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Perspective

Affordable clean energy transition in developing countries: Pathways and technologies

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SUMMARY

The priority of developing countries in the clean energy transition is to attain industrialization primarily with low-carbon energy sources; this presents challenges that industrialized nations did not experience. Developing economies need to grapple with the question: "Should sustainable human development be achieved at the price of economic growth?" Therefore, this article brings perspective to the theme of clean energy transition for development. We highlight three peculiarities of developing economies which will strongly influence their approach to the clean transition: low grid capacity and inefficiency, lower rates of urbanization, and youth demographics. Owing to these, effective low-cost technologies and novel pathways that can facilitate clean transition in a sustainable socio-economic framework are needed. In particular, we propose that mature dispatchable low-carbon energy sources should be prioritized as a strategy to harness local natural resources, and maximize existing indigenous skilled labor. The perspective also highlights several recommendations to help researchers and policy makers look more critically into possible solutions for the Global South's timely participation in the clean energy transition without sacrificing economic growth potentials.

INTRODUCTION

The race toward maintaining atmospheric temperature rise to 1.5°C above pre-industrial levels requires the collaborative contributions of all nations of the world—from the low-income to high-income economies. To achieve global net-zero goals, developed countries will need to change the mix of energy sources in their mature industrialized systems to include a significant portion of low carbon. However, developing countries will aim to attain industrialization with low-carbon energy sources. Owing to the diversity in objectives for high-income and low-income nations, there are several calls for a *just transition*: giving safe allowances to each category to ease the socio-economic shocks that could arise from the ambitious commitments to migrate to low-carbon energy sources (Oyewo et al., 2021). Furthermore, the effects of climate change also require that the new energy systems are not only reliable, but also resilient to high-impact environmental events.

The benefits of the clean energy transition to emerging economies have been thoroughly discussed in the literature, including cheaper sources of power, cleaner and healthier fuels, climate-resilient food production, and job creation (Babayomi and Dahoro, 2021). It is well known that the energy transition comes at a high financial cost to all economies, and those with higher financial resources may transit earlier and more easily (Eicke and Goldthau, 2021; Polzin and Sanders, 2020). Yet, the challenges that low-income countries are facing with clean energy transition due to their unique socio-economic situations and the implications of a late transition are yet to be thoroughly studied. Also, there is still no study on how developing countries can participate in the transition in an affordable manner, without sacrificing their potentials for growth and development. Therefore, this paper intends to close these research gaps by a critical overview of past research and actions by key stakeholders, and presenting perspectives to stimulate effective action, result-oriented research, and debate.

This subject is important for several reasons: (1) The necessary ongoing change in energy infrastructure comes at a price of huge financial investments, early retirement of fossil-based power generation assets, and cancellation of several transactions or contracts that supported fossil-based power systems. (2) There appears to be inadequate affordable energy investment and mitigation finance for the Global South (all

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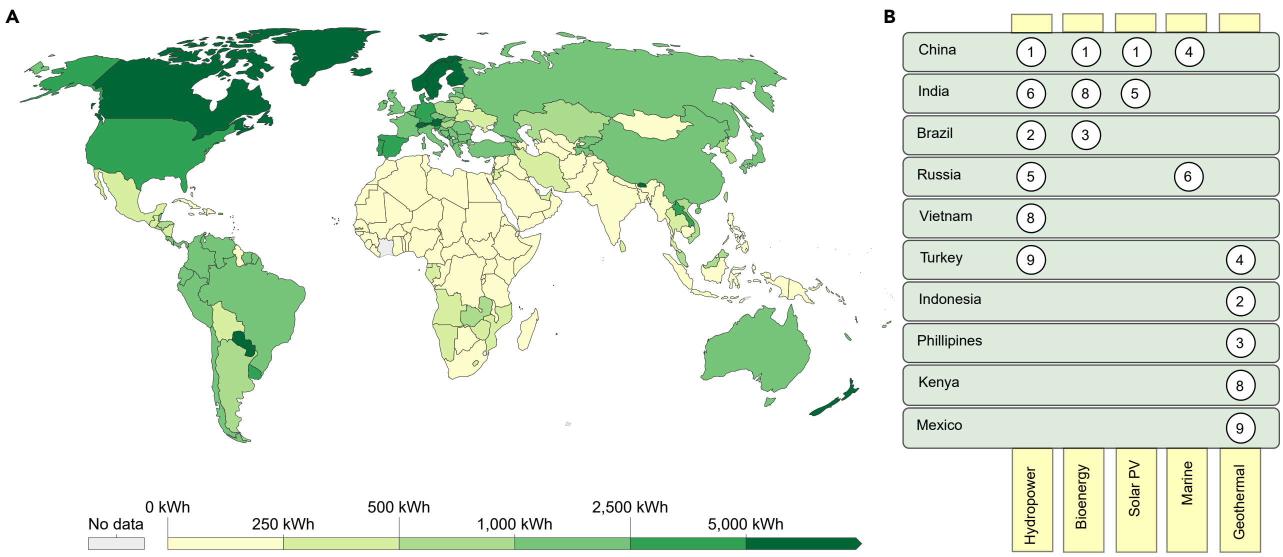

Figure 1. Electricity generation from renewable energy sources, 2019

(A) Global per capita electricity generation from renewable energy sources, 2019 (Our World in Data, 2019). (This is the sum of electricity generated from solar PV, wind, biomass, hydropower, wave, and tidal energy).

(B) Developing countries with global top ten electricity generation from renewable sources and their ranks, 2019 (IRENA, 2021a). All the images used in this figure have been taken from royalty free website: https://ourworldindata.org/.

developing countries, including emerging economies—Brazil, Russia, China, and South Africa) to make timely moves toward clean transition (Eicke and Goldthau, 2021). The limited clean energy finance being accessed (and its use) may not be adequately preparing the Global South to be capable of economic growth and development in the future. Also, there may be need for expert advisory to help these countries invest mitigation funds in the most optimal projects. (3) There are threats of carbon lock-in for several of these countries because the challenges to their transition are not only internal, but external as well, e.g., some higher-income nations have large investments in fossil fuel assets in certain low-income countries (Alova et al., 2021; Goldthau et al., 2020).

Also, there is an uneven spread of geographical activities that relate to the clean energy transition: it is concentrated in the Global North (developed countries), and few upper-middle-income countries, leaving most developing countries out (Eicke et al., 2019). Factors attributable to this include higher cost of finance for countries in the Global South (Goldthau et al., 2020), indicating that investors categorize them as *higher risk* than the North. Hence, this is slowing down their rate of evolution into *green economies*.

Hence, this study aims to use the afore-described foundation to proffer economic and technological perspective for how leaders of developing countries can strategically invest in energy transition in such a manner that the earlier concerns are addressed—especially transition without trading off growth and development. In this paper, the use of the term *affordable* refers to sustainable economic pathways and technologies that will lead to medium to long-term economic growth and development.

The following sections will discuss the current state of the clean energy transition in the Global South, the unique characteristics that distinguish the Global South from the Global North in respect of the theme being studied. The relationship between human development and sustainable economic growth in underserved communities will be discussed. Recommendations will also be made on pathways and technologies that can facilitate growth under the energy transition. The article will also discuss forecasts on this theme, and outstanding research and issues need to be resolved.

CURRENT STATE OF THE CLEAN ENERGY TRANSITION IN DEVELOPING COUNTRIES

The overview of per capita global electricity generation from renewable sources is shown in Figure 1. First, at most one country per region has annual per capita electricity generation of at least 5.0 MWh, except Scandinavia (Figure 1A). Second, all other regions (apart from most of Africa and Southwest Asia) generate at least 500 kWh per capita from renewable sources. Furthermore, in terms of total regional generation, apart from Asia, all other developing regions are lagging behind the world in renewable electricity generation. Figure 1B illustrates that at least one developing country is among top ten in electricity generation from hydropower, bioenergy, solar, marine, and geothermal energy. In particular, there is a huge drive among developing countries for electricity generation from hydropower and geothermal—each technology has at least five developing countries within top ten global leaders by total generation.

Renewable energy installation capacity in the Global South confirms a wide divide compared with the Global North. For instance, Africa accounted for only 1.3% (586,434 MW) of the global installed solar capacity in 2019. In Asia, the situation is similar: excluding China, India, Japan, and South Korea, Asian countries accounted for only 5.4% (330,786 MW) of the total installed solar capacity of (IRENA, 2021a).

In the wind energy sector, Africa boasts only 0.9% of the global installed wind capacity in 2019. In Asia, excluding China, India, Japan, and South Korea, the total installed wind capacity is 2.0% of the global sum (IRENA, 2021a). The renewable energy diffusion figures highlight the slow pace of the energy transition in the Global South.

The slow rate of the clean energy transition is strongly influenced by ease or difficulty of access to finance, and the cost of available finance. Finance is required for innovation, manufacturing, and building consumer infrastructure. First, the bulk of renewable energy patents are filed in China, the United States, the European Union, Japan, and Korea (IRENA, 2021b). Renewable energy manufacturing follows a similar pattern. For example, 70.0% of the photovoltaic cell production market is supplied by China (Philipps and Warmuth, 2021). So, most developing countries are clean technology consumers, rather than innovators or manufacturers.

Also, developing economies (excluding China and India) receive far fewer capital flows for clean energy infrastructure than developed economies (Bachner et al., 2019; Eicke et al., 2019). Attracting investment for low-carbon projects is dependent on the local environmental conditions (Arezki, 2021; Ragosa and Warren, 2019) as assessed by indices including macroeconomic strength, state capacity, economic and regulatory governance gaps, policy uncertainty, and regulated power tariffs (Arezki, 2021; Falchetta et al., 2021; Svobodova et al., 2020). The cost of financing climate change projects, quantified by the composite weighted average cost of capital (WACC), is an indicator of investors' perception of country risk. It represents the cost of the alternative financing options for low-carbon energy developments, and is a critical factor in private sector investment decisions (Egli, 2020; Modigliani and Miller, 1958). Hence, higher WACC is charged to countries with lower gross national product, developing economies (Ameli et al., 2021), and for relatively less mature technologies (Egli, 2020; Steffen, 2020). The increased financial burden associated with building clean infrastructure contributes to the slowing pace of progress in lower-income economies.

PECULIARITIES OF DEVELOPING COUNTRIES

In this section, we will introduce some peculiarities of the developing economies that need to be considered in proffering viable low-carbon energy transition pathways.

Highly inefficient grid infrastructure

Transmission and distribution losses are due to electrical power lost in power lines and transmission and distribution (T & D) equipment (and sometimes due to pilferage). T & D losses from 5.0%–7.0% are considered as normal, and these are typical in developed countries (IEA, 2019). South Asia has the highest average T & D losses (2014) of 18.8%, Middle East & North Africa, 13.5%; Sub-Saharan Africa, 11.7%; North America and Europe, 6.3%; East Asia and Pacific, 5.4%. Among developing countries, there are huge variations in T & D losses: China (upper middle-income) has 5.0% losses, Ghana (lower middle-income) has 23.0% losses, and Iraq (low-income) has 51.0% losses. The high losses in developing countries are due to several decades of non-maintenance of the power grid, as well as poor financial and administrative management (IEA, 2019).

The existing grid capacities cannot supply total demanded baseload power

Several developing countries do not have enough generation capacity to supply baseload demand. Hence, the utility companies implement both scheduled and unscheduled power outages to satisfy a broad

Table 1. Tiers of energy access

	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Power	N/A	≥2*W*	≥50*W*	≥200*W*	≥800*W*	≥2*kW*
Supply technology	N/A	Solar lantern	Standalone solar system, battery	Generator or minigrid	Large fossil-based generator, minigrid, or main grid	Large fossil-based generator, main grid
Tariff (USD/kWh)	N/A	N/A	N/A	0.3–0.7 (subsidized), 0.8–3.91 (cost-reflective)		0.024–0.39 (Grid)

coverage of customers with some amount of power. During 2018 to 2019, 42.1% of African grid customers reported outages lasting at least 24 h. This was significant compared with Asia (13.0%) and Europe (5.2%). This impacts on levels of income and wealth too: if power outages in Sub-Saharan Africa reduced to levels in South Africa, business would make up to 116.8% more money if they did not have to operate backup generators (Cole et al., 2018; Maruyama Rentschler et al., 2019).

High cost of capital and country-risk factors

As discussed in the preceding section, due to low ratings on some or all of indices of ability to recoup capital (e.g., macroeconomic strength, policy uncertainty, regulated power tariffs, country risk, etc.) investors charge most developing countries higher lending rates.

High rural population and low electrification rate

Relative to the Global North, several developing countries have a high rural population. In particular, Sub-Saharan Africa (58.7%) and South Asia (65.1%) have the highest rural population rates compared with Europe (25.0%) and North America (17.0%), respectively (Henderson and Turner, 2020; World Bank, 2018). This high rural demographic characteristic has related challenges including low rural electrification rate, lower quality of education, poorer health facilities etc. Table 1 illustrates the World Bank's multi-tiered classification of household energy access (BloombergNEF and SEforALL, 2020, GovData360, 2019; Bhatia and Angelou, 2015). Tier 0 is without access to electrical energy, Tier 1 with solar lanterns, Tier 2 with solar home systems, Tiers three to four have fossil fuel generators and minigrids (Tier 4 could have some access to the main grid too), and Tier 5 with access to the main grid and enjoys the lowest electricity cost. These tiers also have increasing household income and affordability of electricity as we progress from Tier 0 to 5 (Bhatia and Angelou, 2015).

According to the World Bank, Tiers 2–4 levels of energy access (from solar home lanterns/systems, generators, and minigrids) have limitations of unaffordability for productive use (Bhatia and Angelou, 2015). In this case, affordability is the ''ability to pay for the energy required to run productive applications without unduly sacrificing market competitiveness (Bhatia and Angelou, 2015).'' Table 1 also shows that supply technologies for Tier 5 include large fossil generators and the central grid. At present, subsidized off-grid minigrid tariffs are USD 0.3–0.7/kWh (Bhatia and Angelou, 2015), while cost-reflective off-grid minigrid tariffs are USD 0.8–3.91/kWh (Bhatia and Angelou, 2015; BloombergNEF and SEforALL, 2020). These high rates (usually 2–37 times local grid tariff) can make it difficult for locally manufactured goods to compete with much cheaper imported products. The impact of this is that although such expensive rural electrification could provide some improved living standards, it might not suffice to grow competitive rural markets. In the long run, without increase in income, development efforts (which cannot thrive on grants alone) are likely to fail. It should be noted that most grid electricity tariffs in developing countries are not cost-reflective and are heavily subsidized; on the other hand, minigrids in many cases do not get such a high subsidy support, lack economies of scale, and sometimes serve very remote and complex geographies (Bhatia and Angelou, 2015; BloombergNEF and SEforALL, 2020).

High youth population and attendant challenges

The developing countries with high rural demographics also have a high youth population (Ritchie and Roser, 2019). For this reason, it is likely that for as long as rural areas remain neglected by government economic policies, there would be higher migration rates to the urban areas in search of better financial

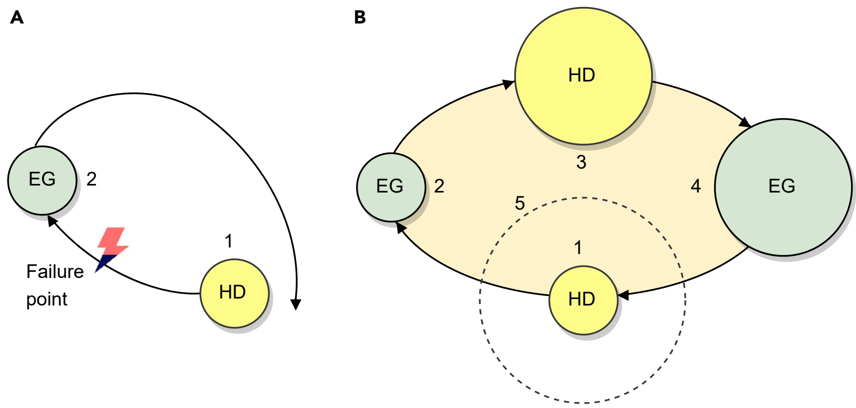

Figure 2. Relationship between human development (HD) and economic growth (EG)
(A and B) (A) HD-EG interaction with unstable equilibrium, (B) Cycle of HD-ED interaction with stable equilibrium. Source: Authors, based on (Suri et al., 2011).

opportunities. Yet, without adequate skills or education, the migrants would likely remain in the lowest classes of urban dwellers. For instance, the accelerating rise in the urban population of Sub-Saharan Africa places greater pressure on existing dysfunctional electricity infrastructure (Wang et al., 2020).

In the following section, we will review the relationship between human development and sustainable economic growth. This will provide context for recommendations that will follow.

HUMAN DEVELOPMENT AND SUSTAINABLE ECONOMIC GROWTH

The needs of developing countries in the clean energy transition are 2-fold: (1) to apply low-carbon energy for economic growth, and (2) to achieve universal energy access and improve human development. These dual objectives can cause a conflict in realization because energy for growth must be low cost to facilitate competitive production of goods and services. On the other hand, universal energy access is currently achieved with Tiers 2–4 energy technologies, which do not facilitate market competitive production at their present scale and cost of deployment. Therefore, this presents a conundrum for policy makers: Should human development (HD) be achieved at the price of economic growth (EG)? This is a difficult question to answer because human development should be the end for virtuous economic policies (Anand and Sen, 2000).

Nonetheless, it is well known that HD is also an important input to achieve accelerated and self-sustaining EG (Suri et al., 2011). Figure 2A shows that when policy is HD-lopsided, it leads to stunted EG, and such a pathway can further deteriorate HD in the long run. However, when HD is a complementary input to EG (Figure 2B), it can produce more income to allocate to improve the quality of HD; this further grows EG and can continue a self-sustaining cycle of HD-EG growth. Thus, if developing economies adopt policies that are HD-lopsided, it can lead to undesirable economic stress in the end.

Based on the foregoing, we suggest that the Global South should have an agenda for ''clean energy transition for development'', i.e., development that encompasses both sustainable human development and economic growth *pari-passu*. For instance, the prevalent philosophy that drives the majority of off-grid energy access investments in underserved communities is that rural electrification has huge impacts on household labor supply, income, and summary measures of well being (Babayomi and Dahoro, 2021; Monyei and Akpeji, 2020). However, randomized controlled tests in India (Aklin et al., 2017) and Kenya (Lee et al., 2016, 2020) indicate that rural electrification efforts yield insignificant impacts on savings, spending, business creation, time spent working or studying, health outcomes, asset ownership, or student test scores. So far, there are few methodologically strong studies on rural electrification infrastructure and economic growth, with key studies not specifically identifying the effect of electricity infrastructure. It has also been pointed out that ''case studies of success stories are suggestive, but firm conclusions on the role of electrification on economic development would benefit from more rigorous statistical evidence'' (Stern et al., 2019). This leads us to point attention to the need for strategic plans to integrate economic growth *pari-passu* with rural human development. Therefore, it is our opinion that if the envisioned rural

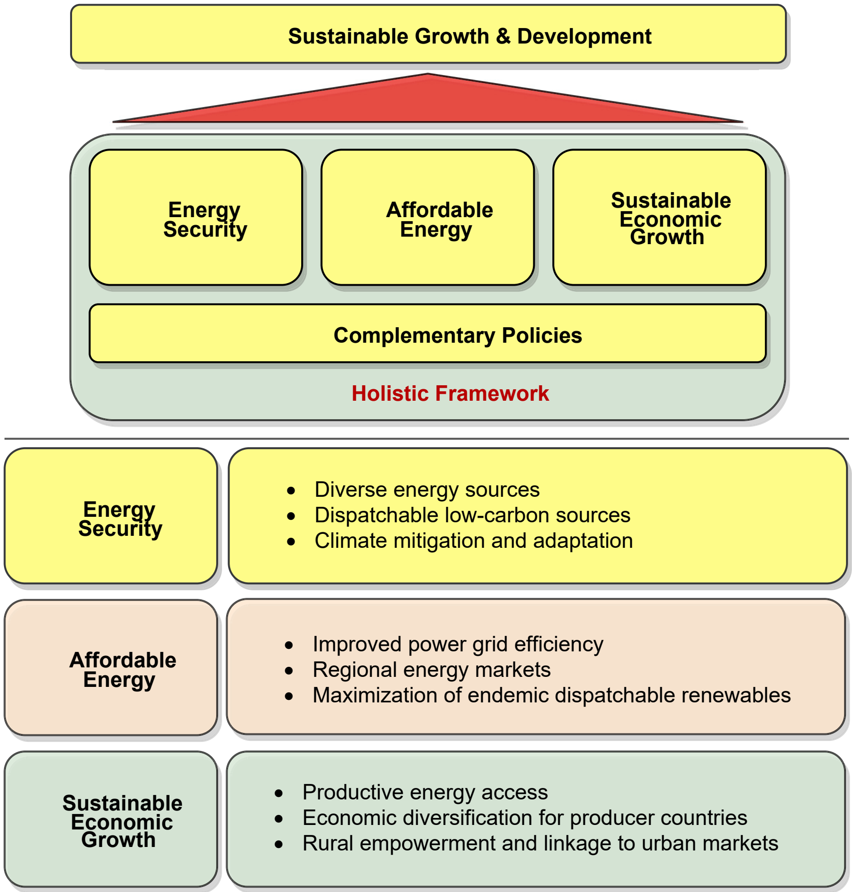

Figure 3. Pathways for growth-focused investment in the clean energy transition for developing countries

electrification will lead to sustainable development, it needs to be facilitated with affordable clean energy: energy that supports productive applications without unduly sacrificing market competitiveness.

RECOMMENDED CLEAN TRANSITION PATHWAYS FOR DEVELOPING COUNTRIES

In this section, we build on the afore-discussed necessity for a sustainable interaction between human development and economic growth to present new recommendations. The recommended pathways will be supported by three main pillars: energy security, affordable energy, and sustainable economic growth (Figure 3).

Energy security

1. There is a need to maximize electricity generation potentials from mature dispatchable renewable and low-carbon sources like hydro, geothermal, bioenergy, and nuclear. Dispatchable power is that which can meet demand as required, at any time of the day. This would help form a strong, reliable, and sustainable source for the baseload. Also, because these technologies are quite mature, there is an adequate local skilled personnel (excluding nuclear energy experts) to not only operate the equipment but also continue to innovate locally to sustain their operation.

   a. Hydropower: Hydropower remains the largest source of renewable energy, and in the form of pumped hydro, it provides the highest capacity for electricity storage. New plants are challenged by limited access to land and water. Water resources are also vulnerable to climate change. Six developing countries are among global ten leaders of annual electricity generation from hydropower. This indicates a measure of maturity with respect to hydropower technology in those regions.

   b. Geothermal power: Geothermal energy is the natural heat within the earth's crust, and is extracted through wells that are drilled to lead out steam through pipes at high pressure. The

Table 2. Low-carbon energy sources and technologies mapped with sectors

Sector	Technology
Residential	• Heat pumps • Demand-side management • Combined heat and power • Distributed renewable generation
Rural/agriculture	• Distributed renewable generation • Bioenergy by-products
Commerce/industry	• Main grid • Distributed generation • Pumped-hydro storage
Transportation	• Biofuels • Hydrogen • Battery storage

derived steam is used to propel electricity turbines. It has near-zero emissions and requires relatively little space for extraction. Figure 1 illustrates that five developing countries from three continents are among top ten global leaders of geothermal electricity generation (IRENA, 2021a). Although great potentials for capacity expansion still exist—e.g., in East Africa Rift Valley (20.0 GW is untapped), Latin America (55.0–70.0 GW is untapped)—the high cost of exploration could be prohibitive (Berman et al., 2018).

c. Bioenergy: Bioenergy is energy produced from plants and animal residues. It is derived from solid biomass, liquid biofuels, and biogas. Its uses include clean cooking, heating, electricity production, and transportation. China, Brazil, India, and Thailand are currently among global top ten in bioenergy, and several other developing countries can learn from their examples (IRENA, 2021a). Further discussion on this is covered in Point 2 on diversification of energy sources.

d. Natural gas and hydrogen: Natural gas with carbon capture, utilization, and storage (CCUS) will be a promising alternative for low-income oil producer economies in the medium term. Hydrogen production from hydrocarbon feedstocks is presently done commercially via natural gas reforming (with some CO2 emissions) and coal gasification (with large CO2 emissions) (Brandon and Kurban, 2017; Hanley et al., 2018). Hence, with CCUS introduced, producer nations can repurpose existing natural gas infrastructure for hydrogen production and distribution. It should be noted that *green hydrogen* from renewable sources is more environment-friendly.

Apart from the above mature technologies, others which are expected to be commercially available in the medium to long-term include ocean energy (wave, current, and tidal), hydrogen fuel cells, CCUS technologies for existing fossil fuel generators and plants, and advanced (safe) nuclear and nuclear fusion.

2. Developing economies need to build security (reliability and resilience) into energy infrastructure by diversifying the sources of energy and incorporating distributed generation. This will entail customizing energy applications to diverse sectors and scale of application, for instance, demand-side management for residential, distributed generation via e.g., small hydro and bioenergy for rural/agriculture, efficient main grid (with centralized and distributed energy sources) for commerce and industry, and biofuels or green hydrogen for transportation. Table 2 shows detailed sectoral technology applications.

   a. Low-carbon fuels: These can serve as primary fuel sources for dispatchable power generation. They can also be produced as fuel storage for use when intermittent clean sources are unavailable. Some of these are hydrogen, ammonia, and natural gas fitted with CCUS.

   b. A case for bioenergy: One major advantage of bioenergy among other renewable sources is that it can be produced from resources that are distributed across most nations, as opposed to other renewable sources (and fossil fuels) that are restricted to certain geographies. China, Brazil, India, and Thailand have top ten global installed capacity of bioenergy—their total combined capacity is 46.4 GW (IRENA, 2021a). Given that developing countries have vast uncultivated arable land (e.g. Africa has about 25.0% of the world's arable land (FAO, 2018)), bioenergy has a huge potential. Some of the challenges associated with expansive commercial cultivation of bioenergy feedstock (starch-rich crops for bioethanol, and oilseeds for biodiesel) include food and water security. As demand and value of biomass increases for bioenergy production, it could compete with existing limited water and land resources used for cultivating food. Other risks include impact on biodiversity conservation, indirect increase of greenhouse gas (GHG) emissions from inefficient fertilizer use, and deforestation (Popp et al., 2014). These risks can be mitigated by cultivating cellulosic crops like perennial grasses (instead of crops like corn) which have lower cultivation-related CO2 emissions; formulating policies that mitigate the risks to food production, reduce CO2 emissions, while ensuring environmentally sustainable bioenergy activities. Studies also point out alternative pathways to improving positive interactions under the water-energy-food nexus. For example, waste from bioenergy installations can serve as biofertilizers for rural agriculture. This also solves the financial challenge of several rural farmers who cannot afford fertilizers (Guares et al., 2021; Marafon et al., 2020; Sheahan and Barrett, 2017).

c. Clean cooking for rural dwellers through improved biomass cook stoves, biogas, or ethanol; and for city dwellers, through liquefied petroleum gas and electric cookers (electric cooking technologies are also being developed for rural dwellers for the medium-to-long term (Kweka et al., 2021; Van Buskirk et al., 2021)). Almost one billion people use biomass for cooking. But affordable, modern clean cooking solutions will reduce forest degradation, minimize GHG emissions from cooking, and improve health outcomes (Dagnachew et al., 2020; Serrano-Medrano et al., 2018).

d. Distributed generation: This is the local generation of energy near or at the site where it will be used. Distributed generation has become more popular with the reducing costs of solar and wind generation systems. Thus, each user network can constitute a microgrid fed by the renewable generation systems. The main challenge with renewable-based generation is that the sources are not available throughout the day and night, thus energy storage would be necessary—and this usually forms a significant portion of total capital cost (30.0%–80.0%), depending on the storage technology and capacity deployed. Nonetheless, distributed generation is suitable for commercial, health, and educational power systems. Another benefit of this system is the potential to supply excess locally generated power to the grid at a grid feed-in tariff, giving the owners alternative sources of income.

3. Climate mitigation and adaptation: Developing countries need to provide more security for vulnerable rural dwellers by making their sources of livelihood more robust to extreme climate conditions. In addition, investments can be made in sustainable agriculture like agroforestry, which co-locates pastures in forests; *agrivoltaics*, which co-locates renewable power generation and agriculture e.g., when solar photovoltaic (PV) panels are co-located with crops, reduced soil evaporation and lower PV-panel temperatures (hence higher generation efficiency) can be achieved. These schemes diversify the income sources of farmers, in a sustainable manner (Barron-Gafford et al., 2019).

Affordable energy

This will be discussed under the subheadings of improvement in power grid energy efficiency, competitive cost of energy storage and renewable energy, and regional integration for energy trade.

1. Improvement in power grid energy efficiency: Energy efficiency is an often-ignored catalyst for sustainable energy access and has received significant attention due to its capability to improve energy access with less generation-related emissions (Babayomi et al., 2020). The electrical power grid comprises three main parts: generation, T & D, and the end-users. Each of these can be significantly improved upon to reduce the losses in the path of power flow. This research will focus only on the latter two.

As earlier mentioned, substantial T & D losses are recorded in developing countries due to technical and non-technical reasons. Because it costs much less to save energy (through energy efficiency system upgrades) than is required to build new power plants (whether fossil-based or renewable), improving the energy efficiency of T & D in the countries with higher than the normal rate of 7.0% should be the first route toward improving the sustainability of the power system (ACEE, 2017). This will also both significantly reduce the amount of CO2 emissions (by about 411 million MtCO2e/yr from technical losses) due to electricity generation that is non-utilized, and secure the usefulness of high-cost low-carbon power plant investments (Surana and Jordaan, 2019). High voltage direct current (HVDC) transmission, flexible AC transmission systems (FACTS), and gas-insulated substations are a few technologies that can improve transmission efficiency by 20.0%–40.0% (ABB, 2007).

Demand side management is the overall means of achieving energy management of the users' load. It includes energy efficiency, energy conservation, time of use, demand response, and spinning reserve (Babayomi et al., 2020; Oluseyi et al., 2020). Incorporating a wide-scale energy efficiency program for energy users contributes to a more sustainable grid.

Furthermore, electricity thefts can be reduced through improved smart grid monitoring technologies. Also, driving down non-direct costs of producing electricity and removing subsidies from grid tariff to make it more financially sustainable, and plugging administrative sources of financial losses are measures that would improve efficiency.

2. Energy storage cost: Intermittent low-carbon sources like solar and wind energy usually require energy storage to provide power when the renewable resource is unavailable (e.g., solar energy is available for about 6 h daily). However, studies indicate that for such renewable sources to power baseload 100% of the time, they are only cost-competitive when energy storage costs less than $20/kWh (Ziegler et al., 2019). State-of-the-art grid-scale battery storage technology is Li-ion, costing an average of $345.00/kWh capacity (Cole et al., 2021). Considering that Li-ion has 80% depth of discharge, it implies that the average cost of available/usable capacity is $431.25/kWh. But the relatively high lifetime of about 1000 cycles or 10 years (where a full cycle is not completed daily), whichever occurs earlier, could justify the high cost (Faunce et al., 2018; Hu et al., 2020). Nonetheless, the current high cost of battery technologies makes them non-ideal for application in low-income developing countries.
3. Regional integration for energy trade: Several of the mature dispatchable renewable sources in the Global South are concentrated at a few geographical locations. More than 90.0% of Africa's hydropower potential remains unexploited and 68.0% lies in East and Central Africa (IRENA, 2021c). Kenya has tapped into her favorable location on the East Africa Rift Valley to develop competence in geothermal power, and is ranked seventh globally by installed capacity. Similarly, Indonesia, Philippines, Turkey, and Mexico all rank within global top ten. Countries that are geographically favored and have deeply explored renewable technologies can serve as regional supply sources of power and engage actively in energy trade (Babayomi and Okharedia, 2019; Guler et al., 2018; Zaman and Kalirajan, 2019). The possibilities of regional trade in the developing world appear uncertain due to civil unrests in some of these regions. Nonetheless, there are cases of successful cooperation despite political tensions (Schwerhoff and Sy, 2019).

Sustainable economic growth

This will be discussed under the subtopics of productive energy access, investments in allied sectors, and economic diversification.

1. Affordable energy access for productivity: There is a need create opportunities for the rural population to engage in commercial agriculture and meet urban food demands. This can be done by providing renewable electrification and other infrastructure to facilitate the commercial output of rural areas via storage facilities for fresh food, and transportation of agricultural inputs and produce. These do not have to be through minigrids alone; bespoke renewable-powered rural interventions that facilitate market-competitive production costs will also be beneficial (Table 3). Very low electrification rates are common in the rural areas of several developing countries (mainly in Africa, with 59% rural population). These regions need energy access through a combination of central grid, minigrid, and standalone off-grid strategies. Although minigrids presently provide some level of energy access at Tiers 3–4 (BloombergNEF and SEforALL, 2020), the business models result in high tariffs (2–37 times local grid tariff, depending on local terrain and policies, see Table 1). For economic growth, affordable energy access that favors market-competitive production of goods and services is necessary, and how to achieve this remains an open question.

Table 3. Recommended affordable clean energy transition pathways and technologies for rural and urban locations

Location	Pathway	Technology
Rural	**Energy security** • Affordable clean energy for lighting, cooking, and agriculture • Diversification of clean energy sources • Climate mitigation and adaptation **Sustainable economic growth** • Productive energy access • Flourishing rural markets • Strong physical and economic linkages between rural producers and urban markets • Protection from cheaper imported alternatives	• **Lighting**: solar lanterns & home systems • **Agricultural production and processing**: bioenergy, small hydroelectric, affordable solar PV/wind energy • **Cooking:** improved biomass cookstoves, biogas, and ethanol • **Transport:** biofuels, hydrogen, batteries
Urban	**Energy security** • Diversification of clean energy sources • Maximal harnessing of endemic dispatchable renewables **Affordable energy** • Improved grid efficiency • Maximal harnessing of endemic dispatchable renewables • Electricity trade with regional neighbors and markets **Sustainable economic growth** • Economic diversification for oil producer nations • Thriving trade with local rural markets • Prioritization of locally sourced inputs over imported options	• **Highly efficient main power grid:** ✓ Demand-side management techniques via energy efficiency, demand response, and energy conservation ✓ Base load i.e., dispatchable low carbon sources: hydropower, geothermal, bioenergy, and nuclear (for locations with scarce or insufficient local renewables). ✓ Peak load sources: solar PV, wind, pumped hydro storage • **Cooking:** Liquefied petroleum gas, electric cookers • **Transport:** biofuels, hydrogen, batteries

Technologies are the mature category in Figure 4.

2. Investments in allied sectors and skill development: The total economic impacts of investments in technology for economic activities comprise direct and indirect impacts. Direct impact is associated with immediate economic activities stimulated around the location of the investment. However, indirect impacts relate to intermediate inputs of goods and services which contribute to the value, and distribution of the main products. Domestic indirect economic impact usually varies in proportion to the quality of available local expertise. It was shown in the study by (Patrizio et al., 2022) that in decarbonizing manufacturing, countries that can locally provide intermediate inputs (goods and services) to manufacturing and other knowledge-intensive sectors will retain the most indirect economic impacts within their borders. Thus, low-carbon policies in developing countries (or regions) should also ensure domestic sourcing of intermediate inputs to manufacturing and high-tech industries which require decarbonization. This will prevent the bulk of indirect economic impacts of decarbonization from being directed to already-developed countries (or regions).
3. Economic diversification: Majority of the leading oil producer economies are developing countries, with oil exports accounting for the significant part of their gross domestic product (GDP). Since several leading net-importers are already increasing the share of alternative low-carbon fuels in their energy mix, the demand of oil will decrease significantly around 2030 when such fuels move from validation state to commercial scale. It is essential that producer economies diversify economic sources urgently to reduce the impending socio-economic pressures that would arise from loss of major revenues. The expertise of the oil and gas sector industry makes them highly competent to diversify into hydrogen, CCUS, and offshore wind technologies (IEA, 2021a; 2021b).

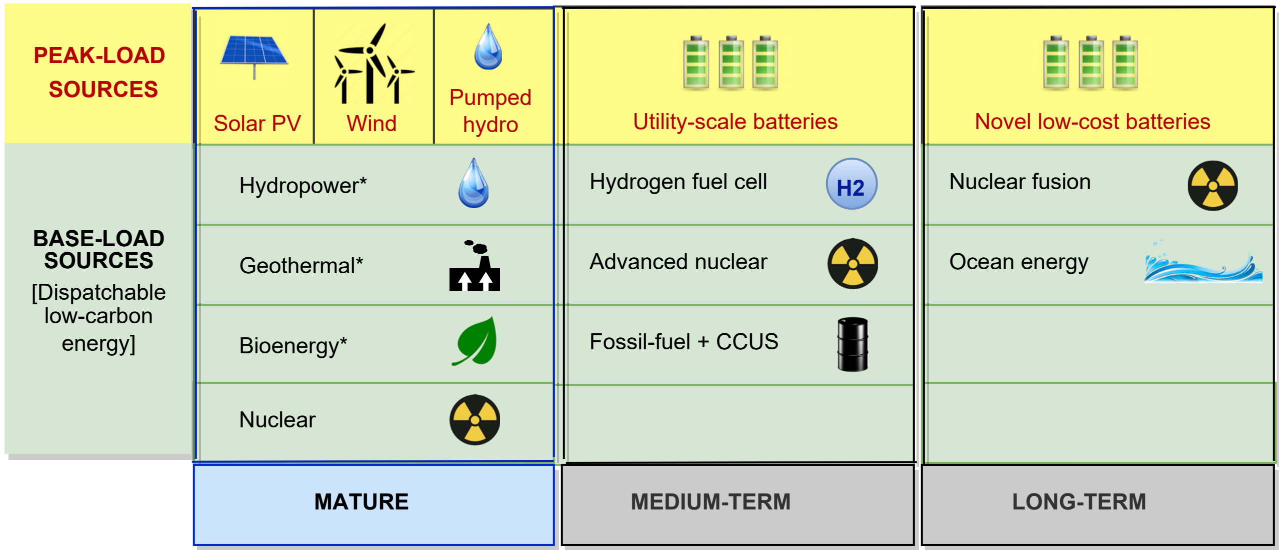

Figure 4. Low-carbon electrical power system flexibility for developing countries

* = recommended priority power sources. All the images used in this figure have been taken from royalty free image website: https://www.freeiconspng.com/.

RECOMMENDED TECHNOLOGIES

The technologies that can be used to complement the increasing penetration of intermittent renewable sources are called flexibility options (Schill, 2020). Figure 4 shows the recommended low-carbon energy sources to power the main grids of developing countries. Several factors were considered (as earlier discussed): present grid supply relative to national demand, availability of skilled personnel, geographical location, and readily available resources. The technologies are classified according to maturity and the kind of load being supplied (baseload and peak load).

Figure 4 shows the mature low-carbon technologies that shall supply baseload include hydropower, geothermal, bioenergy, and nuclear power. Mature technologies that are recommended for peak-load duration include solar PV, wind, and pumped hydro storage. In the medium term, we expect baseload technologies including fossil fuel with CCUS, hydrogen-based fuel cells, and advanced nuclear (that are safer than present-day reactors and are different in operational principle from weapon-applications). Also, utility-scale batteries are only recommended for use in the medium-term future due to their present high cost, as earlier described under *Affordable energy*. Long-term dispatchable low-carbon sources include ocean energy and nuclear fusion, while peak load sources include several types of advanced low-cost batteries under research and development (e.g., molten metal-based battery (Amy et al., 2019) and silicon-based thermal storage (Wang et al., 2014)).

We recommend priority use of mature dispatchable renewable energy sources, namely, hydropower, geothermal, and bioenergy. This is important for several reasons:

(1) The characteristics of power systems that operate mainly on these technologies are well established, and there is available skilled manpower in the developing world for these technologies. However, there is an acute shortage of well trained and experienced personnel in the newer field of power electronics (major components of solar PV and wind energy systems), leaving a risk of low-carbon projects that cannot be sustained by local expertise. Also, as previously mentioned, if most of the inputs to decarbonization of local industries and sectors are outsourced, it reduces the total domestic economic impacts gained from the clean transition.

(2) There are still vast renewable resources in this category that remain unexploited: More than 90.0% of geothermal potentials in both Latin America and Africa remain untapped (Berman et al., 2018); more than 90.0% of Africa's hydropower potentials are still unexploited (IRENA, 2021c)).

(3) Because several developing countries are yet to develop their main grids to satisfactorily supply baseload without load-shedding and power outages, growing the grid capacity to match baseload demand using well-understood technologies should be the first priority (see Table 3).

(4) The IEA recently pointed out that the demand for minerals required to manufacture technologies for the clean transition may increase by up to 6-folds in 2040 (IEA, 2021b). This may result in shortages, increased costs, and burden on policy makers on the most optimal energy mix. An additional advantage of the proposed flexibility mix is that it relies mainly on mature dispatchable low-cost energy. These technologies, as earlier stated, have less reliance on permanent magnet machines, power electronics, and battery storage—which require a higher use of minerals. Hence, the potential demand for minerals will be significantly reduced, and the imminent steep increase in the cost of rare earth minerals will have lesser impact on the Global South. Therefore, the intergenerational utilization of resources will be more egalitarian and sustainable (Anand and Sen, 2000).

(5) The stability characteristics of large power systems with higher percentage of static power converter-interfaced renewable sources (e.g., solar PV, wind, and batteries) are not yet well established by technical researchers. Preliminary research outcomes indicate that power systems with a large number of power converters (i.e., inverters) connected to the grid are prone to instability (Rosso et al., 2019); and methods to address these potential challenges are yet to be industrially validated. Hence, energy sources in this category should be used to form the supplement for seasonal periods of higher load demand (and should only be a fraction of baseload capacity). Nonetheless, synergistic benefits can be derived from co-locating renewable sources; e.g., installing floating PV panels on hydropower reservoirs has the potential to reduce evaporation and increase generated electricity (by 2-fold for 1% floating PV coverage of African hydro-reservoirs) (Gonzalez Sanchez et al., 2021).

Several of the recommended technologies (Figure 4) for powering the baseload will be difficult to access for countries with natural resource constraints. These economies have three options: i) develop bioenergy potential, ii) collaborate with regional partners for energy purchase, and iii) deploy wind and solar with relatively costly grid-scale storage. Also, although transnational renewable energy trade will be beneficial to compensate for uneven distribution of natural resources, this can be hindered by internal political instabilities or inter-country tensions. Yet, there are examples of successful electricity exchange between countries with political tensions (Schwerhoff and Sy, 2019).

FUTURE OUTLOOK

Here, we will discuss our forecast relating to hydrogen production and market structure in developing countries.

1. Hydrogen production: Natural gas reforming, coal, and biofuels gasification (with carbon capture) are medium term sources of hydrogen fuel. There are potentials for countries with abundance of these resources to export hydrogen which will serve as a major source of energy fuel for industry, transportation, and grid-scale storage in the medium term. However, the International Renewable Energy Agency projects that by 2050, this blue hydrogen will be overshadowed by green hydrogen from renewable sources (Gielen, 2019).
2. Market structure: The energy market structure in the Global South is envisaged to be significantly different from that in the Global North. First, the Global South needs to develop their main grids in efficiency, to reduce transmission and distribution losses, and then in capacity to power baseload reliably. Second, rather than having a large number of prosumers (''households that are both producers and consumers of electricity'' (Gautier et al., 2018)) as is envisaged for the Global North, there will likely be a larger concentration of large-scale projects by governments and independent developers to grow the grid capacity, and provide reliable power to consumers during grid downtimes. We also anticipate more synergies between independent grid distribution companies and private power developers to supply reliable power to major commercial and industrial centers. Finally, regional energy markets are expected to flourish. As local electrical power demand increases, and faced with non-existent financing options for fossil-based power projects, countries will be forced to buy power from neighbors who invested early in dispatchable low-carbon energy. Another factor that will engender this interchange is that it takes quite some time to explore feasibility, implement,

and then grow dispatchable energy sources, so, during the local development phase, countries will seek power-partnerships with neighbors.

Open research questions

The proposed framework in this paper rests on several points which require further clarity and analysis; these are discussed in this section.

1. Models, projections, and scenarios for low-carbon energy transition under the proposed growth-facilitating framework, with different timelines and levels of aggressiveness—using net-zero and carbon budget constraints. The proposed low-carbon flexibility (Figure 4) shows technology options that could be more preferred for the Global South in the short and medium term. However, region- and country-specific scenarios are required which encapsulate the endemic natural resources and geography of the region/country.
2. Until the economic productivity of the Global South becomes significant, commensurate growth may be unattainable. So, how rural productive energy access can be implemented—technologies and policies—without unduly sacrificing market competitiveness of goods and services is a critical challenge that needs to be resolved. Some studies point to a minimum threshold for per capita electricity consumption to make a significant improvement in the lives of rural dwellers (Fidelis et al., 2010). If the proposed value is taken as a consensus, how can this be applied in the ongoing efforts of policy makers, donors, and financiers to ensure that there is a correlation between energy access efforts and holistic community developmental progress?
3. Viable financial options and investment scenarios for growth-facilitating clean energy transition for developing countries are needed. Challenges with financing low-carbon transition projects in developing countries include high interest rates that point to "high-risk" assessment of the proposed projects. But when the future sources of income from the investments become clearer, lower finance pricing could result. Hence, it is necessary to clarify how developing countries can repurpose their projects to attract affordable finance.
4. Clear directions and insights on how producer economies can harness vast reserves of fossil assets in a sustainable manner. Although it is now clear that it would be difficult to access international finance for fossil-based power generation projects, it remains unclear how countries with rich coal, oil, and gas reserves can still profit sustainably from those resources under the emerging regime. Hence, studies in this light will be helpful.
5. Practical means are required to enhance economic returns in rural communities and move them from sustenance agriculture to thriving agricultural nerve centers. Developing nations need to reduce importation of several basic necessities including food by becoming self-sufficient. However, this requires removal of long-existing market frictions between the rural and urban markets. Pathways are needed for the creation of more opportunities for rural youth population and reduce the rural-urban migration that could place additional pressure on urban cities in developing countries.
6. The clean energy transition requires the diffusion of new technologies. However, because expertise resides with the Global North and few upper-middle-income countries, technological expertise could be used for political power-play. Hence, policies are necessary that during the purchase of hardware by developing countries, skills and expertise are also transferred as well.
7. Educational institutions and policies are required to scale up the training of skilled labor for the emerging high demand of new renewable generation systems including bioenergy, hydrogen technologies, carbon sequestration, and power electronics.
8. Affordable technologies for clean cooking via cook stoves and low-carbon fuels will be highly beneficial to emerging economies. However, there is a need for policies to enhance the awareness, commercialization, and mass distribution of several existing low-cost solutions (SolarImpulse, 2020) to this challenge. Also, local innovation is also necessary for adaptation and perpetuation of new methods of clean cooking.
9. Policies are needed to increase domestic retention of direct and indirect economic impacts of low-carbon investments in developing countries. Furthermore, regional cohesion and interdependence

among neighbor developing countries will strengthen retention of economic gains from investments in the clean transition.

CONCLUSIONS

The pathway to economic growth for the Global South under the clean energy transition remains an open topic. Thus, new models are necessary to facilitate their growth and development despite the generic socio-economic challenges of participating in the clean energy transition. In this perspective, we highlight that growth-facilitating transition needs to encapsulate the low grid capacity, grid inefficiencies, high rural population, and demographic distribution of developing countries. We also discussed the need for increasing the share of dispatchable low-carbon energy sources to power the baseload of growing economies based on newly-presented low-carbon electrical power system flexibility. This flexibility prioritizes the use of mature dispatchable renewable energy sources, such as hydropower, geothermal power, and bioenergy, to increase the grid capacity in countries with high rates of load-shedding. Finally, several research questions are posed, as pointers to the knowledge gaps that still need to be filled to provide viable options for development in the green economy.

LIMITATIONS OF THE STUDY

Our analysis is subject to several limitations. First, the proposed pathways and technologies for rural and urban areas are still postulations. We are yet to carry out rigorous numerical analysis with field data to verify if the propositions will lead to the envisaged outcomes. Different kinds of data-based studies are essential, and these are discussed in detail under Open Research Questions. Second, the proposed solutions in this article are dependent on several holistic factors which need to work hard-in-hand for expected results to be achieved. For instance, a change of clean energy technologies without implementation of enabling policies to facilitate local trade and remove market frictions is likely to yield sub-optimal outcomes. Therefore, the recommendations are based on the assumption that they will be backed by an enabling socio-political environment for their success. Third, regional and country-specific economic, geographic, and social constraints need to be considered. A one-size-fits-all approach is not likely to provide universal solutions in the Global South.

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AUTHOR CONTRIBUTIONS

Conceptualization, methodology, writing, review, and editing, O.O.B.; writing, review, and editing, D.A.D.; validation, review, and project supervision, Z.Z.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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