autonomous vehicles and drone logistics. A priority is data governance frameworks that promote individual privacy protection and responsible sharing of data for public good purposes (in health surveillance, urban planning and agricultural monitoring). International buyers and standards bodies are setting minimal security requirements for the participants of supply chains, expanding the need for cybersecurity capacity in LDE participation in global digital value chains. Funding is required for investment in national cyber security institutions, mechanisms for public private sector information sharing and international cooperation arrangements to ensure integrity of LDE digital infrastructure in the face of increasing threats.

Pillar 5: Finance and International Cooperation

Domestic resource mobilization as evidenced by effective tax administration, curtailing IFFs and development of the capital market continues to be the most important source of long-term development finance (Mahmood et al., 2026). But to successfully transform the industrial sector,

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international development finance has a pivotal catalytic role, given the magnitude of the investments needed and the risk level of the deals involved. The reform and scaling up of multilateral bank financing, the mobilization of climate financing for green industrial transition, and the scaling up of South-South cooperation mechanisms (including development finance from China, India, Brazil and the Gulf States) all expand the financing landscape of LDE. In the past few years, blended finance instruments combining concessional finance from public sources and commercial financing from the private sector have proven to work in renewable energy, health and agricultural value chains. Blended finance for LDE industrial transformation can take a variety of forms as in the case of the Sustainable Development Investment Partnership (SDIP), the Global Energy Alliance for People and Planet (GEAPP), and IFAD's rural finance programs.

LEAPFROGGING OPPORTUNITY DOMAINS

Digital Leapfrogging • Agricultural Technology • Renewable Energy • Health Technology • Education Technology • Smart Governance • Green Industry

PILLAR 1 Foundational Digital Infrastructure	PILLAR 2 Industrial Policy & Strategic Selectivity	PILLAR 3 Human Capital & Skills Ecosystems	PILLAR 4 Regulatory Innovation & Digital Governance	PILLAR 5 Finance & International Cooperation
Key Actions	**Key Actions**	**Key Actions**	**Key Actions**	**Key Actions**
✓ Broadband connectivity as public good ✓ Secure electricity & digital identity ✓ Open-access tower infrastructure ✓ Regional fiber integration (AU, ASEAN, CARICOM, SAARC) ✓ Cross-subsidy for last-mile access	✓ Target sectors with productivity/jobs potential ✓ Agri-processing, renewables, digital services ✓ Industrial/Special Economic Zones (SEZs) ✓ Domestic linkage & tech transfer provisions ✓ Beyond 'level playing field' — active state role	✓ STEM + critical thinking + collaboration skills ✓ TVET reform: data analytics, robotics, IoT, cybersecurity ✓ Apprenticeships & modular credentialing ✓ Regional R&D networks & South-South cooperation ✓ Diaspora engagement programs	✓ Regulatory sandboxes (FinTech, Agri-biotech, telemedicine) ✓ Data governance: privacy + public-good sharing ✓ Cybersecurity capacity institutions ✓ TRIPS flexibilities for tech catch-up ✓ LDE voice in ISO, ITU, AI governance	✓ Domestic resource mobilization (tax, IFF reduction) ✓ Multilateral bank reform & scaling ✓ Climate finance for green industrial transition ✓ South-South DFI cooperation (China, India, Gulf) ✓ Blended finance: SDIP, GEAPP, IFAD
Key Actors *Governments, DFIs, Private Telecoms*	**Key Actors** *Governments, World Bank, WTO, RDBs*	**Key Actors** *Ministries of Education, ILO, UNESCO, Private Sector*	**Key Actors** *Regulators, ITU, WTO, Civil Society*	**Key Actors** *IMF, World Bank, AIIB, AfDB, bilateral donors*

ENABLING CONDITIONS (Cross-Cutting)

Social & Institutional Capability • Market Size & Demand Aggregation • Regulatory Environment • Development Finance & Risk Absorption

Figure 3: Five-Pillar Policy Framework for Industrial Transformation in LDEs

Discussion: Navigating the Industrial Transition

The evidence also presented in this study does not provide a definitive answer whether prospects for LDE are overall positive or negative and it is interpreted with a lot of caution due to a number of caveats. The evidence from practice of leapfrogging is not uniform, but it is solid: mobile telephony, mobile financial services, solar powered home systems and digitized agricultural services show that LDEs are able to uptake and use advanced technology, make it contextually relevant, and reap their benefits without working through the entire development story of the preceding industrializers. Available enabling technologies in the coming decades, especially connectivity, computing and energy, further boost this potential as prices come down. But concurrently, there are some systemic risks that need to be identified. Because so much of the AI work is centralized and taking place in a handful of U.S. and Chinese companies, the digital version of the colonialist and post-colonial economic dependency can be reproduced. The use of such models in LDE contexts could create dependency instead of capability, if the models destined for agriculture, financial credit, health diagnosis, education, etc. dominate markets and are trained mainly on the data of advanced economies, along with values and priorities of the corporate owners. Capacity building of LDE AI, including data infrastructure, algorithmic capacity and regulatory capacity is thus a strategic priority and not an aspiration for purely technical issues. LDEs have a specific and complex link between industrial transformation and environmental sustainability. Early industrialization has used much of the global carbon budget to achieve the global warming targets set for 2030 and 2100, and has been more carbon intensive. The situation for LDEs is both highly inequitable they are more at risk from climate change than has contributed more to its cumulative effects, as they are now being faced with pressure to change industrial paths for them to remain clean. The aspect of equity has to be made clear for international agreements on climate finance, technology transfer and trade. Advanced economy regulatory capability, standards-setting bodies, and multilateral institutions with a poor mandate to represent LDE collectively will largely set the governance tone for new technologies, particularly for bio-digital convergence, and autonomous systems. This brings an increased involvement of LDEs in relevant international technology governance processes, such as in ISO, ITU, Codex Alimentarius, and AI governance efforts, which is definitely a current and utmost important need so that the rules for tomorrow's industrial world embody more international developmental interests and values.

Conclusion

The journey from the mechanized textile mills of Britain in the eighteenth century to the emerging technological possibilities of an “autonomous” and “bio-digital” and “post-scarcity” global industrial system outlined in the middle of the twenty-first century has been chronicled in this systematic review. In this sweep, it has been looking at the opportunities that less developed economies have this time, and attempting to define and examine these opportunities in a manner that would be considered real, significant and new in accessibility. There are four main conclusions from the review. Leapfrogging is empirically proven and theoretically supported: Any LDE can bypass the intermediate-technology level and gain real development by selectively adopting the newest frontier technologies provided human-capital, institutional quality and physical infrastructure are conducive. Second, opportunities within the LDE are multi-sectoral and intergenerational: the most important LDE opportunities involve both digital financial services, agricultural technology, renewable energy, health technology, educational technology, and skilled manufacturing each with their own opportunity profile corresponding to various phases of industrial progress 4.0-6.0. Third, structural barriers infrastructure gaps, institutional limitations, digital divides and automation risks exist and drive the need for active, rather than reactive, policymaking based on technology diffusion. Fourth, in terms of the international environmental conditions for LDE industrial transformation, there is a need for reform, especially in relation to technology governance, development finance volumes, climate finance, and in representation. A general take-home message of this review is that the less developed economies are but late-comers to an industrial race largely played out. They play a part in a process of a profound nature, an evolution that still has a long way to run, whose eventual form is quite stilling uncertain. The industrial paradigms of Industry 5.0 and beyond centered on topics like sustainability, human-part focus and resilience open up room for new models of development that are not just repeaters of pathways followed by previous industrialisers but may rise to canvass new shapes of sustainable and inclusive and technologically advanced prosperity. The occupation of that space will demand a good eye, institutional power and international solidarity. The evidence presented in this study shows that the conditions for a future, while difficult are actually achievable.

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