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# The green transformation as a new direction for techno-economic development

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**Abstract**

Green is now emerging, albeit not fast enough, as a new direction shaping innovation, investment and lifestyles. Indeed, the requirements of the green transformation give rise to the emergence of entirely new technologies, and it changes the parameters of competitiveness across industry, agriculture and services. These changes have profound implications for latecomer development, both positive and negative. The identification of strategies for seizing opportunities and overcoming challenges in the green economy is a central concern for policy makers and business managers alike. We argue that the theoretical framework of techno-economic paradigms shifts is particularly useful for understanding the dynamics of large-scale transformation and its associated institutional change. To fully grasp the nature of the green transformation, it is necessary to take a step back and locate it in relation to the history of technological revolutions and their regular patterns of diffusion. In this respect, we argue that the ongoing debate about the green transformation and latecomer development must consider two key conditions. First, it must recognize that the green transformation is primarily a direction-driven phenomenon, shaped by aspirational, political, and institutional changes, rather than a technology-driven phenomenon per se. Second, it must acknowledge the potential of information and communication technology (ICT) not only to accelerate and deepen the green transition itself but also to foster latecomer development within it.

**JEL Codes:**
O33, O38, Q55, O44

**Keywords:**
Green transformation; digital technologies; directionality; technological revolutions, techno-economic paradigms, latecomer development; government policy

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# 1 Introduction

The environmentally harmful effects of human economic activity mean that we are currently on course to cross several planetary boundaries. Climate change is the most pressing environmental issue facing humanity, but major and irreversible environmental upheavals are looming in the forms of e.g., biodiversity loss, chemical pollution and land degradation (Steffen *et al.*, 2015). It is still uncertain whether the transgression of key environmental tipping points can be avoided, but there is almost ubiquitous recognition that a new direction for techno-economic development is required to promote a major green transformation of the world economy.

Green is now emerging, albeit not fast enough, as a new direction shaping innovation, investment and lifestyles during the lifetime of everybody who is reading this chapter while it is still within its 'sell by' date. Indeed, the requirements of the green transformation give rise to the emergence of entirely new technologies and changes the parameters of competitiveness across industry, agriculture and services. These changes have profound implications for latecomer development, both positive and negative.

The identification of strategies for seizing opportunities and overcoming challenges in the green economy is a central concern for policy makers and business managers alike. The main purpose of the chapter is to discuss the prospects for leveraging the ongoing green transformation for economic and social development in developing countries, discuss the role of ICTs in this respect and to bring out the implications for policy.

We argue that the green transformation exhibits peculiar features that have major implications for latecomer development. To develop this argument, we proceed in three steps: We start (in section 2) by drawing on evolutionary socio-economic theory to provide conceptual grounding to the analysis of green technologies and to the green transformation as a new direction for techno-economic development. Addressing its specificity, we argue that to fully grasp the nature of the green transformation as a direction-driven phenomenon, it is necessary to take a step back and locate it in relation to the history of technological revolutions and their regular patterns of diffusion. We then proceed (in section 3) by discussing the implications of greening economic development for latecomer countries. In particular, the green transformation creates both opportunities and threats. Achieving a synergistic deployment of Information and communication technologies (ICTs) in a green direction could emerge as a viable development strategy due to (a) the potential learning effects associated with ICTs and their centrality as the current dynamic motor of the global economy and (b) the potential role that ICTs can play in the exploitation of the windows of opportunity opened by the green transformation. We finally provide insights and suggestions for development strategy and global policy (section 4). We examine how, in developing countries, the government could tilt the playing field in such a way that it would favour and enable significant green and digital innovation by the private sector. Global policy should be deliberately aimed at shaping the process of techno-economic and socio-economic development in the direction of a global sustainable golden age.

Our point of departure aligns with the argument made by Lundvall (2023, pp. 14–15) that the framework of techno-economic paradigm shifts (Freeman, 1992; Perez, 2015) is particularly useful for understanding the dynamics of large-scale transformation and its associated institutional change. This is so for the following reasons: (a) it provides a framework for studying 'the present as history', thereby situating technology and policy in their current context, (b) it grounds the analysis in a normative perspective that combines solidarity and sustainability and (c) it combines a critique of the current institutional setting with a certain optimism about the potential of science, technology and innovation (STI) to contribute to 'transformative change'. Indeed, we suggest that a period of global growth which is driven by just transition objectives could lie ahead, but only if governments take profound action by tilting the playing field in the right direction.

# 2 Green as a direction of techno-economic development

A techno-economic paradigm's innovation trajectory is not solely determined by the technology itself. It merely sets the stage for social actors to shape the preferred direction within the new range of the viable (Perez 2016, 11). The urgency to address climate change and transgression of other planetary boundaries increasingly influences decision-making, with environmental concerns influencing common-sense guidelines for techno-economic activities (Mathews, 2013). It is this social construction of direction, rather than the inherent nature of 'green technologies' themselves which may create windows of opportunity for latecomer development. In this section we explore the nature of 'green' as a direction of techno-economic development and the central role of ICTs in this respect.

## 2.1 The specificities of the green transformation

The green transformation is characterised by several disparate circumstances that are fundamental to how it unfolds. First, it has a very clear expression of purpose and direction in terms of its goals. This also includes a clearly specified identification of the problems such a green transformation needs to solve and the processes it needs to replace. Clear goals enable governments and stakeholders to define major mission-oriented projects and it helps private firms to guide R&D investments. Second, green technologies are extremely diverse in terms of their knowledge bases, technological nature and engineering principles.[1] Third, institutional changes implemented to shape directionality are guided by urgency and the fact that there is no alternative to avoid extremely dangerous consequences of environmental tipping points once they are transgressed.[2] Third, it is problem-driven in the sense that, while the goals are rather clear, it involves significant technological uncertainty and vast opportunity space in terms of techno-economic solutions. Fourth, the green transformation is increasingly rooted across all sectors of the economy and is gaining wide critical mass of activity.

[1] Green technologies encompass a spectrum of solutions, from renewable energy sources to waste minimisation, recycling, green buildings transportation and many more. They are often interdisciplinary in nature and draw upon a wide range of knowledge domains, including environmental science, physics, chemistry, biology, and various engineering disciplines (Fusillo, 2023).

[2] The green transition is driven by an unavoidable necessity and in terms of the timeline, "this is the first transformation in history to be achieved against a deadline" (Schmitz, 2015).

The clear purpose is an advantage but the diversity of technologies a disadvantage in terms of reaching self-reinforcing and cumulative dynamics. The important point about the nature of green technologies, is that their advances rarely have technological spillover effects into other green domains. In the energy space, advances in wind power technology do not benefit storage or, say, heat pumps or energy efficient buildings. Their relatedness is rarely technical as such because they use very different engineering principles and requirements with relatively few internal linkages (Carrillo-Hermosilla, Del Río and Könnölä, 2010; Fusillo, 2023). This means that their development is typically not 'technology-driven', in the sense that their own internal synergies do not act as an endogenous propeller of further technical advancement for the reduction of environmental harm.

Rather than being promoted by their internal technological dynamism, green technologies are mainly institutionally promoted and guided by public and private actors, aiming to make them more profitable and eventually to replace the traditional wasteful and environmentally harmful industries or technologies. These developments are typically state directed because they are not necessarily more profitable or of higher productivity from the beginning.[3] Their relatedness stems from the shared visions and similarities in terms of policy and business strategies among actors that actively shape the direction of innovation and economic development (Lema, Fu and Rabellotti, 2020).

These features of the transformation set green technologies apart from information and communication technologies in important ways. Digital technologies have internal self-reinforcing connections in the sense that any advance in mobile phones is sure to benefit computers and connectivity. The ICT revolution is thus strongly endogenously driven and rather than losing steam, is still producing new frontier technologies that are yet to diffuse across sectors and countries. The technologies improve productivity and are frequently profitable and attractive to investors from the outset. For these reasons we argue that ICTs can accelerate and deepen the green transition (see section 3.2), but this depends on the ability of societies and governments to create 'direction' for the ICT revolution. An additional element in the transition is the role of consumers, when it comes to shifting their preferences to environmental sustainability, green features become more attractive, their markets widen and grow, facilitating economies of scale, and profitability is pursued in that direction, multiplying the effect of government policies.

## 2.2 Creating direction in the age of ICTs

As already mentioned, we see the current digital revolution, which emerged in the 1970s, as intensifying and still far from reaching the stage of full deployment. Advanced digital technologies, including the internet of things, cloud computing, machine learning, artificial intelligence, quantum computing and others, are still nascent and bound for further advances and diffusion (Brynjolfsson and McAfee, 2015) . There is widespread agreement that ICTs have a massive potential to be shaped and steered, and especially to transform the

[3] A clear example is the importance of subsidies in helping solar PV gain momentum (Wen *et al.*, 2021). Eventually they would reach price parity, that is, being produced at low enough prices to compete with fossil fuels, not least due to the scale advantages achieved in China.

technologies used by all other industries and services, and that can and should be done in directions that enable the green transformations at scale. ‘

According to the historical pattern identified by the neo-Schumpeterians (Freeman and Louçã, 2001; Perez, 2002) such periods of full diffusion of each revolution are often prosperous ‘golden ages’ and the greening of ICTs could be the key element of the golden age of the fifth techno-economic paradigm. In this respect our interpretation differs from Mathews (2021) who sees green technologies, with green hydrogen at the centre, as the 6th techno-economic paradigm superseding the fifth (ICT) one. Schot and Kanger (2018) see the current technological, social and institutional changes as the 2nd deep transition, while the first, for them, would have been the Industrial Revolution from the 1770s. We agree that green hydrogen (if the efficiency of the technology can be enhanced significantly) can revolutionise energy systems, especially when combined with other storage technologies, as well as hard so-called ‘hard-to-abate’ sectors such as steel and cement. Yet, efficient green hydrogen technology may not have the economy-wide effects typical of technologies underlying earlier technological revolutions. The diversity of technologies involved, means that the green transformation differs from a technological revolution which has a strong internal technological dynamo. The recognition that the great variety of green technologies are not necessarily synergistic, allows seeing green as the direction for the powerful digital technologies and leads to the conscious use of ICT to shape all sectors and activities in a socially and environmentally sustainable way.[4]

The world economy is not alien to profound and direction-driven transformations in the context of distinct techno-economic paradigms. In this respect it is useful to think of the example of the post war golden age and its drive for suburbanisation and home ownership which was a ‘guided effort’ to give direction to the mass production paradigm after the second world war, especially in the USA (Perez, 2010). A whole set of policies, from government backed mortgage and tax exemption for payments, through unemployment insurance to support continuity, and the strengthening of the labour unions to keep salaries increasing with productivity, all of it made it possible for the majority, down to blue collar workers, to own a home and all the electrical appliances that come with it, a car for commuting to work etc. However, the system depended on low cost of energy and raw materials from the countries of what was then called the Third World and it counted on a second direction –the Cold War – for innovation and investment in military and space technologies.

It all gave markets a clear direction for innovation and investment, with guaranteed dynamic demand as well as suppliers of all the inputs they would need, given the synergy effect that

[4] A techno-economic paradigm is the common-sense direction for innovation resulting from the logic of the technological revolution (Perez 2010); what governments do when they provide directionality is to choose from within the range of the possible provided by the paradigm the most favourable direction for fair development, in this case it would also be for environmental sustainability.

the common direction induced. Suburbanisation also completely transformed the lifestyles of the time, as indeed, every technological revolution has done.[5]

At that time, the concerted effort to direct economic activity was also rooted in confronting the threat of communism, which is why governments accepted and even promoted strong labour unions which also benefitted business by broadening mass consumption demand for increasing scale in mass production.

The threat of climate change has already prompted governments to make initial institutional changes. Over time they could become full institutional packages for creating direction. Some of the key elements of those packages are shown in Table 1 making the comparison with those which supported suburbanisation.

**Table 1: Creating direction – Institutions for suburbanization and greening compared.**

| | Suburbanization (mainly advanced countries) | Greening (countries worldwide) |
|---|---|---|
| Demand-side policies | - Unemployment insurance<br>- Strengthening of unions<br>- Minimum salaries<br>- Pensions<br>- Rental not tax exempt (while mortgage payments were)<br>- Lowering driving age | - Feed-in subsidies for green energy<br>- Institutions for inter-country collaboration<br>- Public procurement of green technologies<br>- Environmental requirements in public tenders<br>- Timelines for ending fossil fuel use (e.g., only EVs after 2030)<br>- Subsidies for solar panels, EVs, insulation, etc. |
| Supply-side policies | - Government backing of mortgages (e.g. Fannie Mae)<br>- Favourable planning laws (incl. facilitating shopping centres)<br>- Government housing construction<br>- Housing associations | - Carbon tax<br>- Support to green R&D<br>- Provision of human capital<br>- Public procurement rules<br>- Direct investment in green technologies<br>- Favoured tax treatment.<br>- Compulsory facilitation of disassembly, and recycling |
| Public Goods | - Suburban infrastructure (roads, water, electricity, sewage, telephone)<br>- Public transport (except in US) | - Public research and demonstration projects<br>- Green infrastructure such as recycling and electric charging infrastructure |
| Finance | - Subsidies for veterans<br>- Savings & Loan banks<br>- Mortgage tax exemption<br>- Separation of savings from investment banks<br>- Lowering minimum down payment<br>- Fixed interest rate payments | - ESG Ratings<br>- Green investor alliances<br>- Green bonds<br>- Subsidies |
| International institutions | - (Not relevant for suburbanisation in advanced countries)<br>- | - United Nations Framework Convention on Climate Change (UNFCCC)<br>- Kyoto protocol<br>- Paris Agreement and COP meetings<br>- UN SDGs |

[5] Moreover, it opened or rejuvenated a range of sectors from consumer goods to automobiles and saw new countries entering the 'core' of world economy, not least Japan and most of Europe.

Increasing temperatures, fires, floods and other climate catastrophes are making environmental sustainability a key guidepost for discourses and reference point influencing important decisions shaping current directions of macro-societal and technological change (Lema, Fu and Rabellotti, 2020). The table provides indicative examples only and it is clear that institutional packages to achieve a green golden age would need to deepen existing initiatives and to go beyond those listed in the table. We return to the need for an institutional revolution in the final section of the paper (Section 4).

At this point it must be recognised that the institutional set up required for a profound greening of the world economy is more complex than the drive for suburbanisation, not least for the following three reasons.

First, the green transition is driven by an unavoidable necessity. There is no alternative to avoiding extremely dangerous consequences of climate change, whereas suburbanisation, although the favoured model, was not the only possible one. In the Soviet Union, the same technologies for the production of capital goods (Freeman, 2019). Second, there is both urgency and enormous uncertainty regarding speed: we do not know when (if at all) the efforts in the green direction will reach the tipping-point threshold level at which their impact can become cumulative and overcome the complex of factors working against it. Third, the green transformation needs to be a global phenomenon whereas suburbanisation took place mainly in the developed world and it is clear that collective organization and agreement on global actions and on the creation of effective supranational institutions is highly difficult, given the complexities of the process and the powerful interests involved.

We might add here that the corporate landscape is also different. Since a key part of creating direction is to steer ICTs as the engine of the prevailing techno-economic paradigm, it is of crucial importance that the direction is significantly influenced by a handful of tech giants such as Google, Microsoft, Amazon and Tencent and they have vital influence over the direction of ICT development worldwide. For example, development of artificial intelligence – which also requires massive amounts of energy in both development and use (see the next section) – is dominated by these firms, and they make it more difficult to slow down growth in energy and material consumption since algorithms to increase consumption is core to their business models.[6] This is why we emphasise the role of governments in establishing the policies that will make it more profitable to innovate and invest in a green direction than to follow the traditional paths.

## 2.3 The role of ICTs in the green economy

We have conceptualised the emerging green transformation as a new direction for techno-economic development, capable of radically shaping the way information technologies are deployed and integrated across sectors. It is a radical change of context in which all the participating technologies become interdependent and synergistic. But once environmental sustainability as a guiding rationale becomes dominant, thanks to appropriate government

[6] These companies are so powerful that they have sometimes been referred to as defining an independent technological regime and they accused of slowing down overall innovation system dynamism due to their unmatched power in ICT ecosystems (Rikap and Lundvall, 2020; Bessen, 2022)

incentives, regulation, procurement conditions and so on, such technologies may achieve economies of scale and growing market demand driven by the constructed incentives and the power of ICT.

An analysis of the current situation observes a vast range of possibilities for innovation within the ICT industries as well as across all sectors with the aid of ICT (Brynjolfsson and McAfee, 2015; Perez, 2015). Already 30 years ago, Freeman (1992) noted that there were several ways in which the initial advancements in ICT were conforming to the needs of reducing energy and materials intensity and they had begun to contribute to a path of sustainable development (see also Freeman, 1996). (Freeman, 1992). It is interesting though, that the burst of green investments he was referring to, occurred when the high oil prices made it financially attractive to move away from oil. As soon as prices came down in the 1990s, green investment practically stopped, and many companies went bankrupt. Thus, Freeman was right when he pointed out at the time, that the institutional frameworks, the necessary resources and the political will were not in place for a green paradigm to form (Freeman, 1992).With reference to Nelson (1977), Freeman observed that in the case of space technology, the USA showed what could be achieved with ICTs already in the 1960s (computing, remote sensing, long distance communication etc.) given the enormous power of the military industrial complex. However, the same interested institutions either did not exist or lacked the necessary resources and political muscle to realise the potential of new technologies in many other areas of potential application (Freeman, 1992, p. 200).

There is now much traction in terms of institutional framework, and, at the same time, there is more innovative activity and new digital technologies that did not exist in 1992 and which have a major potential to create progress in the environmental area of economic development. Arguably, the most recent stages of the ICT paradigm with the introduction of even more advanced digital technologies have the potential to increase this contribution significantly.

There are thus important opportunities to leverage IT technologies for the green transformation, as captured by the notion advanced by the EU of the 'twin transition' as digital and green reinforcing each other (Bianchini, Damioli and Ghisetti, 2023).

We may distinguish between three different types of green-digital innovations.[7] The first type is the use of innovations to reduce the environmental footprint of ICTs themselves. This is done by addressing their 'side effects' in terms of both energy and e-waste. Patent analysis shows that this type currently takes centre stage in the innovation efforts of information technology companies globally. They mainly seek to reduce energy consumption (increase efficiency) of individual processors, wider IT systems and big data centres (Menendez 2023). Digital technologies use large volumes of electricity, they are resource-intensive and create huge amounts of electronic waste (Muench *et al.*, 2022). This clearly means that the drive for renewable energy and green materials is as valid for the electronics and digital industries as it is for all the others. But it also indicates that the

[7] These three types draw on but also differ from those identified by Hilty (2011) who in turn draws on Berkhout and Hertin (2004).

energy- and materials-intensive paradigm of the mass production revolution and the 'planned obsolescence' model adopted by manufacturers to stretch saturated demand has been adopted fully by the electronics industry. It too must shift to a no-waste, low materials, low energy model (which given the intangible nature of information, should be feasible).[8]

The second is the use of ICTs to improve innovations that occur in the green economy, i.e., related to those activities and companies devoted primarily to sustainability-oriented activities. These are still dwarfed by the first type in terms of volume, but from the perspective of expanding and deepening the green economy they are important. Renewable energy technologies are increasingly enhanced with the use of ICTs (Kangas *et al.*, 2021) An analysis of leading wind turbine manufacturers show that their innovations are substantially and increasingly drawing on ICT general purpose technologies, as opposed to traditional fields such as aerodynamics and mechanical engineering (Lema 2023).[9] In terms of energy systems, the variety of sources and the possibility of an interactive grid would have been unimaginable and impractical without ICT. In this respect the technological diversity of energy technologies can be made to converge, as in the case of smart electric grids, which not only optimise the use of several different sources of energy but also incorporate consumers interactively and allow them to sell to the grid and to minimise their own costs by choosing times of use.

The third type is the use of digital technologies related to innovations outside either the ICT sectors or green energy sectors. These are introduced, for example, to abate their activities through electrification (such as transport), bring them into the green economy by introducing principles of genuine circularity (manufacturing), etc. Obviously (as will be discussed further below), digital technologies do not have this effect by default. As mentioned earlier, they may indeed have the opposite effect. In fact, recent studies have pointed out that AI capabilities only deepen the green-tech specialisation of regions when they already have a pre-existing strong foundation in green technology. They only reinforce existing trajectories and in regions that lack this foundation, AI reduces their capacity to specialize in green tech since it favours non-green tech sectors (Cicerone *et al.*, 2023).

However, new digital technologies have the potential to augment green trajectories across activities of the economy. For example: (a) blockchain technology can be used to increase traceability of inputs, ensuring sustainable sourcing and increasing opportunities for enhanced recycling, (b) digital twinning can simulate physical objects to optimise maintenance strategies, (c) the internet of things may reduce overall demand for power and (d) big data analysis can identify ways to reduce materials and resource waste (Lema and Rabellotti, 2023).

[8] Although in the long term we can envisage that renewables can produce enough electricity for ICT and everything else, incentives and regulation could target ICT production and waste from now. Unfortunately, the electronics industry has not been encouraged to abandon its waste practices in hardware, though it can constantly upgrade software online.

[9] Mbula (2024) shows that South African firms in the green economy are significantly more innovative when they use advanced digital technologies in the innovation process.

Furthermore, digital technologies can dematerialise products, turning them into services as has already been done by streaming much of music and film as well as written material. Many current recycling technologies depend on computer-aided 'intelligent' identification of materials to separate glass from plastic and from paper. Equally, they could enable greater durability of tangible products by facilitating the 3-D printing of spare parts, as well as rental models in various industries, rather than possession and short-lives and waste, imposed by the planned obsolescence that characterised the mass production paradigm.[10]

# 3 Implications for latecomer development

In this section we discuss the importance of the direction-driven nature of the green transformation in terms of the implications for latecomer development. The nature of green technologies creates both opportunities and threats in such countries, depending on local preconditions and responses. Windows of opportunity in the green economy, such as the shift from fossil fuels to renewables-based energy systems or from petrochemicals to biomaterials, or from ultra-mechanised to hydroponic or regenerative agriculture, may therefore create both winners and losers.

Previous experiences suggest that the 'endogenization' of these windows of opportunity is key (Yap and Truffer, 2019). The centrality of institutional instruments to the green transformation means that governments in latecomer countries need to create their own demand windows, shape selection environments, and invest in requisite capabilities. It is in such a context, clearly favourable to green innovation and investment, that entrepreneurs would be able to make bold – but not excessively risky – bets in advanced green innovations, counting on the synergy from other innovators, on the availability of the required demand and the necessary suppliers as well as on a stable policy context supporting that direction. This positive interaction between the government and the agents in the market is what creates the systemic advantages and synergies that can mobilise economic growth with the green transition, harnessing the power of ICTs.

## 3.1 Green windows of opportunity

Within a technoeconomic paradigm, the constraints to latecomer development are not always equally formidable but vary over time as particular technologies develop and open windows of opportunity (Perez and Soete, 1988; Pérez, 2001). Disruptions at the sector level open opportunities and enable caching-up if governments and enterprises have the capacity to turn opportunity into realised potential (Lee and Malerba, 2017). Once the green economy, becomes the norm both for production methods and consumption patterns, new opportunities will arise for further green products or services. This can create opportunities for latecomers to develop innovative green products and services and enter the market (Mathews, 2018). As such, green windows of opportunity provide a temporary advantage to these latecomers to catch up and compete with early adopters who have already established themselves in the green economy, primarily because latecomers may have

[10] A company that rents electrical appliances and even charges per wash in the 'rented' washing machine is an example of what could be ahead (Bocken *et al.*, 2018)

fewer path dependencies that make the shift away from highly polluting domains that are likely to be difficult and costly (Lema, Fu and Rabellotti, 2020).

Historically there has been a close connection between technological trajectories, global economic shifts, and changes in national technological leadership. Crucially, there is a difference between early and late entry into technological trajectories and significant latecomer development has often occurred in the initial phases of new techno-economic paradigms (Pérez, 2001). This is to say that while the biggest changes have occurred historically during technology-driven revolutions, catching up may also occur in the context of maturing and rejuvenating technological trajectories, such as the Japanese reviving of mass production (Kenney and Florida, 1988) .

The green transformation may provide new opportunities for latecomer development in a similar way. This is because many industries are completely changing due to sustainability imperatives, and this creates spaces for innovation by late entrants. Take the case of China in the automotive industry. While China has developed a strong automotive industry and considerable production capability, experts agreed for a long time that domestic innovation capabilities still lagged far behind those of leading nations (Altenburg, Schmitz and Stamm, 2008). It was not until the radical shift in technology associated with electromobility that China could use the sectoral paradigm change to electromobility to catch up technologically, decreasing the technological gap vis-à-vis global leaders in electric passenger cars, while leapfrogging in terms of technology and market leaderships in domains such as electric buses and battery production (Altenburg, Corrocher and Malerba, 2022; Lema, Konda and Wuttke, 2024).

In this way, the green transformation creates new opportunities for latecomer development by disrupting established industries and creating new markets for sustainable products and services. In the case of Brazil's agricultural sector, the shift towards sustainable agriculture practices has created opportunities for latecomer companies to develop new supply chains for commodities such as soy and palm oil that are produced in an environmentally responsible way.[11] Precision agriculture is using all the ICT possibilities from drones and satellites to precise dosage of water or fertiliser plant per plant.

The examples of the Chinese automotive industry and Brazilian agricultural sector are clear cases of windows of opportunity that have implied achieving greater productivity and therefore lower costs than the traditional competitors. They are cases of opportunities that emerge mainly externally because of technological change and disruption of markets.

[11] By embracing sustainable practices, Brazilian companies can differentiate themselves in the global marketplace and compete with established players from developed countries (De Abreu Sofiatti Dalmarco, Hamza and Aoqui, 2015). Brazilian firm Natura's combination of sustainably sourced ingredients from the Amazon Forest and advanced science for the personal care products has enabled the firm to gain leadership in the sustainability-focused segment of this business. Research institutions such as Embrapa have developed new technologies for precision agriculture and soil conservation that increase productivity while reducing environmental impact. By developing these new technologies, Embrapa has helped to position Brazil as a leader in sustainable agriculture and create new opportunities for latecomer companies to develop innovative products and services that promote environmental stewardship (Figueiredo, 2016).

However, many such windows of opportunity may also be endogenously created with target setting, regulation and promotion (UNCTAD, 2023)

While the greening of the global economy may open new opportunities for developing countries, it is important to recognise that it may also introduce new costs and increase the obstacles to economic development. Technological change associated with the green transformation may introduce extra costs of adopting new technology as the greening of manufacturing becomes an entry-ticket for operating in the global economy, not least on global value chains (Lema and Rabellotti 2023). To be sure, there will be both winners and losers across countries and sectors in latecomer countries: the green transformation creates both opportunities and threats and the risk that 'unjust transformations' could be the default scenario needs to be the starting point for policy deliberations.

Our main argument is that digital technologies are often key to creating and utilising green windows of opportunity, but their presence alone is insufficient. These opportunities can sometimes be utilised by bringing external technological change and leveraging it by internal institutional change that, when successful, may lead to entirely new pathways.

## 3.2 Using ICTs to promote sustainable development

Such new pathways may be opened by green-digital combinations in products and services used on an everyday basis in the developing countries, in particular when digital technologies are used to create sustainability-oriented directions of mass-consumption practices that would otherwise be rooted in carbon or pollution-intensive models of production and consumption.

For example, in the field of electricity provision, new access to energy-poor households has been provided with the aid of leveraging digital technologies. In Kenya, the fusion of digital finance innovations (Kingiri and Fu, 2020) with small-scale deployment pathways in renewable energy (Bhamidipati and Hansen, 2021) has created entirely new models of energy provision where Solar PV replaces diesel generators as a source of local electricity provision. The Kenyan industry leader, M-KOPA Solar, uses mobile money technology to provide pay-as-you-go solar energy solutions to off-grid households. It enables its customers to use the solar systems by paying in small, affordable instalments using their mobile phones (Ogeya *et al.*, 2021). However, it is not just the customer-facing elements of the model which are enabled by digital technologies. The technology platform uses cellular data signals to connect the 'plug-and-play' solar kit to centralized information systems. The data chip in the kit is thus connected to a technology platform that handles customer payments, inventory, accounting, and customer relations (Karjalainen and Byrne, 2021). By leveraging these digital technologies, M-KOPA has been able to provide clean, renewable energy to over a million households in Kenya and other African countries, while also reducing their reliance on fossil fuels. In addition, there was a drastic reduction in the investment costs (and the carbon footprint) of the traditional infrastructure in buildings, cables etc. Connectivity itself and self-generated energy open opportunities for local production and improvement of living conditions, which is a feature of digital technologies that has scarcely been used intentionally towards local development.

In transportation, India's e-rickshaws have helped to reduce air pollution and traffic congestion in Indian cities. Pushed by the FAME scheme implemented by the government of India, these battery-powered three-wheeled vehicles are becoming increasingly popular in India as a low-cost and eco-friendly mode of transportation (Singh *et al.*, 2022).[12] They integrate digital technologies into their low-carbon alternative to petroleum or gas rickshaws. Digital technologies have thus played a crucial role in advancing and enhancing the viability of e-rickshaws. GPS tracking and mobile payment systems have made e-rickshaws a viable alternative to traditional rickshaws by providing efficient navigation and convenient cashless transactions. At the same time the integration of IoT connectivity, telematics systems have streamlined the operations and management of e-rickshaws. IoT devices and sensors enable real-time monitoring of vehicle performance and maintenance needs, while telematics systems allow fleet managers to track and optimize e-rickshaw operations (Khan and Quaddus, 2020; Singh, Mishra and Tripathi, 2021).

These technological solutions have also led to improvements in efficiency, convenience, and affordability for end-users. Overall, these cases demonstrate the potential for technology to both help address environmental challenges and promote sustainable development.

## 3.3 The interface between green transformations, natural resources and ICTs

Opportunities for new pathway development may also develop in natural resource rich societies. The idea that the green transformation can provide substantial opportunities for economic development based on natural resources in the Global South has gained significant traction, but it is also universally accepted that such effects depend on action by governments as well as local and global stakeholders.

According to some analysts, this transition presents a unique 'green window', i.e., an opportunity for countries in the Global South, which often possess abundant natural resources (Lebdioui, 2022; Menéndez de Medina, Pietrobelli and Valverde Carbonell, 2023). The idea is that the green transformation is opening new demand windows as green technologies such as solar panels, wind turbines, and electric vehicle (EV) batteries rely on various critical minerals and rare earth elements.[13]

There is a big debate, however, about whether the sustainability agenda will just exacerbate resource curses or whether it will indeed provide a springboard for new development pathways (Månberger, 2021). Many resource-rich countries have remained unsuccessful in translating natural resource wealth into economic and social wealth. There is no evidence so far that resource availability is associated with the greening of economic development,

[12] Fame is an acronym for 'Faster Adoption and Manufacturing of Electric Vehicles in India'.

[13] These minerals include lithium, cobalt, nickel, copper, rare earth elements, and others, which are essential to produce energy storage systems, electric motors, and other components of green technologies (IEA, 2021). The World Bank has estimated that the production of some of those minerals needs to increase by nearly 500% if renewable energy and other green technologies industries expand to the degrees required to avoid dangerous climate change (World Bank, 2019).

based on forward linkages from natural resources to domains central to the green economy (Cheng et al., 2021).[14]

In many cases, linkage-based strategies have been difficult to become widely successful. For example, while Chile has a substantial mining sector the country has not been able to develop a competitive cluster of mining services suppliers. The current supplier support programs lack the necessary scale to achieve the desired impact. To effectively facilitate the sector's transition towards higher-value products and services, a comprehensive industrial policy is imperative (Lebdioui, Lee and Pietrobelli, 2021).

Menendez et al. (2023) identify a new opportunity window in green transformations, emphasizing two key aspects: quantity and quality of demand. In the short and medium term, heightened demand boosts prices, leading to increased mineral rents. Long-term benefits also stem from sustained demand. Additionally, the shift towards green technology sectors prompts a move away from commodifying mineral production, driven by the growing demand for low-carbon minerals.

The authors predict a unique 'green' window of opportunity, shaped by sustainability considerations influencing demand preferences. This stands in contrast to earlier attempts at leveraging natural resources for development. The study underscores the advantage for resource-rich developing countries, including China, Brazil, Chile, Mexico, and Zimbabwe, in capitalizing on this opportunity. The focus is beginning to shift from inexpensive raw materials to eco-friendly, specialized materials in limited quantities. They stress the importance of green energy sources like solar and wind for hydrogen production and electricity in manufacturing, transportation, and processing.

These findings lend support to arguments for knowledge-based strategies. Reviewing evidence from the Argentinean agricultural sector and the mining industry in Chile, Marin et al (2015) found that the window of opportunity that natural resource industries offer was significant. They suggested that development strategies can also promote more innovative knowledge intensive NR-based industries rather than moving away from them (Perez 2010; Marin, Navas-Aleman and Perez 2015). Every mining project should become a local development project, not only to compensate the affected (avoiding conflicts) and to guarantee that resources, such as water, are fully shared and/or replenished, but also to integrate the local population with direct services to the project and with other job creating activities and enhancing the local quality of life (avoiding migration to city slums). Multilevel governance structures (discussed in the final section) can take advantage of the territorial nature of some of the energy sources and the global nature of ICT to set up local development projects (Pérez, 2010).

[14] In fact, some authors argue that it could result in further exploitation of resources, environmental degradation and social inequalities. If so, the benefits of mineral wealth can perpetuate the negative effects associated with the resource curse and benefits may not reach the broader population. Rather, minerals may become fuels of conflict in the transition to a low-carbon economy (Church and Crawford, 2018). For a similar discussion about the relationship between critical materials and digital technologies, see Diemer et al (2022) who argue that ICTs with significant mineral inputs create significant spatial disparity between where minerals are extracted (sources of conflict) and where technological returns are appropriated (sources of wealth).

Importantly, digital technologies can play a crucial role in optimizing and managing extractive industries and facilitate upgrading, particularly for those dimensions of upgrading which are connected to sustainability objectives (Litvinenko *et al.*, 2022). For instance, advanced data analytics, remote sensing, and Internet of Things (IoT) devices can assist in geological surveys, resource mapping, monitoring of mining operations and reduction of waste (Nwaila *et al.*, 2022) . Digital platforms and supply chain management systems can enhance transparency, traceability, and efficiency in the extraction and processing of critical minerals and rare earth metals as well (Calvão and Archer, 2021).

# 4 Conclusions and policy recommendations

We started this paper by proposing that the green transformation exhibits peculiar features that have major implications for latecomer development. The big debate about latecomer development needs key conditions: First, it needs to consider the specificity of the green transformation as a direction-driven phenomenon –resulting from aspirational, political and institutional changes – which is beginning to shape our modes of production and innovation. Second, its speed and depth can be greatly augmented if ICT is made to go in the green direction. There are potential but crucial synergies in the economy that would not be there by pursuing green without the power of ICT.

Both conditions are observable as emerging phenomena, but they are uncertain. We have provided evidence and examples in support of the proposition that these conditions are strengthening, but we have also pointed out the path dependencies and political economy factors that work against them. As we have suggested, the range of the viable with digital technologies is already astonishingly wide, but profitability has naturally favoured telecoms, social media, games and finance, giving insufficient attention to serving the innovation needs of the green transformation. That shift of attention can only happen if governments tilt the playing field decisively and it can only succeed if it is based on a vision of a truly global green economy. In this final section, we summarise the main issue and provide policy suggestions.

## 4.1 Development strategy in transformative times

All leaps in development have been made in a favourable global context, i.e., in times of changes in the global market context that have created windows of opportunity for surges in economic and social improvements (Perez, 2001). Do we currently live in times of such favourable conditions? Clearly, changing global contexts come with constrains as well as opportunities and both divide unequally between countries; nevertheless, we do argue (a) that there is ground for cautious optimism and (b) that a tailored development strategy is a prerequisite for turning opportunity into successful reality.

As suggested earlier, redirecting the digital revolution towards the green transformation does provide windows of opportunity due to its constituent changes in institutions, markets and technologies. For example, carbon taxes in OECD countries may significantly favour production where sun and wind conditions are better suited for renewables-powered supply of products and services. Sun radiation conditions around the equator produces significant environmental advantages (and therefore cost advantages) for energy-intensive

products ranging from agricultural crops to steel (Hausmann, 2023). For example, it may soon become unviable to produce cut flowers with intensive farming method technologies involving heated greenhouses and high carbon fertilisers in Europe. While agricultural systems in OECD countries will naturally transform in response to carbon taxes on agriculture, this may eventually favour producers in Kenya and Ethiopia where conditions for environmentally sound production are more favourable, especially in conjunction with a concomitant green transformation in transport. Hence, rejection of environmentally damaging economic activities in OECD countries may favour creation of low carbon alternatives in Global South countries with more favourable natural conditions for low carbon energy production (sun, wind and water) as well as for the sustainable production of critical minerals.

In addition, countries that are less tied to past investment in old technologies of the high emission models of techno-economic development may find it easier to follow the new paths and even become leaders in certain green practices and technologies.[15] This requires state guidance to prepare for the requirements of the future green global economy. Development strategy must therefore consider, and indeed push, the long-term objectives of greening and transforming economic development, e.g., in consumer goods, adapt to and push for durability, simplicity of repair and recycling. They need to envisage and leverage different models of consumption both at home in the Global South and in the key demand-markets of advanced economies.

As mentioned, many countries across the Global South are currently responding. In the automotive sector, a range of upper middle-income countries – China, India, Malaysia, Vietnam and South Africa – are investing seriously to respond to the current sector level shift to electric vehicles, although with varying degrees of success and constraints (Altenburg, Corrocher and Malerba, 2022; Lema, Konda and Wuttke, 2024). Developing countries are also responding to the windows of opportunity in green hydrogen by developing national hydrogen strategies and policies, investing in green hydrogen research and development, attracting investment in green hydrogen projects, and collaborating with other countries on green hydrogen development (Altenburg *et al.*, 2022; UNIDO, 2022)[16]

In renewables, as well, a large number of developing countries are investing and designing strategies to maximise the economic benefits involved in the energy transition. To be sure, developing green technologies is very often an expensive proposition and due to the presence of incumbents and the importance of economies of scale, key preconditions – such as large internal markets and threshold levels of technological capabilities – may often be a prerequisite for the development of sectoral systems in core green technologies (Lema and Rabellotti 2023). For many countries, the opportunities for job creation and entrepreneurship lie much more in the deployment system, involving tasks such as

[15] The earlier high emission models include both mass-production based on cheap oil and the current misdirection of the ICT paradigm which actually contributes to the environmental crises.

[16] Some specific examples of green hydrogen initiatives in developing countries include India's National Hydrogen Mission, China's Hydrogen Energy Industry Development Plan, Brazil's National Hydrogen Strategy and South Africa's Hydrogen Valley Initiative (Bacil et al 2023).

organising projects, domestically sourcing ancillary products and services etc., than in core technologies.

Our main point here is that synergies with ICTs have enormous potential to augment all of these initiatives. Digital technologies are often key to innovating in a green sustainable direction. Development strategy is about identifying windows of opportunity and potentially dynamic sectors, but the new condition for success, given the inevitable shift of markets towards environmental sustainability, is about taking the opportunity into green and leveraging digital technologies for that end. This means that development policy needs to span a wide range of domains across environmental, technological and industrial spheres, while also innovating institutionally.

## 4.2 Shaping transformation for development

We have thus emphasised the potential of ICTs to both accelerate and deepen the green transition and to foster latecomer development. The fusion of green latecomer development strategy and ICT not only addresses environmental challenges but also seeks to foster catalytic synergy for economic development and social progress.

One key message that arises from our analysis is the need for policymakers to move beyond the 'usual suspects' such as those mentioned in the prior section: renewable energy, electric vehicles, etc. Many new industries have emerged as new 'green industries' due to especially the threat of climate change, but also dangerous local air pollution and other environmental hazards. However, while what is called the green economy may provide important opportunities in the Global South, it is important for policymakers to monitor and identify market opportunities in existing products and processes and to innovate in 'greening' them.

In this respect there is substantial disruption in global production networks involving consumer goods, minerals and agricultural goods. The issue for the developing countries is to avoid limiting themselves to becoming passive assemblers, enclaves and low-value export-platforms. Both upstream and downstream innovation possibilities are open, especially given the new green requirements. In the case of minerals, the availability of local low-cost green energy could facilitate processing downstream and using greener transport to deliver lower-volume, higher-value materials, directly to the final user-producer. The carbon footprint of the whole value chain would thus be significantly reduced. Equally, regarding consumer goods much innovation could rejuvenate the goods themselves and their innovation processes, favouring durability and the circular economy. Most importantly, fostering the proliferation of high-tech technical services, digital biotechnological and many others for testing, tracing, measuring and so on, would elevate the country's capacity to improve what it already produces and to venture into new areas. Proactive strategies are likely to bring advantages in terms of competitiveness and the gaining of footholds in future dynamic markets (Pegels and Altenburg, 2020)

By implication it is important to recognise that the relevant preconditions are not confined to the 'green' sectors; they are economy-wide and substantially rooted in the ability utilise ICTs for greening. Of course, making the best of such opportunities will require consensus, clear directions, availability of finance, already acquired capabilities and obviously sufficient

funding. And the likelihood of success may also very much depend on the institutional conditions, both in each country, and at the global level.

## 4.3 The need for an institutional revolution

The pursuit of simultaneous and combined development and greening in the Global South aligns with the interests of advanced economies, not only from a justice standpoint but also from several practical perspectives: (A) Climate change poses a global threat, and mass migrations from the Global South could destabilize entire regions. (B) Promoting green industrial and economic development as a viable path to growth is essential for fostering widespread public support for global climate action. (C) Expanding market opportunities for sustainable products, services, and practices will generate economies of scale, facilitate labour division, and create new market opportunities for green capital goods, knowledge-intensive business services and other key domains. This transformation will require a massive shift towards relative dematerialization and a redistribution of global production, ultimately benefiting both the North and the South.

All that implies a shift in gear in global institutions and policy-action. Recently, the global landscape has been experiencing rising tensions between the United States and China, technological sovereignty strategies, protectionism, and a financial system that has become a global casino, decoupled from the real economy, profiting from tax havens, capable of avoiding national regulation and resulting in rentier capitalism (Palma, 2023). Facing those problems already requires multinational agreements and probably supranational arrangements. In the meantime, inequality has increased with globalisation, both in the advanced and in the developing world, where some of the advances have been marred by income polarisation.

Globalisation has not delivered the general increases in wellbeing insistently promised by the unfettered free market advocates and the resulting frustration has produced a wave of populism across the world, multiplying autocracies and not delivering in its new promises either. However, as one of us has shown (Perez, 2002) this is typical of the way technological revolutions have historically propagated and it is precisely when responding to that with proactive policies, giving direction to investment and innovation, that the golden ages have occurred: the Victorian Boom for the Age of railways, the Belle Époque ('Progressive Era' in the USA) for the Age of Steel, and the Post War boom for the Age of oil and the automobile. Today, the information revolution confronts the challenges of social and international inequality and the existential threat of climate change. The current Bretton Woods institutions have proven inadequate to meet them. They were originally designed for a different world, and then shifted to back the free market globalization from the 1980s. They are now insufficient to support the lifting of the Global South and the green transformation.

The institutional revolution that we need today will be no less profound than the ones that brought the golden ages of the past. It will require new ways of thinking about global governance, economic development, social justice and appropriate technologies as well as new ways of funding them.

At the supranational level, a set of important institutional changes are needed to support the green transformation as a new direction for techno-economic development which is global, effective, and fair: a Global Green New Deal.[17] This deal should collate a set of concrete initiatives aimed at addressing both climate change and economic inequality on a global scale. Drawing on the analysis in this chapter, we propose the deal should include the following core elements:

- A global financial transactions tax (GFTT), which could become the main source of funding for the greening of the Global South, managed by a transparent global bank with enforcement power and channelling funds towards green infrastructure.[18]
- A global green innovation fund supported by government in advanced economies to stimulate innovations in the science and technology systems that could respond to many global challenges, facilitate synergies between the digital and the green transformations and foster transformation in the Global South.
- Abandonment of the extreme WTO prohibitions against using tariffs, subsidies, and public procurement. It has become obvious that infant industry protection is indispensable for development. So many governments, even that of the US, now use them both for the green transformation and for strengthening technological leadership, to the extent that they have become obsolete in practice.
- A specific intellectual property regime for green technologies which also accommodates the needs of less technologically advanced developing countries.
- The incorporation of a global institution to codify, monitor and certify environmental, social and governance (ESG) metrics, which include metrics for New Deal objectives such as green investments and localisation on low- and middle-income countries.
- Rolling our progressive standards and digital product passports for interoperability of all electronic and electrical appliances, availability of software for diagnostics and maintenance, recyclability and other measures to contribute to the end of the waste economy.

Obviously, global institutional change needs can only be a complement and a reinforcement of national policies. Many of the required initiatives are already clear but do not gain enough traction: Investing in renewable energy and in energy efficiency, promoting sustainable transportation, conserving nature, supporting sustainable agriculture etc.

[17] Several commentators have taken inspiration from the original New Deal, a series of programs implemented in the United States during the 1930s to combat the Great Depression and stimulate economic recovery to propose a Global Green New Deal (Barbier, 2010; Pollin, 2020; Chen and Li, 2021). Those institutional changes became the foundation for the whole set that brought the Welfare State of the Post-War Golden Age.

[18] The original proposal for a GFTT came from Nobel laureate James Tobin who proposed a tax on currency conversion. Subsequently a European Union financial transaction tax was proposed by the European Commission on the exchange of shares, and bonds and derivative contracts (Kitromilides and Rosa González, 2013). Something similar was recently proposed by seventy economists led by Stiglitz, Gosh and Tubiana (2023) and published in Le Monde.

Essentially, though, national policies need to change the context in such a way as to make it more profitable to invest in a sustainable direction than along the old trajectories.

In addition, as we have argued, there are possible changes that are enabled by internet and digital technologies that have not been fully understood or utilised. The traditional way of 'industrialising' and creating employment has been a process of urbanisation that ejects the rural population into the cities, often into urban slums. As has been discussed above, the use of information technologies, centrally including full and low-cost internet access across the whole country, is a powerful instrument for shifting to a greener world, while creating better lives. Two major elements make a difference: the opportunity for complementing globalisation with 'localisation' and the possibility of setting up consensus building mechanisms that will turn each major project on the territory – be it mining, agriculture or energy production – into a development project *in situ*. Both require setting up consensus building mechanisms that will reduce conflicts and provide good livelihoods for the local population. Both will depend on devolution, multi-level governance and training of the civil service in the new conditions.

The combination of the information revolution, the green transformation and the new politics of globalisation may open new avenues for development that, if systematically supported by supranational funding, could result in a massive leap forward in the Global South. We have argued that the green transformation is a unique opportunity for latecomer countries to leapfrog ahead and achieve rapid and inclusive economic growth. We have also suggested that full global development is a win-win game between advanced and developing countries. Governments, with adequate financial support, may thus unlock crucial synergies and opportunities by pursuing development in a green direction, using the power of ICT.

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