Environmental Science Advances

ROYAL SOCIETY OF CHEMISTRY

CRITICAL REVIEW

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Cite this: *Environ. Sci.: Adv.*, 2023, **2**, 570

Sustainable energy technologies for the Global South: challenges and solutions toward achieving SDG 7†

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The United Nations (UN) expectations for 2030 account for a renewable, affordable, and eco-friendly energy future. The 2030 agenda includes 17 different Sustainable Development Goals (SDGs) for countries worldwide. In this work, the 7th SDG: Affordable and Clean Energy, is brought into focus. For this goal, five main challenges are discussed: (i) limiting the use of fossil fuels; (ii) migrating towards diversified and renewable energy matrices; (iii) decentralizing energy generation and distribution; (iv) maximizing energy and energy storage efficiency; and (v) minimizing energy generation costs of chemical processes. These challenges are thoroughly scrutinized and surveyed in the context of recent developments and technologies including energy planning and supervision tools employed in the Global South. The discussion of these challenges in this work shows that the realization of SDG 7, whether partially or in full, within the Global South and global contexts, is possible only if existing technologies are fully implemented with the necessary international and national policies. Among the key solutions identified in addressing the five main challenges of SDG 7 are a global climate agreement; increased use of non-fossil fuel energy sources; Global North assistance and investment; reformed global energy policies; smart grid technologies and real time optimization and automation technologies.

Received 12th October 2022
Accepted 3rd February 2023

DOI: 10.1039/d2va00247g

rsc.li/esadvances

Environmental significance

This work will provide important insights on the state-of-the-art concepts, problems and solutions on the application of sustainable technologies for clean and affordable energy generation. This paper is aligned to the following topics of interest within this issue: (1) present and future scope of renewable energy technologies in developing and under-developed countries, (2) prospects of renewable energy resources in terms of environmental sustainability and (3) energy engineering towards the progress of sustainable development goals.

1. Introduction

It is undisputed among the scientific community that anthropogenic activities have upset the equilibria of nature. Strategic actions must be taken to address the related adverse ecological and social effects by finding and employing sustainable solutions.[1,2] Sustainable development is a concept that aims to couple environmental concerns with socio-economic issues.[3] This topic has been extensively discussed over the last decade, leading to international treaties, conventions, and so forth.[4] The

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† Electronic supplementary information (ESI) available. See DOI: https://doi.org/10.1039/d2va00247g

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United Nations has formulated the "2030 Agenda", which proposes 17 different "Sustainable Development Goals" (SDGs) to radically reformulate the current development status-quo. The aim is to migrate towards a truly sustainable praxis by 2030, which would address the risks associated with anthropogenic climate change.[5] These 17 SDGs encompass various aspects, including gender inequality, hunger, poverty reduction, responsible consumption, production, *etc.* Of these, three major challenges underpin the whole 2030 Agenda: (a) social inequality; (b) environmental pollution and damage; and (c) the fossil-fuel energy crisis.

Challenges (a) and (b) must be addressed with respect to criticisms regarding the means and methods of production in the current economic framework. Challenge (c) should be approached by transforming how energy is generated and distributed. The current energy crisis continues not only due to the fossil fuels polluting the atmosphere, but because the annual energy demands are aggressively growing around the globe annually.[6,7] According to the 2030 Agenda, it is imperative to change the energy paradigm to renewable, non-polluting sources, and greatly enhance the efficiency of the generation units and the production capacity. With this in mind, the fossil fuel challenge which is the focus of SDG 7 (Affordable and Clean Energy) encompasses the concept of the energy transition paradigm, moving from the current fossil-based status of energy generation to a new one, anchored in the search for a healthier future for nature and ecology.

The Global South refers to low and middle-income countries located in Asia, Africa, Latin America, and the Caribbean, in contrast to the high-income nations of the Global North.[3] The use of the term Global South is a reference to the large inequalities stemming from colonialism and neo-imperialism. The differences from the Global North, and indeed differences between countries within the Global South; such as energy distribution, population, dependency burdens, agricultural production, and the means for energy transition require nuance and particular attention in the cultural, political, and economic contexts of each country. This is important to recognize the drivers of transition: income, energy prices, energy access, local fuel availability, and workability of proposed solutions for current infrastructure. From the unprecedented growth in transportation, infrastructure, and industry in some Global South countries, such as Brazil, Russia, India, and China, it seems evident that increasing population and associated rising energy demands require abrupt changes in the energy system, regarding generation and distribution strategies. The energy sector in the Global South has to be far more efficient, integrated, and cost-effective, which creates an opportunity to ensure a sustainable and clean system. Furthermore, the contribution of the Global South to global greenhouse gas emissions, is also set to increase, making achieving SDG 7 a major priority.[8]

The main aim of this research is to provide possible routes to the successful implementation of SDG 7 in the Global South by 2030. Often missing from discussion of the achievement of SDGs is the necessity for interaction between approaches, resulting in a silo approach rather than a holistic one. That is to say, with the example of achieving SDG 7, the focus of this review, that we can make contributions to achieving SDG 7 that also contribute to other SDGs. There has been some discussions around the interaction between achieving different SDGs including, for example, the ranking of synergies and trade-offs,[9] or through learning lessons from case studies of sustainable development practices.[10] Following attempts to analyze projections of SDG trends in the future,[11] we continue this discussion through focusing specifically on ways of achieving SDG 7 in the Global South. Through the prioritization of SDG 7, and by understanding the connections between different SDGs and sustainability generally, we hope to avoid some of the issues that might cause the 2030 Agenda to fail.[12]

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method was used while systemically reviewing available technologies that can opportunely act to tackle and resolve the challenges of SDG 7. In the identification phase, a literature search with the data source from ISI Web of Science and Scopus through web search were collected with the keywords including "Global South", "SDG 7", "efficient energy", "cost-effective energy", "sustainable energy", "clean energy", "energy technology", "greenhouse gas emissions technology", and "integrated energy system". After removing the duplication, search results were combined. During the screening phase, abstracts and titles were reviewed and removed based on the relevance to the subject of interests. Afterward, the full text of the literature was reviewed for eligibility check. In the inclusion phase, selected articles ($n = 40$) were included in quantitative synthesis, and analyses were conducted to distinguish five main challenges regarding how affordable and clean energy could be achieved by 2030.[13] The novelty of our approach here is undertaking the search for a holistic approach to achieving SDG 7 through collaboration of researchers from wide-ranging disciplines. We identify synergetic relationships with other goals, and review the most appropriate technologies to achieve SDG 7, and related SDGs in the Global South. In doing so we highlight potential solutions to five key challenges and identify strategies with potential synergies with achieving other SDG goals. Each of these five challenges is individually scrutinized in terms of the available technological routes to tackle them.

2. Main challenges

What should energy systems in the Global South look like in 2030, and what can be expected from them? It is evitable that the targets and the strategies of the SDG 7 have potential synergies and trade-offs across other SDGs.[14] A synergetic strategy is achieved when the solution to one goal is related to progress towards achieving other goals. On the other hand, a trade-off is considered if solution to one goal becomes an obstruction for another goal. However, the large parametric space and the scarcity of methods to quantify the synergies and the trade-offs between goals and their targets can lead to a complex framework.[14] Of particular interest, considering the three key targets of the SDG 7, *i.e.*, universal accessibility, share of renewable and rate of improvement in energy efficiency, there are five main challenges to be addressed in answering these questions. The first and obvious challenge is the necessity to limit the use of fossil fuels. Apart from being heavy pollutants, the price of fossil fuels rises each year, due to scarcity, shortage, and operational limitations.[15] The current scale and trend of GHG emissions globally and the remaining carbon budgets mean that the abundance of fossil fuels, specifically for the countries with the large availability of domestic fossil fuels, is a threat to climate change mitigation.[16] Therefore, this issue goes hand in hand with the second challenge which is migrating towards diversified and renewable energy matrices.[17]

The use of viable renewable sources is very important, being indeed a good alternative to avoid GHGs emissions and reduce environmental impacts.[16,18,19] Today, there are many kinds of renewable energy technologies available such as wind energy, solar power, a huge variety of possible biomass and biogas routes (derived from sugarcane residuals,[20] micro and macro algae,[21,22] animal waste,[23] *etc.*), geothermal heat and biofuels (bio-ethanol, bio-diesel, *etc.*).[24,25] More possibilities are progressively becoming feasible as verified over the last few years.[26] Today, energy is generated in heavily centralized generation units; this practice is seen around the world.[27,28] The literature indicates that the choice of which renewable energy source to use has to be made according to *in loci* availability and characteristics.[29–31] Therefore, the third challenge to be faced for SDG 7 is to decentralize energy generation and distribution. One can expect the energy generation of the future to be sustained by many sparse units that profit from the local availability of renewable energy carriers, with each unit being responsible for power and meeting the demands of neighborhood areas.

The fourth and fifth challenges are, respectively, to maximize energy and energy storage efficiencies; to minimize energy generation costs of chemical processes, so that energy generation can be clean but also affordable. It seems that the decentralized generation paradigm presents benefits to both these issues:[32] distribution costs are significantly reduced with respect to current centralized generation units. Moreover, technologies are available to manage these distributed renewable units so that minimal pricing and optimal energy efficiency can be made available, as discussed in the sequel. However, in the short to mid-term, it is challenging to transform some of the existing energy systems of the Global South into decentralized and renewable ones due to the current locked-in carbon-intensive infrastructure. Table 1 shows a summary of the key solutions for each respective challenge of Global South in achieving SDG 7. The discussions on the key solutions are presented in the subsequent sections.

2.1 Challenge (i): limiting the use of fossil fuels

This challenge remains very difficult to be reconciled because most of the energy systems of the current society are driven by large quantities of fossil fuels where such quantity usage will lead to significant carbon dioxide emissions and hence global warming. For global warming to be reduced to 2 °C above the average global temperature during pre-industrial times, a cumulative carbon dioxide emission of not more than 870 to 1240 Gt is required to be maintained within the year range of 2011 to 2050.[33] Carbon dioxide emissions can originate from natural or anthropogenic sources. Natural sources include ocean-atmospheric exchange, biological respiration, soil decomposition, and volcanic eruption whereas anthropogenic sources include transportation, electricity generation, agriculture, commercial, residential and industrial activities. While it is not possible to reduce carbon dioxide emissions from natural sources, the focus has been placed on anthropogenic sources instead. Against this backdrop, limiting fossil fuel usage thus becomes a viable solution to the aforementioned problem.

An estimation of the current global fossil fuel reserve reveals a total CO_2 emission of 11 000 Gt.[34] Two extreme scenarios can be drawn from this estimation: (1) unabated fossil fuel production and usage will certainly exceed the 2 °C limit of global temperature rise, leading to uncontrolled global warming, (2) huge suppression of fossil fuel exploration will be required to meet the global temperature rise limit. The latter scenario reveals this challenge to be more than just a scientific problem, rather of political and economic natures. As many countries are involved in the fossil fuel industry due to their existing fossil fuel reserves, the latter scenario will cripple their economies. This scenario was modeled by McGlade and Ekins where the study revealed that an estimate of 82%, 49%, and 33% of the current global coal, gas and oil reserves must remain unexplored to meet the 2 °C limit of global temperature rise.[34] This is also made possible if carbon capture and sequestration (CCS) are done during fossil fuel exploration. Without CCS implementation, greater global coal, gas, and oil reserves (88%,

Table 1 Key solutions for the five challenges of Global South in achieving SDG 7

Challenge	Solution
(i) Limiting the use of fossil fuels	Global climate agreement; higher efficiency fossil fuel conversion technologies; intensification of non-fossil fuel energy sources; use of hydrogen-lean fuels; carbon capture and storage; and cooperation of energy industries
(ii) Migrating towards diversified renewable energy matrices	Implementation of renewable energy technologies, Global North assistance and investment, global reformed energy policies
(iii) Decentralizing energy generation and distribution	Decentralization; microgrids/smartgrids, automatic optimal EMS
(iv) Maximizing energy and energy storage efficiencies	Real-time optimization permitted by the Internet of Things; smart grid technologies
(v) Minimizing energy generation costs of chemical processes	Use of renewable energy; identification of important target chemicals

52%, 35%) must remain unexplored to meet the 2 °C limit. To put things in perspective, these translate as 887 Gt of coal, 100 trillion m^3 of gas, and 449 billion barrels of oil which are certainly huge amounts that are not possible to be phased out immediately without any effects on the global economy.

This fossil fuel challenge can be addressed based on its two parts: consumption and production. Over these recent years, the reduction of fossil fuel consumption is evidently instilled in various countries through their efforts in migrating toward diversified renewable energy matrices. The automobile-based transportation sector which is one of the major gasoline consumers and carbon dioxide emission sources had also undergone a gradual transition from gasoline-based internal combustion engines to battery-powered engines. Supply-side climate policies were also implemented to constrain fossil fuel production. A typical example would be the control of oil production in California by the Division of Oil, Gas, and Geothermal Resources (DOGGR) of the California Department of Conservation. DOGGR functions as the state permitting agency in controlling the amount of oil well projects based on the climate, industrial, and public policy bases. Among the oil production limiting policies implemented by DOGGR are: (1) halting the issuance of new oil well permits to be consistent with Paris Agreement goals, (2) reducing oil production in areas of high pollution vulnerability, (3) charging carbon adder as a severance tax on oil extraction, (4) removing oil production-related subsidies, (5) phasing out oil production processes with more than 600 kg CO_2e per barrel or oil with break-even price greater than US$60 per barrel.[35] These policies were reported to be effective where the Scoping Plan by California state reported the possibility to reduce oil production by 70% or 40 million barrels by 2030.[36,37]

As of now, these policies were not implemented in coal and gas production globally. Thus, if the majority of the fossil fuel-based countries were to adopt such approaches, the fossil fuel industry can certainly be made more sustainable with lesser environmental impacts. However, in the execution of such policies, global economic development and countries with fossil fuel industries will certainly be affected. Therefore, for a long-term solution, a global climate agreement that identifies and balances potential gainers and losers of climate change mitigation is necessary.[33] As for near term solutions, several action plans can be recommended such as (1) development of fossil fuel conversion technologies of higher efficiencies, (2) intensifying the usage of non-fossil fuel energy sources, (3) substitution of hydrogen-rich with hydrogen-lean fuels, (4) intensifying implementation of carbon capture and storage technologies and (5) promoting bilateral cooperation of Western and Eastern energy industries.[38]

2.2 Challenge (ii): migrating towards diversified renewable energy matrices

Indeed, the implementation of renewable energy technologies over a few decades across the Global South saw an increase in capacity. However, the rate at which they are increasing is still not sufficient to match the rate of increase in fossil fuel usage. Energy matrices of Global South countries are still apparently shifting towards the non-renewable spectrum of energy matrix despite their efforts to accelerate the implementation of renewable energy technologies. The energy matrices of several Global South countries are highlighted and compared in Table 1 across the four regions of Global South: Asia-Pacific, Central, and South America, Africa, and the Middle East. Energy matrices of the years 1990 and 2017 are juxtaposed to analyze the migration initiative of countries towards a diversified and renewable energy matrix. Based on Fig. 1 and Table S1,† the achievement of SDG 7 by 2030 *via* reduction of fossil fuel usage and migration towards a diversified and renewable energy matrix is unlikely to be fully implemented. Even with the significant implementations of renewable energies in the energy sectors of Global North countries which tend to advocate strongly for renewable energy sources, the global energy matrix

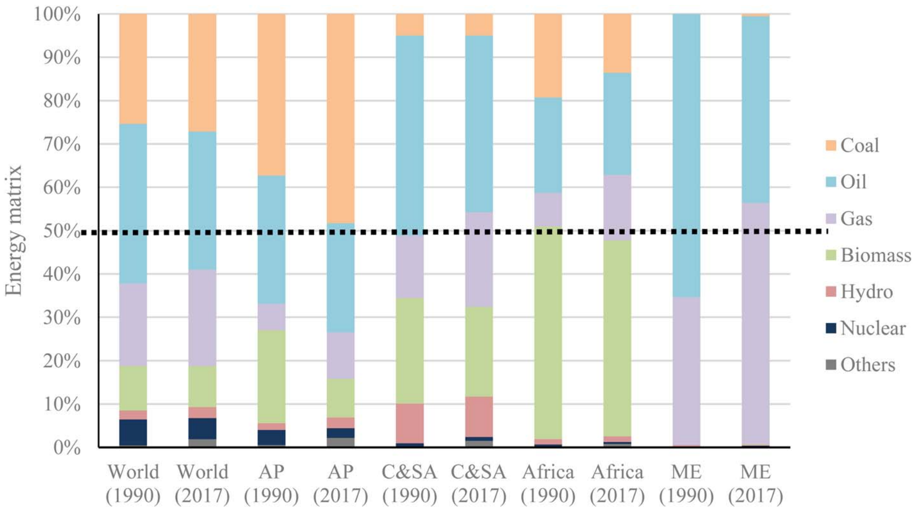

Fig. 1 Energy matrices of Global South regions in 1990 and 2017.[39,42,44,52,82–84] * AP = Asia-Pacific, C&AS = Central & South America, ME = Middle East.

did not show obvious migration towards a renewable energy matrix.

While energy matrices do offer important insights on this matter, one may require additional indicators to affirm such migration initiatives. For instance, the energy matrix of China showed a similar percentage range for coal despite its approximate fourfold capacity from 1990 to 2017. For such cases, the emission intensities of these energy matrices must also be considered as such trends are masked by the increasing trends of other energy sources, and are certainly not aligned with the spirit of global warming mitigation. Therefore, various Global South countries are increasingly more committed to addressing this issue. For instance, China has set several sustainable energy goals: 40–45% carbon intensity reduction by 2020 from 2005, 15% non-fossil based energy source by 2020, and also approved 2685 Clean Development Mechanism (CDM) projects under the auspices of the Kyoto Protocol to build aeolian, hydro and biogas power stations since 7 September 2010.[39–41] India, one of the main players in the energy sector of Asia has also identified eight "National Missions" under the National Action Plan on Climate Change (NAPCC) to accelerate the utilization of renewable energy technologies while reducing national carbon intensity per capita.[42] Several government tax incentive schemes such as Generation-Based Incentive (GBI) and Accelerated Depreciation (AD) schemes are also implemented in India to attract private investors in the field of renewable energy generation.[43]

It is instructive to further accelerate the implementation rate of renewable energy technologies and limit the use of fossil fuels to create a net increase in renewable energy usage. However, the energy issue at hand is more convoluted as it involves several deep-rooted technological, geographical, political, and socioeconomic complications. Global South is made up of developing countries in which their economic, population, and energy growths are very much inevitably intertwined. On a national scale, economic growth will lead to population growth which increases energy demand. To cope with this trend, energy output must be increased which in turn further increases the economic growth, leading to a cycle of accelerated increase in energy output for the economic growth of the Global South.[44] Even though fossil fuels are plagued with environmental issues, they are the only energy sources that could provide such energy security to cope with the aforementioned trends in the Global South. As the Global South economy becomes more heavily invested in these energy sources over these few decades, this issue has become a deep-seated problem and is worsening over time. If this conflict is to be addressed *via* a total and immediate renewable energy transition by themselves, the economy of the Global South will certainly be jeopardized. Therefore, Global North assistance and gradual reformation of energy policies must be considered to ensure a smooth renewable energy transition in Global South.

Another factor that strengthens this conflict is fossil fuel being the main commodity of the Global South. China, Malaysia, India, Brazil, Mexico, Venezuela, and the Middle East countries are some of the global main fossil fuel players where fossil fuel commodity remains their major national revenue source. A total phase-out of the fossil fuel industry would certainly accentuate the paradox of plenty in such countries.[45] Over these recent years, conventional oil exploration has seen increasing competition from non-conventional oil exploration and renewable energy generation. To curtail this competition, conventional oil exploration-based industries had increased the conventional oil production volume. It created an oversupply in the oil market, fueling a surge in fossil fuel demand and gradually losing the upper hand in the price war of energy sources.[46–48] For renewable energy technologies to become feasible and to achieve SDG 7, large amounts of investment are needed as well as a long payback period which would slightly offset the economic growth of the Global South during the energy transition period.

The common struggles of such transition are often reported to be due to scarcity of rigid environmental and financial policy, low government incentives and long-term follow-up services, low interests of private investors, technology immaturity, and geographical constraints.[43,45,46,49–51] Implementation of nuclear power generation has received mixed receptions within the Global South as not many countries have uranium reserves except Kazakhstan, Namibia, South Africa, Niger, Brazil, China, *etc.*[52,53] In addition, the Fukushima nuclear accident in 2011 has also raised the global nuclear safety standards causing global nuclear development to proceed slower with higher precautionary measures.[39,48,54] Hydropower is a mature renewable energy source where its challenges are often associated with precipitation fluctuation due to seasonal droughts and environmental impacts due to its massive land use.[53,55]

Efficiencies of solar and aeolian powers have been steadily increasing over the years due to the respective development of cheaper advanced photovoltaic materials such as silicon, perovskite, and semiconductor-based photovoltaics and stiffer lightweight wind turbines.[53,56] As initial photovoltaic materials are common in the single p–n junction, their theoretical solar efficiencies are limited by the radiative recombination as the sole loss mechanism within the solar cell which is the Shockley–Queisser limit.[57] To overcome this limit, several photovoltaic technologies are implemented: multijunction photovoltaic cell,[58,59] intermediate band photovoltaics,[60,61] photon upconversion,[62,63] concentrated photovoltaics,[64,65] thermophotovoltaics,[66,67] and fluorescent downconversion.[68] However, the uneven distributions of solar irradiation and wind have caused these power plants to be highly geographically constrained and centralized. This would increase the costs and the complexities of transmission networks, making grid parity a challenge to be achieved.

Biomass is perhaps one of the oldest and most sustainable renewable energy sources which can be processed *via* numerous established conversion technologies and feedstock types. It gives higher flexibility in optimizing its energy output and efficiency. Biomass is highly abundant in the Global South regions of South America, Asia, and Africa. Biogas is one of the major biomass types used for industrial and household energy generation in the Global South. However, different regions experienced different challenges in sustaining biogas technology. In Africa, poor access to water inhibits biogas development as anaerobic digestion requires an equal mixture of water and biomass to produce biogas.[69] In India and Andean communities, the high-altitude regions require digesters of higher complexity to maintain the optimum condition of anaerobic digestion.[70] The lack of technical supervision and inconsistent financial support for these technologies had also caused the biogas plants in these areas to be abandoned or not functional within the first two decades after their commissions.[52,71] In the development of biomass technology, the focus of the Global South should perhaps be shifted towards bio-oil which can be produced at a higher rate and better consistency than bio-gas *via* pyrolysis.[72–74] Bio-oil also offers a greater possibility to create highly functionalized and cleaner substituted fuels such as bio-crude oil[75–79] and jet fuel[80,81] which is in line with the cascading use of biomass.

2.3 Challenge (iii): decentralizing energy generation and distribution

The third main challenge that should be put into practice regarding the Global South is decentralization. This challenge mainly refers to how electric energy is distributed and generated and how this should change to establish SDG 7 by 2030. Decentralization based on renewables plays a vital role in alleviating poverty and facilitating socio-economic growth; moreover, it is a prerequisite to achieving sustainable development of rural communities. The current paradigm is heavily anchored on the following baseline: central power plants produce power outlets that are carried by high-voltage transmission lines to neighborhood areas, then transformed down to regular household or industrial facilities. The central power stations are usually located far from the end-user. There is a huge cost associated with these transmission lines, from maintenance to power losses, not to mention the land use and the space requirements to set up such coordinated generation-distribution operation; furthermore, there are many environmental impacts that appear to this centralized generation paradigm from large-scale region matters to localized concerns regarding the area that surrounds the large-scale power plant.

It seems very reasonable and thoroughly debated in the specific literature that the centralized energy generation paradigm must be transformed by a decentralized generation paradigm.[27,32,85] This new paradigm would also tackle the distribution problem since each region or local network would be self-sustained. Such a decentralization paradigm is illustrated in Fig. 2. Local neighborhoods and communities including households and industrial agents should collaborate and exchange energy within their boundaries ensuring that each demand is supplied. This is achievable when the local availability of renewable sources is considered. The global south panorama plays a vital role in this matter, since, as previously discussed, there is a great variety and availability of possible renewable sources in these countries that could be integrated into such decentralized generation networks.

Regarding distributed energy generation schemes, as illustrated in Fig. 2, we emphasize next the main divergences, advantages, and disadvantages with respect to the standard paradigm of centralized generation. Conventionally, since the establishment of larger power distribution chains, energy access reaches households and industries by the means of main network, which is physically connected to a large-scale generation facility in a central location. The major benefit is that, consistently, a broad number of end consumers can be reached within a considerable area, often physically far from the central energy dispatch plant. Nevertheless, centralized generation schemes exhibit major deficiencies in the sense that, since it relies in a single power supply, power shortages and bottlenecks often occur.[27] Accordingly, many works have debated on how centralized energy generation schemes cannot ensure reliable, nor sustainable and equitable energy access to people.[86,87] As an

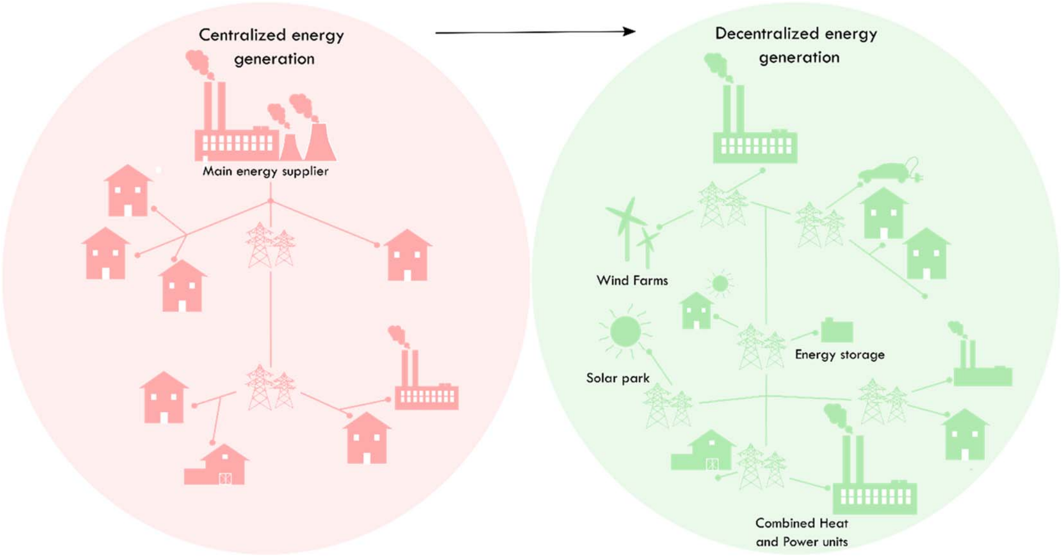

Fig. 2 The transition from centralized to decentralized energy generation paradigm.

example, we highlight that centralized energy systems usually "benefit the rich and bypass the poor and are underpowered, inefficient and unequal".[87]

In opposition to this standard paradigm, distribution energy schemes comprise more focused dispatch, especially encompassing small-scale conversion units that expedite power transmission to a smaller number of consumers. Moreover, decentralization also refers to "transferring authority, power resources, and responsibilities" from centralized operators to lower-level ones.[88] Accordingly, the major benefits of distributed generation is that it is able to provide enhanced energy and more democratized access, with improved reliably and efficiency. Furthermore, since security and resilience issues are easier to be addressed due to the local and reduced-order size of these schemes, decentralized schemes can also encourage "equity, inclusivity, information, accountability, and adaptability" of energy systems, which also work towards the mitigation of climate-related issues.[89]

The key disadvantage of the decentralized energy system is its low economic scale. The microeconomic benefits to the society from the decentralization could be detrimental macroeconomically. Societies seeking for decentralized energy infrastructure could end up with higher consumption compared to their contribution to the cost of the infrastructure. If the energy generation cost is lower than the energy price in many countries, the decentralized infrastructure might be effective. If the participating players in the decentralized energy infrastructure have a small impact with high energy demand, the decentralization is the most attractive option. It can be further analyzed by accessing the effect on the partial or fully decentralized beneficiaries. However, there is a need to analyze the optimum degree of decentralization to address the energy policy and associated integration costs challenges.

Recent technology developments can enable a renewable, affordable, and eco-friendly energy grid if established using proper energy planning, supervision tools, and enforcement policies. The intermittent nature of the current renewable energy carriers when operated using standalone generation units induce fluctuations and variability in the energy outlet quality. When multiple renewable energy carriers are plugged into a microgrid as the core generation sources, their intermittent behavior is overlapped. The smart grid can compensate for the power fluctuations by the use of storage units and demand-side management operations.[90] The concept of microgrids or smart-grids enables decentralized generation with multiple renewable carriers. Microgrids, as introduced by Lasseter[91] and discussed in other works,[92–94] are self-contained structures that comprise energy generation, storage, and distribution devices, subject to variable demand loads. They can operate in island mode (supplying local neighborhood needs), or connected to the grid (to exchange energy to nearby areas, for instance). Moreover, the microgrid tool is essentially linked to the idea of available measurements of all power inlets, outlets, and flows, using a variety of sensors. The core idea of building energy units as microgrids are to use all possible renewable generation and store it when there are lower demand periods. The stored energy can then be further utilized when demand is higher than renewable production.

The use of a decentralized smart-grid paradigm ensures a drastic reduction of distribution costs. However, complementary technologies must be employed to reduce the production costs and maximize the energy production capacity efficiently, the two major challenges of SDG 7. Two important technologies tackle these challenges, the Energy Hubs modeling concept, and the use of automatic optimization-based controllers. They define the coordination policies within these microgrids (as when to store energy or when to dispatch it to meet demands), also known as "Energy Management Systems" (EMS). To define adequate coordination rules for microgrids leading to guaranteeing maximal generation and optimal efficiency, advanced mathematical models are required. The high-fidelity dynamic models are the preliminary requirement of any automation system, such as these optimal EMS. The Energy Hubs concept by Geidl *et al.*[95,96] provides a framework that offers mathematical rigor and standards to characterize the dynamics of multi-carrier microgrids. The Energy Hub considers a unified energy generation unit, called a "hub", which comprises the transformation, conversion, and storage of various forms of energy and combined transportation of different energy carriers in single transmission interconnectors.[20,97–101]

The final major technology that is needed to face the mentioned challenges is the use of automatic optimal EMS. The engineering behind smart-grid technologies allows to naturally achieve more efficient use of locally available energy sources. The EMS-based units can "shift" electric load demands to the period when the intermittent renewables are unavailable, employing intermediate storage units. Based on Energy Hubs models, optimization techniques, such as Model Predictive Control (MPC)[98,101] have been shown the best possible energy efficiency and the maximized dispatch of renewable-based microgrids under regular operation conditions and stochastic demands and loads.[102] MPC as the framework to formulate these EMS is an elegant solution with high-quality results and a computational burden. This technology is applied in many situations for the problem of efficient operation, satisfying a time-varying request, and operational constraints. The overall problem is formulated using either Mixed-Integer Linear Programming (MILP) or Quadratic Programming (QP). MILP and QP are solved efficiently by most commercial solvers without resorting to complex heuristics or decompositions techniques. Illustrative examples of the effectiveness of MPC in the management of renewable smart-grids can be referred to from the previous application-oriented MPC works.[97–105] The adequate operation of EMS depends on the availability of prediction curves for renewable sources. For instance, when coordinating a solar-power based microgrid, local solar irradiance data is necessary within a span of a few hours ahead, so that the EMS knows when the microgrid should store energy (excessive sun power available) and when to use it from the storage (cloudy period, nighttime). For instance, a study by Neupane *et al.* has shown the potential and the necessary data on solar and wind energy outputs at Nepal.[106] It was reported that about 47 628 MW and 1686 MW of solar and wind energies could be harvested in Nepal across a large share of provinces with minimal energy fluctuation. These enable an efficient decentralized solar and wind energy generation in Nepal at provincial level. Further, AI tools are available to make these predictions using time series for the vast majority of cases (sun forecast, wind forecast, *etc.*).[107]

In decentralized energy generation operations, many different agents play the role of the central power plant of the previous paradigm: local industries may produce energy from excédent bio-sources,[108] households may produce excédent energy with solar PVs,[109] buildings with large thermal storage[110] can inject heat demands to compensate for electric energy usage. The issues that arise, thus, in this decentralized generation scenario are (a) coordination, cooperation, and integration of the decentralized generation units, and (b) privacy and security concerns. The available literature digresses on the topic of integration of the decentralized paradigm through different available technologies, but majorly residing in central coordination schemes. To truly establish a healthy decentralized energy generation system, local energy markets must be regulated.[111] The central management systems must coordinate the operation on when and how each agent can inject energy into the decentralized network.[112] There are many results regarding this matter; the possibilities include barter-like energy sharing between neighborhoods with efficient results.[113] The microgrids of the same owner should cooperate which are interconnected by sharing electric energy and bio-sources through the decentralized solution.[108] They need to employ power exchange[114] for efficient results. The planning of which structure and solution to implement regarding the decentralization should be planned by local governments. There should be fair competition between the energy production and consumption agents and an optimal plan sizing for the local networks.

Once the decentralized energy paradigm is planned, the issue that remains is to ensure the privacy and security of the energy distribution operation. The literature points out one major technology regarding this issue, which is the use of blockchains. Blockchains enable a decrease in the costs of interconnecting distributed energy resources in the decentralized, transactive network paradigm. Blockchain is a ledger technology that allows multiple parties or agents to share a common database infrastructure where the central management system would operate.[115] The parties would exercise editorial control over the database where blockchain removes the intermediary necessity of transaction settlement systems and the decentralized generation network would be able to operate standalone. In addition, it blinds the network to malicious intentions for outside safety breaking.[85,116]

2.4 Challenge (iv): maximizing energy and energy storage efficiencies

Energy efficiency is the key to supporting economic and sustainable development while limiting or curbing the increase in energy consumption. Energy intensity indicates the energy usage by the global economy. According to data analysis from the International Energy Agency (IEA), there have been global improvements in primary energy intensity in the order of 1.4% to 2.9% from 2000 to 2015. However, the rate of improvement was significantly reduced in 2018 to 1.2%.[117] The main challenge to overcome is that the emerging and growing economic activities in emerging countries lead to a boost in energy demand. It is mainly due to step increases in industrial activities that boost energy demand and the need for reliable, cost-effective, mature conventional low-efficiency technologies. Economic growth also leads to changes in consumer behavior, which has been identified as a key driver for growth in energy demand: living in larger houses (more floor area per person), greater and wider use of appliances, higher appliance ownership, and other factors including population growth and access to new energy-intensive services. Higher standards of living might boost energy demand per person, which can overwhelm or significantly limit the benefits of using modern, energy-efficient technology.

The energy demand in India doubled from 2000 to 2017, yet energy efficiency prevented 6% of additional energy usage in 2017.[118] Likewise, the population and economic growth of Southeast Asia have led to a continuous increase in energy demand. It seems that it is well on track to achieve SDG 7 by 2030 when it comes to electricity access, even if about 45 million people have remote access and many of them use solid biomass as cooking fuel.[119] According to IEA, China has made significant improvements in energy efficiency from 2000 to 2017. Without such improvements, 12% more energy usage would have been required, being the main energy savings being obtained in the industry and service sectors.[120] In Africa, a key task toward SDG 7 achievement still clearly remains on providing access to affordable electricity. There are still around 600 million people who do not have access to electricity and around 900 people lack access to clean cooking. With the estimated population growth from 1.29 billion people to 2.1 billion by 2040, rising demand will challenge the achievement of SDG 7 goals. Yet, Africa has been a minor contributor to global energy-related cumulative GHG emissions (with around 2%). The case of Africa offers a unique opportunity for a different energy pathway for pursuing a less energy-intensive, more efficient, and cleaner energy system, with energy efficiency playing a central role.[121] A decentralized energy paradigm with smart grids seems to have potential benefits in Africa. However, it must be carefully assessed since systems thinking assessments have shown that implementation of mini-grids in regions of Africa might be more challenging than anticipated if its assessment is based only on technical considerations.[122]

Energy technologies are required across the entire energy conversion chain, and some of them might result in energy and cost savings. Yet, several barriers could prevent the widespread implementation of the technologies, such as economic viability, required payback, and realistic potential which requires taking into consideration of political, economic, and social dimensions during the implementation process. A technological solution that spurs from the digital revolution includes the optimization of energy systems using tools such as the Internet of Things (IoT) which enables real-time optimization, and smart grid technologies[112–115] across sectors and infrastructures along the

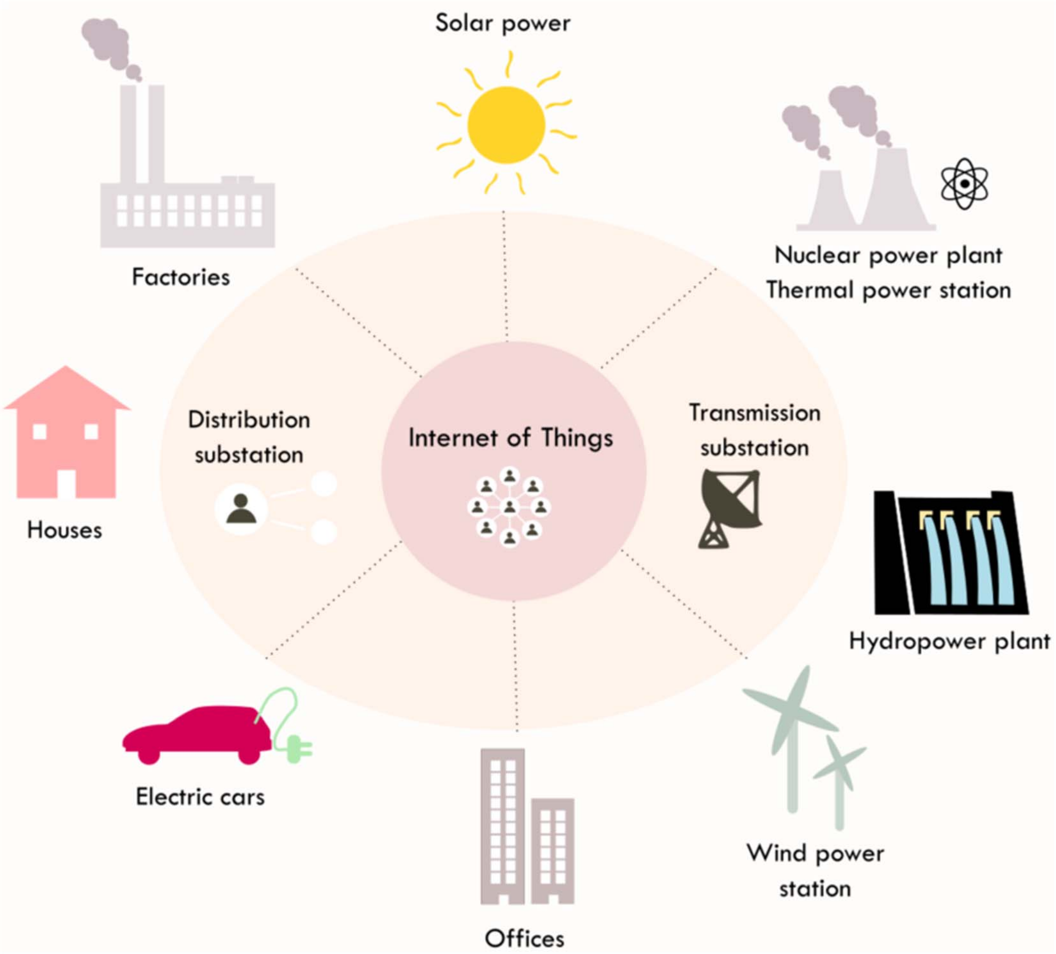

Fig. 3 IoT for maximizing energy and energy storage efficiencies.

energy chain and across regions.[116] International Telecommunication Union (ITU) defines IoT as "a global infrastructure for the information society, enabling advanced services by interconnecting things based on existing and evolving interoperable information and communication technologies".[123] For example, with an IoT-based smart energy platform, energy efficiency can be maximized by energy information collection, demand-side management, and energy sharing and transaction. IoT makes interconnection and integration between energy supply-delivery-utilization energy systems possible in the entire life cycle. Fig. 3 shows IoT connecting transmission, distribution, generation, power consumers, operations, markets, and service providers in a secure manner which shows the critical role in improving energy and energy storage efficiencies.

2.5 Challenge (v): minimizing energy generation costs of chemical processes

The chemical industry is one of the major industries with the highest energy expenditure. Its energy intensive processes often require energy in various forms for material pre-treatment, conversion, storage and recovery. Thus, it is crucial to design simpler and greener processes or materials to minimize their energy expenditure without compromising the process performances.[124,125] At present, the chemical industry is still heavily reliant on fossil fuels as energy and material sources. Thus, an increasingly available supply of low-cost renewable energy derived from solar and wind holds the promise to decarbonize the chemical industry (Fig. 4). This approach would revolutionize the chemical industry and play a crucial role to diminish the carbon footprint of chemical production. A complete overhaul of the time-tested and commercially relevant processes would not make much feasible economic sense. Thus, the first step in this direction should be the identification of the important target chemicals with significant contributions to the energy-carbon equation and that could be further transformed into economically viable final products.[126,127] Preliminary *in silico* studies on the properties of fine chemicals should also be used as a supplementary tool to streamline the commercialization of desired chemical syntheses.[128–139] The top five chemicals with the highest energy expenditures are methanol, ethylene, ammonia, propylene, and benzene/toluene/xylene mixture. These important feedstock chemicals *en route* to other fine chemicals and commodities.

An important example is ammonia, which is essential for the production of hydrazine, phenol, nitric acid, and urea; which in

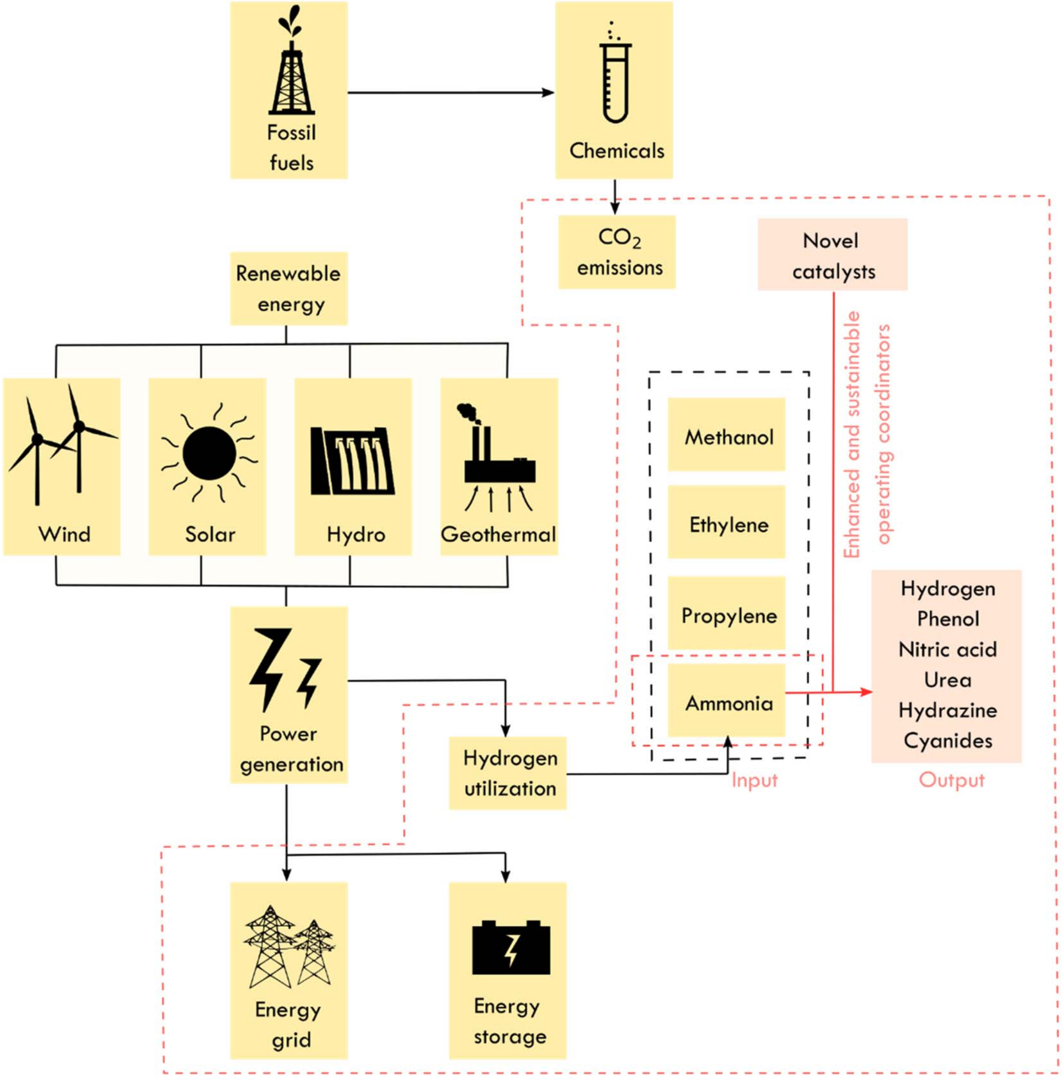

Fig. 4 Roadmap to chemical industry decarbonization.

turn, is employed for the synthesis of fertilizers, detergents, pharmaceuticals, and plastics. At present, there are more options to be considered to optimize the Haber–Bosch process towards a greener route to minimize the use of fossil fuels and reduce carbon emissions. To reduce these harmful effects and yield massive rewards both in terms of economic and environmental benefits, there is great interest in the development of small-scale local ammonia production plants. The energy required is based on renewable hydrogen generated from the water *via* electrolysis and powered by sustainable electricity sources such as wind energy.[140,141] In such a context, it is necessary to develop novel ammonia synthesis or reductive catalysts.[142] These catalyst technologies are to be active under less severe operating conditions, appropriate to smaller-scale reactors, and could be practiced in the global south. By addressing its catalyst component, many of the problems associated with the process can be solved or could contribute to a greater solution.

Power-to-X (P2X) concept could be broadly defined as an umbrella term incorporating various means to convert primary energy (especially derived from renewables) into an energy carrier (*e.g.*, hydrogen), heating, cooling, or new products. This concept is considered to be a viable means for efficient utilization of excess renewables using existing infrastructure and has recently found considerable policy favor and investment support. For example, the Power-to-X alliance in Germany has committed over EUR 1.1 billion to invest in green energy carriers, hydrogen, and methane. The two major sources of GHGs during the synthesis of chemicals are the burning of fossil fuels to generate high reaction temperatures and the production of important feedstock like hydrogen, which is still mostly derived by steam reforming.

Herein, the most important P2X approaches which are fundamental to the decarbonization of the chemical industry are discussed. The bulk of the heating requirements in the modern chemical industries is still met with fossil fuels. As an alternative, the excess renewable energy may be used to generate heat *via* electric boilers or heat pumps. This heat will then be transferred using the surrounding vectors such as air/water to the buildings which is one of the P2X strategies: power-to-heat. The heat pumps could also be used to manage the demand-supply paradigm of renewable electricity generation by load transfer and/or peak shaving. For example, in 2014 the Inner Mongolia Autonomous Region in China has an installed wind-power capacity of 22.3 GW which however suffered about 15% curtailment losses by 2015 due to poor transmission.[143] To mitigate this issue, electric boilers with a capacity of 50 MW are planned to be installed by the end of 2020. Once completed, the heat derived from the excess electricity would provide for about 3% of the heating requirements of the district. Another example is the Swedish company of Vattenfall which installed three power-to-heat units in 2019 with a combined capacity of 120 MW in Berlin. They would harness excess energy from wind to heat water for 60 000 residences. This facility is poised to replace the existing 330 MWh coal-fired plant thereby reducing fossil fuel consumption.

Power-to-hydrogen is also another P2X strategy. Hydrogen is an important energy vector with a very high calorific value of 150 kJ g^{-1}. The vision of a "hydrogen economy" that is built on hydrogen as an energy vector has been around for a long time, but has never gained much traction due to how it was produced and the obvious cost disadvantage vis-à-vis fossil fuels. However, in the face of abundant renewable electricity, there has been a renewed interest in this direction. The most promising approach is that of electrocatalytic water splitting which uses renewable electricity to "break" water into its constituents, H_2 and O_2.[144] Three existing water electrolyzer technologies are differentiated by the electrolyte used, namely alkaline water electrolysis,[145,146] polymer electrolyte membrane electrolysis,[147] and solid oxide electrolysis.[148,149] The H_2 and O_2 produced from these technologies can be used as cleaner fuel sources to reduce the carbon footprint and improve the sustainability of energy generation industries. In addition, the high purity H_2 produced in this manner is also a potential precursor source for various value-added chemicals in chemical industries.

3. Conclusion

In an era with rapid technological advancements, energy sustainability presents itself as an important aspect in securing a renewable, affordable, and eco-friendly energy future. Against this backdrop, SDG 7 which is Affordable and Clean Energy is the present goal strived by countries worldwide following the 2030 agenda set forth by United Nations. This work has discussed the five main challenges in SDG 7 attainment by the year 2030 in the Global South context. The challenge of phasing out the use of fossil fuels is possible with the advent of numerous renewable energy sources and policies. With the help of microgrids, fluctuations of renewable energy can be compensated through the harnessing of multiple energy sources and types at the same time. The challenge of migrating towards a diversified renewable energy matrix remains an insurmountable task in the Global South context. This challenge also reveals a deep-seated problem in Global South on their heavy reliance on non-renewable energy sources for energy and economic security. The challenge of decentralization of energy generation and distribution could be overcome through the use of multiple renewable energy sources in tandem with microgrid and blockchain technologies. As for the last two challenges of maximizing energy and energy storage efficiencies; reducing energy generation costs of chemical processes, much of the present efforts are placed on the development of decarbonization technologies. These in turn provide a cleaner energy source that is of higher efficiencies. All in all, the realization of SDG 7 whether partially or in full is not impossible within Global South and global contexts, only if existing technologies are fully implemented with the necessary international and national policies.

Author contributions

Andrew Ng Kay Lup (lead): writing – original draft, conceptualization, data curation, writing – review & editing, supervision. Vikram Soni (equal): writing – original draft, conceptualization, data curation, writing – review & editing, supervision. Benjamin Keenan: writing – original draft, data curation. Jaewon Son: writing – original draft, data curation. Mohammed Ramezani Taghartapeh: writing – original draft, data curation. Marcelo Menezes Morato: writing – review & editing. Yalinu Poya: writing – review & editing. Rubén M. Montañés: writing – review & editing.

Conflicts of interest

The authors declare no conflict of interest.

Abbreviations

SDG	Sustainable Development Goal
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
CCS	Carbon capture and sequestration
DOGGR	Division of Oil, Gas, and Geothermal Resources
CDM	Clean Development Mechanism
NAPCC	National Action Plan on Climate Change
GBI	Generation-Based Incentive
AD	Accelerated Depreciation
EMS	Energy Management Systems
MPC	Model Predictive Control
MILP	Mixed-Integer Linear Programming
QP	Quadratic Programming
IEA	International Energy Agency
IoT	Internet of Things
ITU	International Telecommunication Union
P2X	Power-to-X

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