Global Renewable Energy Transition: A Multidisciplinary Analysis of Emerging Computing Technologies, Socio-Economic Impacts, and Policy Imperatives

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Abstract: The advent of the fourth industrial revolution takes along progressive and exponential digital transformation. This study presents an overview of policies, best practices and regional strategies that supports renewable energy adoption around the globe. The transition to 100% renewable energy requires political support, innovation in both technology and policy, and efficient governance. However, it has been analysed through extensive literature review that previous measures have significantly reduced renewable energy costs through technological advancements, market expansion, and economies of scale. To further increase renewable energy adoption across all sectors, financial incentives, concrete support schemes, intervention of advanced computing, market designs and robust business models are essential. Defining clear short and long-term goals for energy system transition is a critical first step, providing the regulatory stability necessary for both public authorities and private operators to ensure a successful transition. This study contributes to the trends, socio-technical perspective, challenges of conventional energy systems and identifying the contemporary digital technologies in the renewable energy transition. The technologies involved in achieving 100% seamless integration of renewable energy in the paradigm of smart grid and super smart grid include cyber-physical systems, Internet of things, metaverse, cloud computing and big data along with the other tools. Energy storage options and hydrogen storage are also discussed in this study and further explored the role of digital technologies in energy storage for an ultimate transition.

Keywords: energy transition; digital technologies; transition policies; smart grid; renewable energy

1. Introduction

Transitions as large-scale transformations within societal subsystems provide a framework for understanding the long-term processes involving significant upheaval to new configurations and the engagement of multi-stakeholders. In transition studies, these mechanisms are often viewed through a normative lens, particularly concerning sustainability [1,2]. For example, energy transitions advocates to address various challenges in the energy sector, including fossil fuel resource depletion, associated high cost, greenhouse gas emissions (GHG) and energy poverty [3]. The transition to a 100% renewable energy (RE) system represents a pivotal shift in the global energy landscape, driven by the urgent need to mitigate these challenges. As the world grapples with the environmental and economic impacts of conventional energy sources, RE has emerged as a viable and sustainable alternative [4,5]. Other than environmental hazardous, the high dependence on fossil fuels have led to their depletion, which constrained its effective use in other sectors of society.

Urgent climate action is necessary, as highlighted by the "IPCC's Special Report on 1.5°C global warming", which indicates that climate change effects are more severe than previously anticipated [6]. In 2017, human activities had caused approximately a 1°C rise above pre-industrial levels, which lead to significant climate-related consequences. Therefore, immediate action is required. The 2015 Paris Agreement sets forth global goals to balance anthropogenic emissions and GHG removals by the end of this century.

Through Nationally Determined Contributions (NDC) countries pledge to strive for climate actions every five years [7,8]. Achieving this target depends on managing total cumulative emissions, as stabilizing atmospheric GHG levels would result in continued warming [9]. Contrary to the agreement, the global carbon emissions started growing in merely three years [10]. In this respect, the role of important actors like Europe, United States and China needs to be closely monitored for actions and policies as they are responsible for 50% global emission. Hence, it has been seen that governments and policymakers have started developing policies which are oriented towards RE adoption [11,12].

The emerging "green growth" concept states that sustained economic growth can align with effective environmental measures through technological innovation and substitution, leading to the decoupling of gross domestic product from resource utilization and CO_2 emissions [13]. Governments can expedite this process through the implementation of appropriate policy regulations and incentives. For this reason, the European Green Deal explicitly targets the decoupling of resource use from economic growth by the year 2050.

Energy consumption accounts for the majority of anthropogenic GHG emissions, contributing 75.6% (37.6 GtCO2e) globally. For the energy sector, heat and electricity generation are the leading sources, producing 15.8 GtCO2e in 2019, or 31.8% of total emissions. Therefore, in recent years, the focus on RE has predominantly centred on the electricity sector. However, a holistic approach encompassing all sectors of the energy system is essential for achieving a complete transition. While numerous studies have analysed the final state of 100% RE systems, understanding the pathways and strategies required to reach this target have gained much attention. This review paper addresses both the end state and the transitional processes, offering insights into the diverse approaches being undertaken worldwide. Global energy forecast in present in Table 1 [14]. The drivers of energy transition discusses in this review are given in Figure 1.

Table 1. Global energy status forecast.

Parameter	Unit	FY 2030	FY 2040

Total CO_2 emissions	$MtCO_2$	38,177	39,549
Total primary energy consumption	Mtoe	15,867	17,487
Total final energy consumption	Mtoe	11,308	11,775
Final demand of electricity	TWh	31,907	35,407
Installed electrical capacity	GW	10,087	12,420
RE share in power generation	%	32.8	37.1

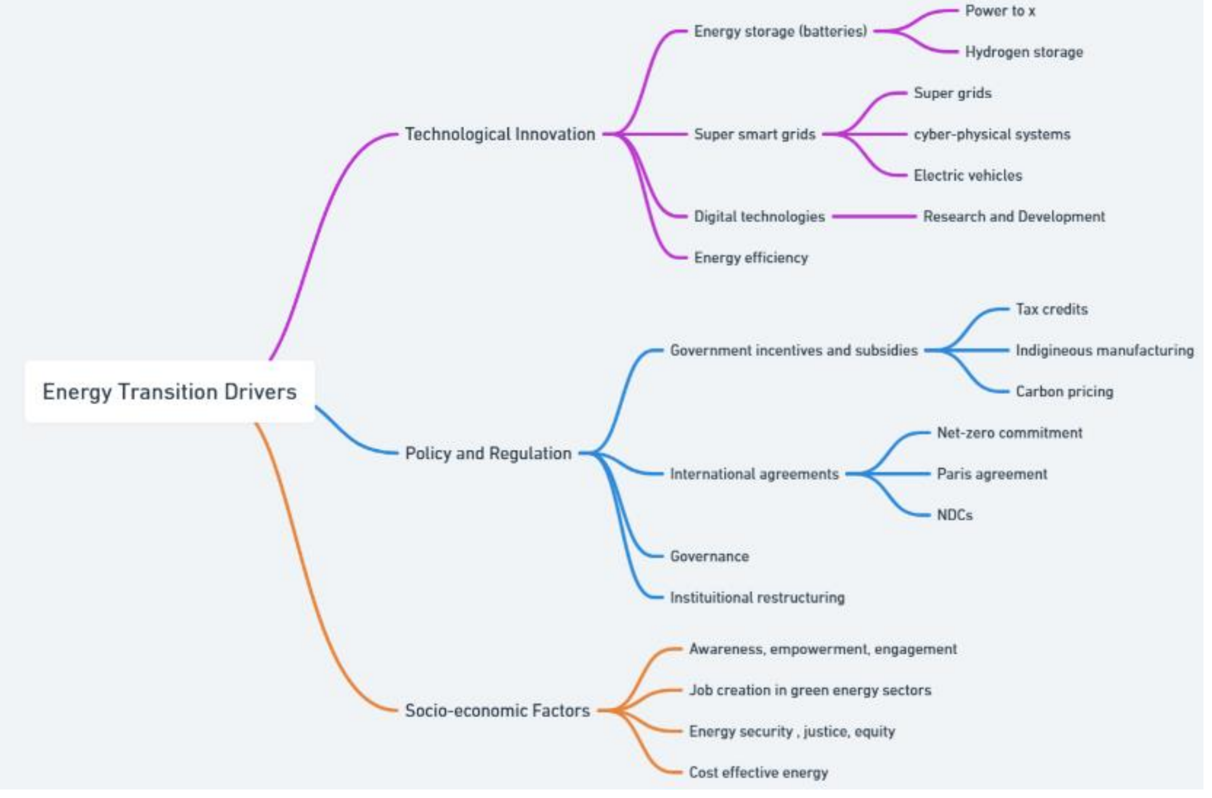


Figure 1. Drivers of energy transition

1.1. Socio-technical perspective

As eliminating emissions necessitates essential innovation; the rapid dissemination of innovative technologies, and the transformation of socioeconomic systems and markets [15]. This involves measures that vary from a carbon price adjustment to adopting ambitious emissions targets. They also include a more targeted, proactive, and strategic policy narrative is essential to reconfigure technologies, business models, infrastructure, and markets across all greenhouse gas-emitting sectors. Crucially, this approach recognizes that the shift to a low-carbon economy is not solely a technological or economic endeavour, but also a social transformation [16]. New technologies can emerge and spread within economic sectors or systems, ultimately reshaping the associated social and economic activities. Digitalization [17] can enable more energy-efficient lifestyles but may also lead to rebound effects in energy consumption. By 2050, a society embracing digital practices could use 10–20% less energy compared to one with 2020-level digitalization [18].

Coordinated international action, aligned with the transformation can expedite the transition by rapidly recognizing potential technologies [19], enhancing investment incentives, achieving economies of scale, and ensuring competitive fairness so early movers are not disadvantaged. Although formal climate diplomacy is organized around countries, the primary focus for both industry and governments must be on coordinating sectoral or system-wide actions [20]. Greater efforts are required to align the interest of stakeholders in each sector to meet the goals of the Paris Agreement. Figure 2 presents the low-carbon transition function policies and associated effects [15].

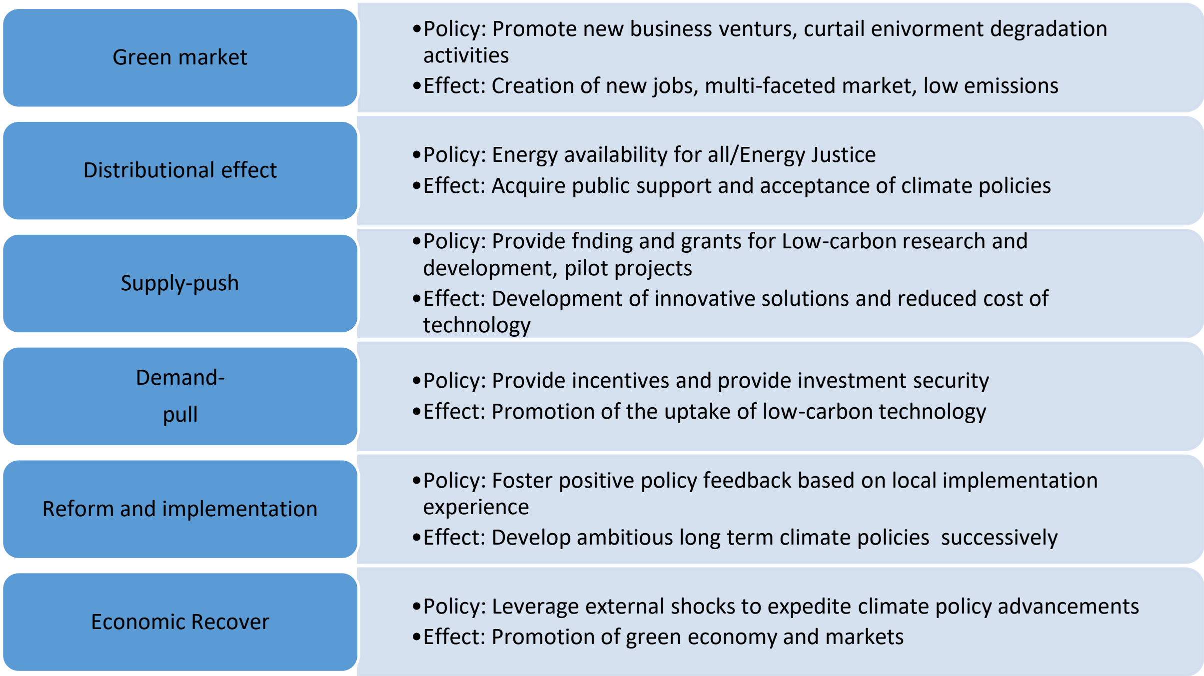


Figure 2. Low-carbon transition function policies and associated effects.

.Regarding technical perspective, the conventional energy networks are now transforming into community based energy systems with enhanced consumer's participation, information and data sharing as well as cross-business cooperation. They are deeply rooted in stakeholders active participation with decentralised and independent decision making. These transitioned systems are driven by RE due to being decentralised and locally available and digital technologies such as Multi-agent systems (MAS) [21].

This comprehensive survey aims to provide a detailed overview of the current status and challenges associated with the transformation to a fully renewable energy system across the globe. Many articles on energy transition predominantly centred on the electricity sector. Nevertheless, a growing number of studies are adopting a cross-sectoral holistic approach to the whole energy system [22]. While most research examines energy systems in their ultimate 100% renewable state, an increasing number also explore the pathways to achieving this target. Europe, US and Australia, are well-studied, whereas other regions lag behind and there is a significant emphasis on studies of individual countries. Therefore, it is essential to adopt a cross-sectoral holistic approach and coordinate individual country studies within the global context. The objective of this survey is to synthesize the existing body of knowledge, identify key challenges, and highlight best practices in the transition to 100% RE systems. By doing so, it seeks to contribute to support policymakers, researchers, and stakeholders in their efforts to accelerate the global RE transition. Table 2 presents the comparison of this study with available literature on the topic.

An extensive review of the literature revels that a sustainable RE transition requires an inclusive approach that involves sustainable investment in infrastructure, swift policy reforms and innovative technology, improvements in governance and management, high quality research and development, diversification in the RE mix, and efforts to enhance energy efficiency and conservation [23,24]. Such transition can only be effective if supported by well-established and thoroughly investigated RE policy. It can create a robust energy supply-demand system that ensures reliability, affordability, and sustainability for the region, thus enhancing energy security. This will help achieve climate mitigation targets as well as improve the socio-economic situation of the masses.

Table 2. Comparison with existing literature.

Reference	Global Energy Transition	Grid Modernization	Global Status	Challenges	Policy perspective	Digital Technologies
[25]	✓	✓	✗	✗	✗	✓
[26]	✗	✓	✗	✓	✗	✓
[27]	✗	✓	✗	✓	✗	✓
[28]	✗	✓	✗	✓	✗	✓
[14]	✓	✗	✓	✗	✓	✗
[29]	✗	✓	✗	✗	✗	✓
This study	✓	✓	✓	✓	✓	✓

2. Global status of RE transition

Regions such as Europe, the United States, and Australia have made significant strides in RE research and implementation. The significant progress in transitioning to clean energy is the result of cumulative actions by numerous countries worldwide. Early research and development support from the US and Japan, deployment incentives in Europe, and substantial production investments by China have collectively led to dramatic cost reductions, particularly in solar energy modules, which have decreased by a factor of 3,000 over the past 60 years [30]. While the transition in the power sector is now marked by competition among countries and businesses to lead in supplying global markets with zero-emission technologies, there are still opportunities for coordinated efforts to further accelerate progress. Yet, other parts of the world still lag behind, often due to socio-economic, technological, and policy-related challenges.

The share of RE in electricity generation rise to about 30% in 2021 from 20% in 2011 having hydropower as the biggest share. This makes the fastest year-on-year growth of 8% (8300 TWh) [31]. Accordingly, it is estimated that RE share in global electricity should be 90% until 2050, similar to Iceland where electricity solely comes from RE sources. In 2021, the investment on RE based power generation is 70% of the total spent on all new generation capacity, which is USD 530 Billion. This results in massive decline in the cost of electricity from solar i.e. 85% lower in 2020 as compared to 2010. Similarly, cost of wind energy fell down by 48% for offshore and 56% for onshore projects [32].

According to International Energy Agency (IEA), an estimated annual investment of $4 trillion in RE technology and infrastructure is needed by 2030 [33]. About 70% of this investment comes through private sector driven by government policies and price signals. In contrast, plummeting pollution and climate change effects could save up to $4.2 trillion annually [34]. Additionally, transitioning to a low-carbon economy could result in economic benefits of at least $26 trillion by 2030. It is projected that electricity generation from RE must be twice within next few years and RE investments needs to be triple by 2050 to achieve net-zero emission targets [35].

A study on G20 countries, the authors have seen a noticeably decreasing trend in levelized cost of energy (LCOE) until year 2030 for RE power generation. The lowest LCOE (€/MWh) for various RE technologies include 16 to 90 for onshore wind, 16 to 117 for utility solar photovoltaic (PV), 31 to 126 for rooftop solar, 64 to 135 for offshore wind. Solar PV systems with batteries have competitive LCOE ranging from 21 to 165 and 40 to 204 at utility and residential sector respectively [36]. In contrast to nuclear power generation and fossil fuel based generation, the RE based LCOE is economical, thus driving the RE transition.

Between 2015 and 2022, China and other advanced economies were responsible for more than 95% of global heat pump and electric vehicles sales and nearly 85% of the growth in solar and wind capacity expansions. Meanwhile, clean energy investment in other regions has remained largely unchanged in real terms since 2015. To achieve the goals of the net-zero emission scenario, investment in these areas would need to increase by more than six times over the next decade [37]. However, several challenges, including restrictive fiscal and financial conditions, large amount of government debt, and the elevated capital cost for green energy projects, hinder this progress. Addressing these challanges will require stronger domestic policies and greater international support and attract large-scale private capital. Among these challenges, the most crucial task is to improve risk-adjusted returns through more concessional funding.

The world energy outlook discuss three scenarios to estimate the rise of electricity generation from low emission resources, thereby enabling both advanced and developing countries to lower their dependence on fossil fuels. The global share of electric power production from these sources increase from 39% in 2022 to 80% in 2050 in case of Stated Policies Scenario (STEPS), more than 90% in Announced Pledges Scenario (APS) and almost 100% in Net-zero Scenario (NZE). In STEPS, RE produced 30% of global electricity in 2022, which would be increased to 50% by 2030.

The framework strategy of European Commission is to create an Energy Union focused on enhancing economic competitiveness, energy security and sustainability. This union seeks to foster cooperation among Member States by pooling and diversifying energy resources, strengthening transmission interconnections, integrating energy markets. Two key governance issues have emerged, including the necessary level of interconnection required to achieve these objectives. In July 2018, France, Spain, and Portugal agreed on the strategic importance of interconnections in Europe. These interconnections aim to enhance value, support commitments under the Paris Agreement [38].

The proposed approach integrates the decentralized smart grid with the centralized super grid, forming a super smart grid [29,39], which are complementary and essential technologies for a transition to a decarbonized economy [40]. This vision aligns with the notion that potential for energy cooperation already exist within Europe and such macro-regional collaborations can facilitate deployment of smart grids with cost optimization, RE, and energy efficiency. Therefore, energy system can be viewed from the perspectives of individual prosumers, national frameworks, macro-regional collaborations and partnership, and the pan-European context [41–43]. Moreover, appropriate policies should be developed to support these comprehensive energy system visions such as those presented in Table 3. Figure 3 and Figure 4 shows the growth of solar and wind around the globe [44].

Table 3. Overview of global policies and their distinct features for maximizing RE adoption.

Policies	Highlights
United States	
• Inflation Reduction Act[45] • Updated Nationally Determined Contributions (NDCs) [46] • State-level clean electricity targets [47] • Zero emissions vehicles (ZEV) targets [48] • Bipartisan Infrastructure Investment and Jobs Act [49] • Fuel Economy Standards [50]	• Allocates USD 370 billion for climate change and energy security` • Allocates USD 190 billion investment for clean energy • Aim to reduce carbon emissions by 52% till 2030 and reach net-zero by 2050. • 100% clean electricity by 2050 in 22 states • Improving fuel efficiency in vehicles and increase the deployment of heavy and medium duty ZEVs.
The Caribbean and Latin America	
• Net zero emissions (NZ) targets [51] • Access Targets • NDCs [52] • Hydrogen Strategy [53] • Zero Emission Vehicle Policy [54]	• 16 out of 33 countries follows NZ policy • NDCs are submitted by all 33 countries • Hydrogen Strategy is in place • 24 from 33 countries achieved 95% electricity access rate • 16 countries follow zero emission vehicles policy
European Union	
• Fit for 55 [55,56] • Sustainable recovery [57] • REPowerEU [58] • Net Zero Industry Act [59] [60] • EU Taxonomy [61]	• Electricity market design, rules for single energy market, European Green Deal • Emission reduction targets for vehicles and buildings • With the support Energy Efficiency Directive, RE Directive and EU Emissions Trading System reform • Development of taxonomy for sustainable investment
Africa	
• Just Energy Transition Partnership [62,63]	• Rapid adoption of RE in power sector of South Africa and Senegal

• Electricity Access Policy [64] • Net zero emission targets [65,66]	• Aim to provide electricity to 300 million people by 2030 with investment opportunity of USD 9 billion. • 9 countries set to achieve zero emission target.

Table 3. Continue

Policies	**Highlights**
Middle East	
• Net-zero ambitions [67] • Hydrogen ambitions and partnerships [68,69] • UAE's updated NDCs [70]	• United Arab Emirates set target of 19% lower emissions in 2030 relative to 2019 levels. • UAE sets target to achieve 25% of global hydrogen markets. Also presented hydrogen leadership roadmap.
Eurasia	
• Azerbaijan and EU memorandum [71,72] • Russia: Strategy of socio-economic development [73] • Kazakhstan: Strategy on achieving carbon neutrality by 2060 [74]	• Aim to increase energy co-operation including gas pipeline capacity to EU by 2027 • Support reduction in venting and flaring of Methane • Reduce 80% GHG by 2050 and achieve net zero by 2060 • Achieve carbon neutrality by 2060 and decarbonisation among key sectors
China	
• Updated Nationally Determined Contribution [75] • 14th Five year Plan for Renewables [76] • Made in China 2025 [77] • New Energy Vehicle Industry Development Plan [78] • 14th Five year Plan for Energy • Carbon peaking and neutrality blueprint [79]	• Achieve carbon neutrality before 2060, reach 1200 GW of installed RE capacity by 2030 and lower CO_2 intensity of gross domestic product by 65% by 2030 [80] • Targets 3300 TWh installation of RE by 2025 and more than 50% of electricity consumption met by RE • Support innovation, green manufacturing, digitalisation, clean energy based vehicles • Retrofitting of buildings to be 20% more efficient by 2030 [81]
Southeast Asia	
• Net zero emissions • Just Energy Transition Partnership • ASEAN Plan for Action on Energy Cooperation and Power Grid [82,83]	• 8 out of 10 countries make commitment to net zero emission[84] • Just Energy Transition with Vietnam of USD 15.5 billion [85] and Indonesia of USD 20 billion [86] • Reduction of energy intensity by 32% and increase in RE to 23% by 2025
India	
• Net Zero Emissions by 2070 [87]	• Aim to achieve net zero emissions by 2070, 50% of electricity generation through non-fossil fuels, target of 500 GW of RE capacity

• RE and transmission targets [88] • Production incentives[89] • National Green Hydrogen Mission [90] • Carbon Markets [91]	• Increase transmission capacity to accommodate RE through Green Energy Corridor Project • Subsidies and incentives for manufacturing of solar modules and batteries • Increase hydrogen production capacity and generate its demand from industry • Law passed in 2022 to form carbon credit trading system and Indian Carbon Market

Table 3. Continue

Policies	Highlights
Japan	
• Basic Hydrogen Strategy • Green Transformation (GX) basic policy [92]	• Foster hydrogen supply chain with public and private investment of USD 98.8 billion in the next 15 years [93] • Achieve energy security, decarbonisation and economic growth. The investment of USD 1 trillion in coming 10 years[94] • Provide funding for RE research and development, wind cost reduction and transition.
Republic of Korea	
• 10th Basic Plan for Long-term Electricity Supply and Demand [95] • 1st National Basic Plan for Carbon Neutrality and Green Growth	• Increase RE share in power mix to 30.6% and reduce coal to 14.4% by 2036, increase RE generation capapcity to 204.4 TWh by 2036 [96,97] • Adjusted sectorial targets in 2023 NDC with 40% reduction in GHG levels from 2018 [98]

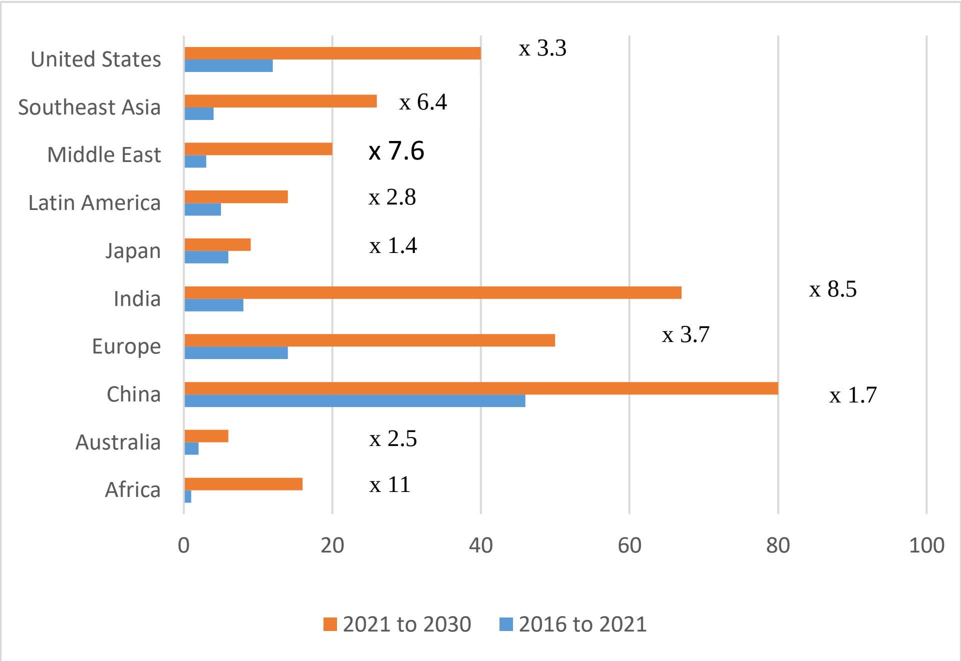


Figure 3. Average yearly installed capacity with accelerated required installation to meet the target by each country, 2016 to 2030.

Case Study: RE Transition in Germany

The German transition towards renewable energy technologies (RETs) from 1990 to 2016 laid the groundwork for the Energiewende policy. Initially stirred by the 1970s oil crises [99], German R&D in solar photovoltaics (PV) and wind faced limited deployment due to high costs and perceived poor performance. The 1991 Feed-In Law, mandating utilities to purchase RE electricity at 90% of the retail price, significantly boosted onshore wind deployment and expanded support for RE [100]. Despite initial challenges, including insufficient Feed-In Tariffs (FiTs) for biogas and solar PV, advocacy from industrial firms, social and development welfares led to increased support in RE uptake.

The 2000 Renewable Energy Act (EEG) guaranteed fixed premium payments for over 20 years for power generation from RE, varying by technology maturity. In 1998, liberalization of the electricity sector and subsequent market concentration by the Big-4 utilities (RWE, Vattenfall, E.ON and EnBW) led to a focus on coal and gas plants rather than renewables [101]. However, between 2005 and 2011, the share of RE in electricity production increased twice from 10% to 20.1% [102], driven by substantial FiTs, declinig solar PV costs, and growing social interest. The solar industry's export sales surged from €273 million (in 2004) to almost €5 billion (in 2010). The rapid adoption of solar post-2006, despite Germany's limited solar resources, resulted in Germany accounting for nearly one-third of global PV capacity (in 2011). This act facilitated the social liberalization of the electricity sector by diverse stakeholders entering the market, while incumbent utilities remained minimally involved in RET deployment [15].

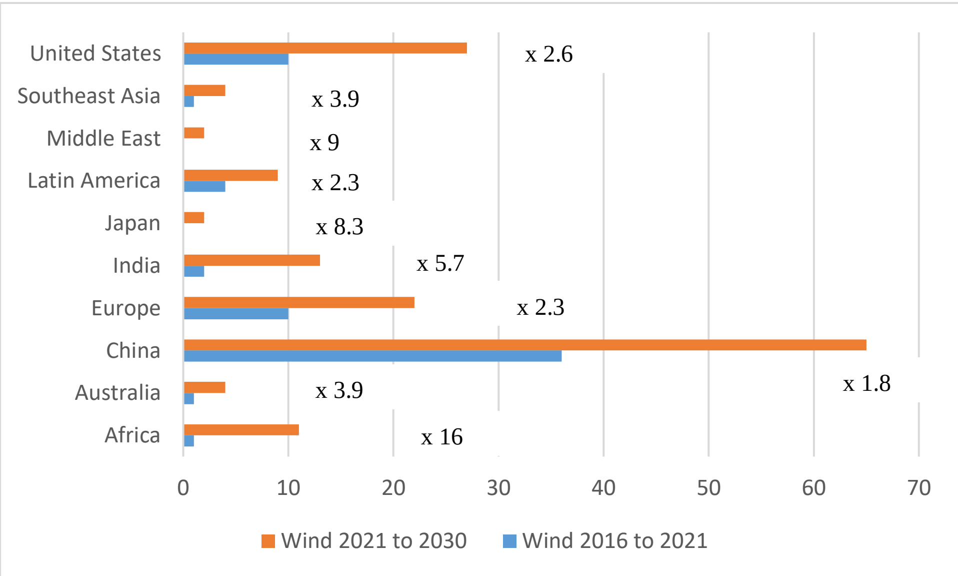


Figure 4. Average yearly installed capacity with accelerated required installation to meet the target by each country, 2016 to 2030.

Economic pressures from the global financial crisis, expanding renewables, and declining wholesale electricity prices post-2008 led to declining net incomes for utilities. By 2016, 29% of electricity generation was coming through RETs. The Fukushima accident in 2011 catalyzed the the phasing out of nuclear energy and the establishment of ambitious RE electricity targets under the Energiewende policy. Despite successes, the transition faced challenges, including the bankruptcy of German PV manufacturers due to Chinese competition, increased EEG surcharges leading to high retail electricity prices, political opposition to the surcharges, and grid stability issues due to intermittent renewables [103,104].

To integrate RE technologies into the market, policies such as demand-side management (DSM) and capacity markets were introduced [105], alongside the promotion of offshore wind deployment. These measures aimed to address the disruptions caused by the expansion of intermittent renewables, highlighting the need for flexible and adaptive policymaking in energy transitions. Consequently, the government made several adjustments to the EEG policy, including a substantial reduction in subsidies in 2012 and a shift to energy auction system to achieve target capacity by 2017.

Table 4. Measures for RE transition taken around the globe.

No.	Countries	Measures for RE transition
1.	California [47]	Mandatory RE portfolio standard, lowering of utility rates, tax credits for RE projects, consumer awareness programs, flexible policies of regulators e.g. consent for small PV projects, rebate program and net metering.
2.	Denmark [106]	Combination of carbon pricing, federal procurement programs, feed-in-tariffs, research and development subsidies, demand-side management (DSM) programs.
3.	Colombia [107]	Factor Susbidy, tax exemptions for green and energy efficiency projects, tax reduction on sale of RE power and exemption from value-added tax on imports of RETs. They also offers risk premium to incentivize the deployment of RETs in non-interconnected zones.
4.	India [108]	The government pays capital cost of 20% and 25% as an incentive for projects located inside and outside the special economic zone, respectively. Other schemes include 100% of real cost subsidy by the federal in case of inventive application of solar PV systems. Other measures include no excise duty for indigenous solar technology and Renewable Purchase Obligation (RPO)
5.	Japan [109]	Feed-in tariff (2012), special depreciation in tax credit. The Green Transformation (GX) Act and Hydrogen Basic Strategy, RE auctions, decarbonisation auctions. Feed-in-premium scheme (2022), investment opportunities in energy storage.

6.	Mexico [110]	Full incentive for taxpayers who invests in RET. Import and export tax exemption and a tax credit.

3. 100% RE transition challenges

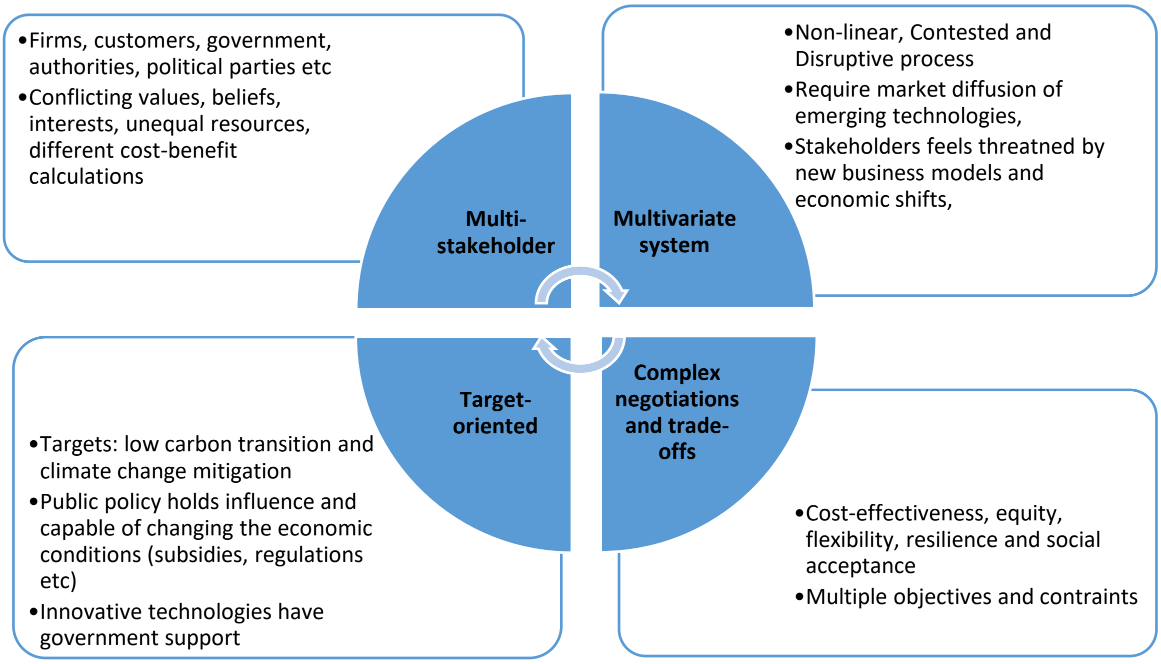
Between year 2013 and year 2016, G20 nations and the multilateral development banks they influence financed $38 billion in international coal projects, compared to only $25 billion in RE projects. While institutions like the World Bank, the European Bank for Reconstruction and Development, and the European Investment Bank are shifting away from funding new coal power, international investments still constitute the majority of the estimated $28 billion annually for coal power, predominantly provided by public finance institutions [111].

One of the challenges faced by Industry 4.0 is security and connectivity of different technologies, software solutions and infrastructures. Moreover, the transition has challenges on both demand and supply side. On supply side, the challenge is the acquisition of sustainable renewable energy and technologies in economical manner, while the demand side challenge is the energy efficiency and DSM [21].Another challenge faced by conventional power systems is the nonlinear load profiles and demand variations from short-term forecasting errors can lead to power network overloading. The situation worsens if a fault occurs in the power system, further exacerbating the overload [112]. The unpredictable demand response from consumers and the variability of RE sources make transient stability and load flow balancing difficult in power systems. These challenges are usually arise by the three-phase (L-L-L) faults instigated by power quality disturbances [113,114].

The common problems in conventional grids are the lack of real-time monitoring of the system and information granularity. The existing power grid faces significant challenges due to its limited and inefficient operations. Without effective energy storage or backup capacity, the grid relies on a just-in-time supply model, which is strained during peak load hours. This strain often leads to power outages, quality issues, and reduced reliability. To meet peak demand, fossil fuel based peak load plants are activated, but this approach is inefficient, uneconomical, and increasingly unsustainable as energy demands rise as a slight malfunction in such plants can lead to cascading shut down of entire grid. Additionally, the reliance on aging infrastructure and non-renewable resources exacerbates issues of resource scarcity and environmental impact. Utility companies recognize the need to modernize, shifting from dependence on an aging workforce's knowledge to leveraging advanced information management and automation systems [115–118].

Some peculiar issues faced by conventional power systems especially in developing countries due to high population. This include highly inefficient grid, which results in high transmission and distribution (T&D) losses as South Asia has 18.8%, highest average T&D losses. The grid capacity is constrained and cannot supply the load demand under baseload generation, thereby suffers from power outages. The high capital cost makes investors lend money has higher interest rate due to economic risk factors [119]. These challenges have forced countries to find alternate fuel technologies like RE technology that are flexible, robust, durable, readily available, and environment-friendly. It is equally important that such technologies can also sustain the long-term developmental policies and energy reforms. However, their adoption on high level also comes with challenges. Grids powered by solar energy face significant fluctuations in energy generation due to varying weather conditions, seasonal changes, and the diurnal cycle [120].

To ensure a stable energy supply during night-time, these grids require large rechargeable batteries, which necessitate additional recharging circuits, driving up production costs. Severe weather conditions can damage solar panels and turbine blades [121] thereby makes them



intermittent in nature. However, advanced control, communication and sensing technologies can greatly facilitate the integration of RETs into the grid. Figure 5 presents the socio-technical challenges in the way of RE transition [12].

A 100% RE system cannot depend solely on wind power, solar, and electric vehicles. The rapid expansion of these technologies must be supported by larger, more intelligent, reconfigurable and adaptable infrastructure. Also, the substantial amounts of low carbon fuels, and intelligent technologies for capturing and permanently storing or converting CO_2 into climate neutral fuels. Currently, these areas lack investment. In the Net Zero Emissions (NZE) Scenario, transmission and distribution (T&D) grids are expected to grow annually by around 2 million kilometers until 2030, alongside the installation of 30,000 to 50,000 kilometers of CO_2 pipelines and new hydrogen infrastructure.

Achieving this level of investment requires accelerated planning and permitting processes. Wide spread, modernized, fully autonomous, and cyber secure T&D grids are essential for

Figure 5. Socio-technical challenges in transition to RE technologies.

electricity security. Investment in system flexibility is crucial to avoid the risk of surplus wind power and solar PV when production exceeds demand. Meeting climate goals through RE transition presents a challenge, particularly for emerging markets and developing economies. While advanced economies and China have the financial resources to support clean energy projects, the main hurdles lie in policy and regulatory issues. For other emerging markets, however, the challenge is even greater; they need to increase their clean energy spending almost three times by 2030 if taken year 2022 as reference to stay on track [122] .

The global energy crisis has heightened concerns about the costs of transitioning to renewable energy. Countries are particularly worried about the added expenses required for clean energy such as the higher cost of EVs or heat pumps. While some clean technologies are already cost-competitive, others still need significant incentives to close the gap. Effective policy interventions, like subsidies or adjusting fossil fuel pricing, are crucial but must be carefully crafted. If there is large financial liability on government or if the households or industries face

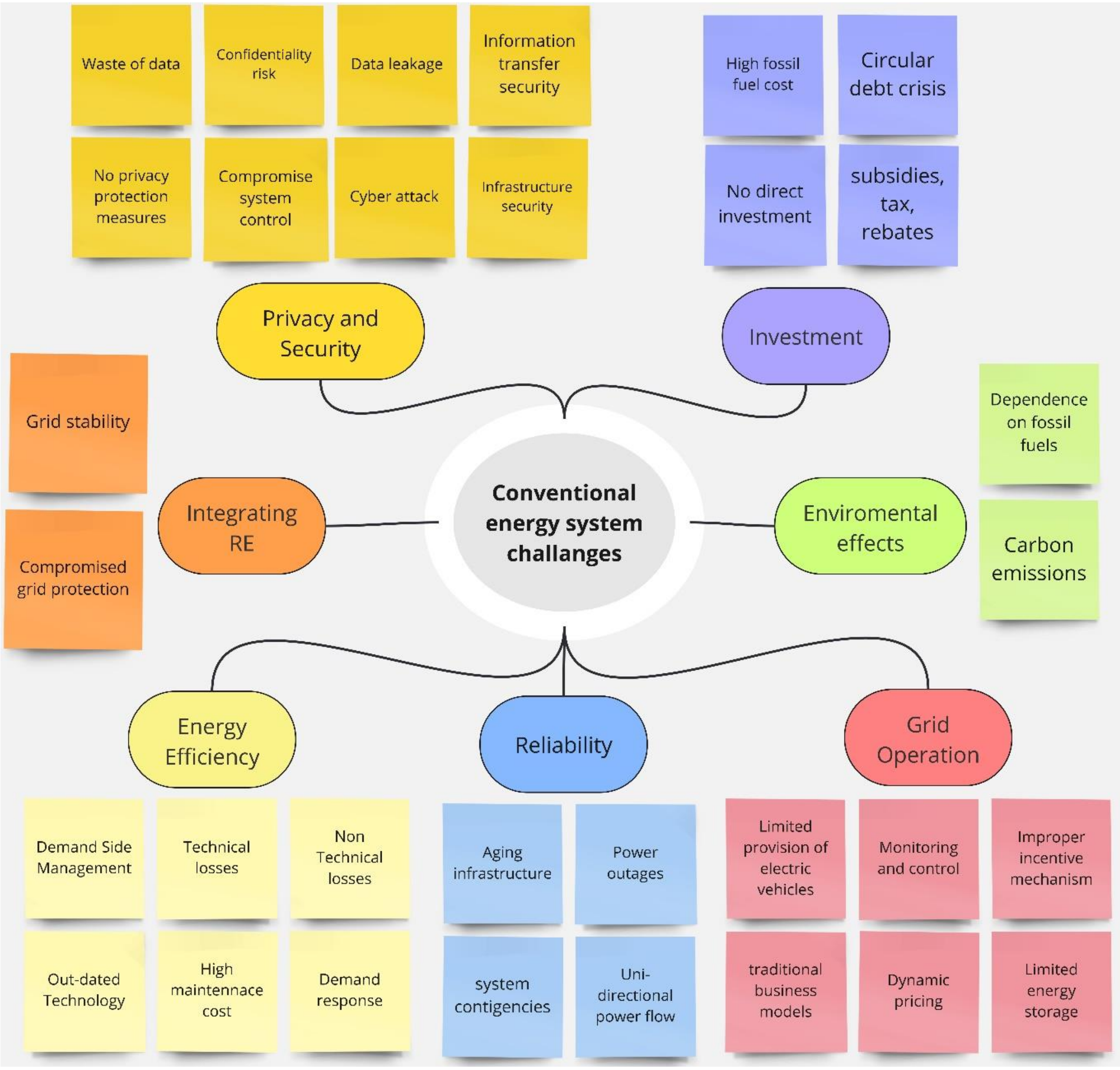


Figure 6. Multifaceted challenges of conventional energy systems

high upfront costs without immediate benefits, political support for the transition could wane. Figure 6 shows the multifaceted challenges of conventional energy systems.

4. Digital technologies as way forward

The fourth industrial revolution (Industry 4.0) is supported by digital technologies [123,124], particularly big data analytics [125], the energy sector is undergoing a profound digital transformation [126]. This transition is reshaping all segments of the energy supply chain; generation , transmission [127], consumption, and storage by introducing innovative business models [128] and presenting new scientific challenges. Digital technologies are playing a critical role in this transition, enabling capabilities such as detailed characterization of individual energy consumption patterns through smart home data and sophisticated, data-driven planning of regional energy systems [129]. Figure 7 presents the applications of digital technologies.

Digitalization is essential for facilitating the energy transition. By enabling the monitoring and recording of vast amounts of both real-time and static data [123,130], digital technologies empower timely decision-making for optimized operations, anomaly detection [131], DSM and more. Regular assessments of the progress and future prospects of energy system digitalization are crucial to ensure alignment with the ongoing energy transition. As the shift from high carbon based systems to net-zero energy systems progresses, characterized by structural changes and the integration of variable RE resources like wind and solar, the significance of digital technologies will become even more significant [132].

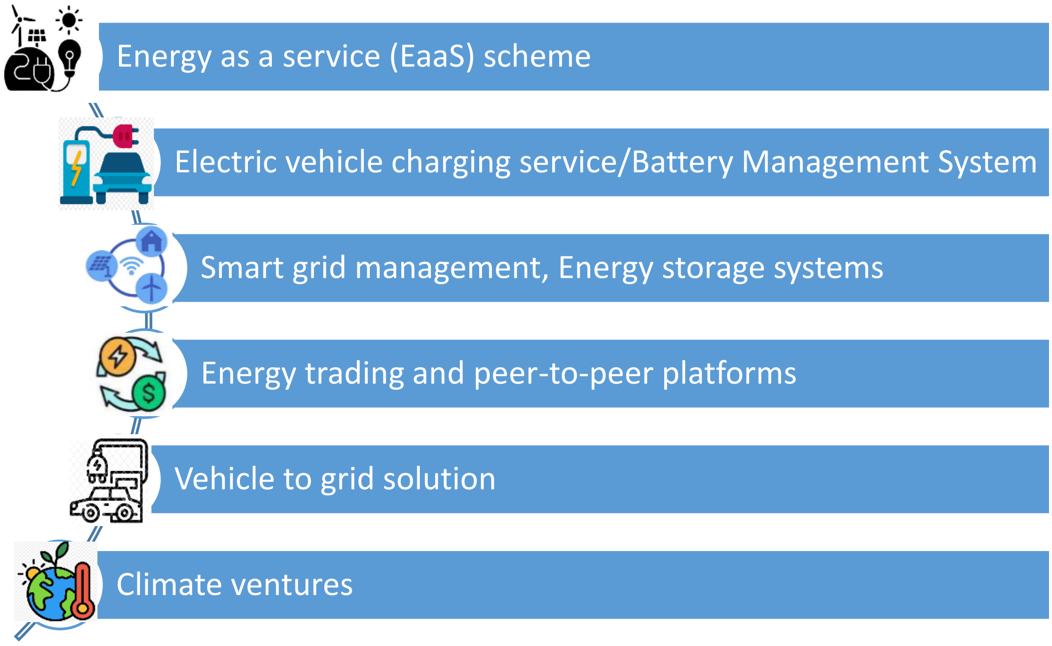


Figure 7. Application of digital technologies in 100% RE based system.

Early-stage venture capital investments in demand-side flexibility start-ups and energy efficiency have increased to approximately USD 900 million in 2020 [132]. This trend underscores the escalating role of digitalization in the impending energy landscape. By addressing common challenges to energy transition—such as limited access to finances, perceived risks, high upfront costs and lack of trust in new technologies— digitalization supported ventures are making clean energy solutions more affordable as well as accessible, thereby accelerating the energy transition.

4.1 Smart Grid and Super Smart Grids

Evolution of RE integration from microgrids [133] to smart grids and current super smart grids [134] is now driving the renewable energy transition and involve complex process engineering. The functions of real-time optimization, planning-scheduling and control theory [135] are pivotal for the efficient and reliable operation of energy systems in this paradigm. Leveraging modern communication technologies, the smart grid enables real-time data transmission and instantaneous management of demand and supply. The integration of energy storage operations, demand response, communication between end-users and power companies creates a complex, data-driven grid system. This complexity enhances the capabilities of traditional grids, fostering sustainable progress for both utilities and consumers [136,137].

Digital technologies contributes significantly to the RE transition by supporting the effective integration of RE into the grid and making RE utilization at maximum possible rate. Digital technologies are being employed in DSM and fault identification with advanced metering infrastructure [138]. Electric utilities use predictive analytics to enhance smart grid efficiency, reliability, and economy. By predicting renewable energy transmission, managing equipment downtime, and integrating distributed generation, utilities improve grid management and ensure robust energy generation. This integration also allows for accurate forecasting [139], refined load planning, and optimized unit commitment, reducing inefficiencies in energy transmission.

A super smart grid contains all the advanced infrastructure including Internet of Service (IoS) [140,141], a crucial enabler of IoT, leveraging the Internet to offer and sell services, providing a competitive edge in energy markets). The interconnection of various independent systems like IoT, IoS, cloud computing and applications such as communication [142], results in high

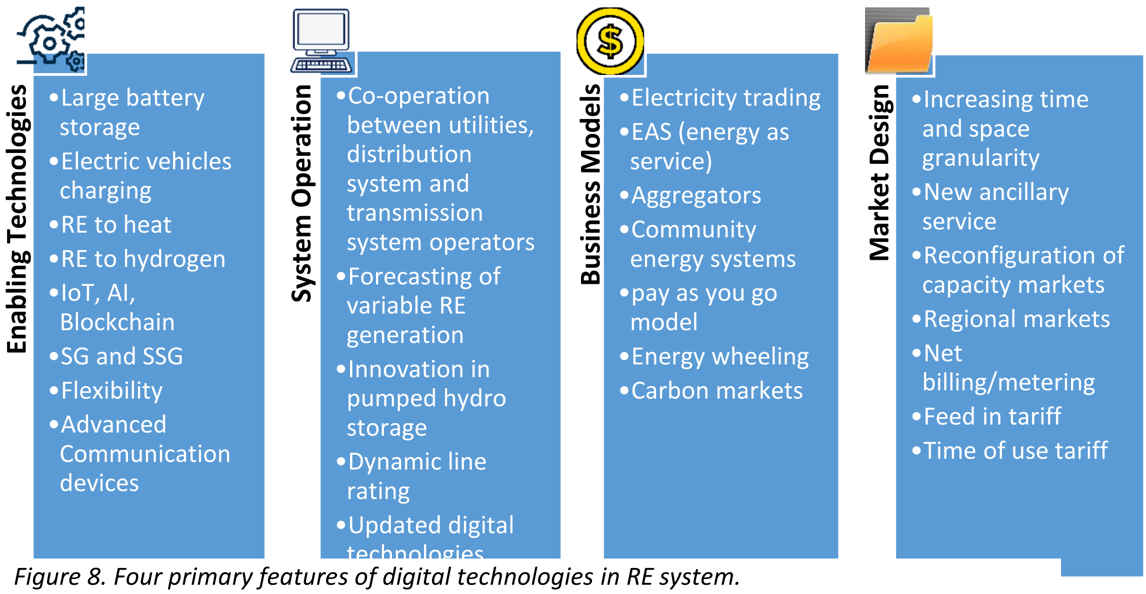


Figure 8. Four primary features of digital technologies in RE system.

complexity. This increases the risk of unintended access, data leaks, security breaches, potentially leading to large catastrophic failures. Cyberattacks could cause cascading effects, resulting in significant technological and financial losses for the grid [143,144]. Figure 8 presents four primary features of digital technologies in RE system.

Smart and super smart grid applications are crucial for the uptake of 100% RE energy system[145]. It includes demand response, also known as demand-side management (DSM) [146,147], involves utilities to adjust electricity consumption over time by temporarily altering loads on the distribution grid. By taking into account usage pattern, grid manage short-term peak demand, benefiting from lower prices. In the long term, demand response reduces peak demand, lowers capital investment costs, and enhances grid reliability, reducing the need for network upgrades and preventing inefficient operations. The consumer data is recorded through Advanced metering infrastructure (AMI) is used to record consumer data which consists of sensors, smart meters, communication technologies, monitoring system and data management software etc [148,149]. Other applications include substation automation with advanced routing network [150], wide area monitoring [151], peer-to-peer energy trading [152,153], transmission line monitoring [154,155], outage management [156,157] , wide range of energy storage options and asset management [158].

4.2 Digital Twin and Metaverse

Cyber-physical systems [159,160] are the manifestation of this new era digital technologies. They integrate physical and computational components, represent an advanced evolution of IoT [161], embedded systems, cloud computing, and ambient intelligence. CPS enables the creation of virtual representations of real-world entities, facilitating the exploration of optimal solutions to physical problems through cyber space [162]. This process involves collecting data via sensors, analysing it on distributed computing platforms, and iteratively simulating and applying strategies until an optimal solution is achieved.

The core elements of cyber-physical systems in energy systems are data, analysis, and connectivity, which are crucial for digital assistance, ensuring that information is accurately collected, insightful analysis is conducted, and seamless communication occurs between humans, devices, and machines, thereby advancing the energy transition. A prime aspect of cyber-physical systems like metaverse is the integration of physical devices and cyber components providing gateway to other components for a deterministic, fast and reliable data exchange. These systems with feedback loops and embedded systems, monitor and control physical processes, which act as central hubs for overseeing and managing feedback loops and the performance of physical processes.

The cyber-physical system allow the exchange of highly synchronized data between the physical and virtual environments, enabling new levels of control, efficiency, transparency, and oversight in the grid. By leveraging data processing, analysis, actuator control, and connectivity to digital networks through multimodal human–machine interfaces, they can effectively manage distributed processes. This capability allows for the rapid response to contingencies within the energy infrastructure [163–165]. A detailed discussion on metaverse in smart paradigm is discussed in [166].

4.3 Artificial Intelligence (AI) and Big Data

The application of machine learning algorithms [167], deep learning [168–170], generative AI [171], support vector machine [172,173] and artificial neural network [173–175] are largely adopted to predict the utility demand of various process. Big Data technologies [105,106] analyze large, unstructured datasets, generating new insights into production processes by identifying issues early and improving data-driven models. For example, scheduling functions can become more informed about underlying processes, and control strategies can be automatically adjusted to different scenarios. These capabilities are vital for enhancing the efficiency and adaptability of energy systems, thereby supporting the energy transition [178].

Demand Response is crucial for sustainable energy systems and cost reduction. AI and Machine Learning enhance it by managing complex tasks, optimizing user selection, pricing, and device control, and improving consumer engagement. Efficient demand response, driven by AI, supports the energy transition by optimizing resource use and integrating RE [179,180]. Unlike conventional power systems, where load forecasting was often neglected or imprecise, it is now an essential practice in ensuring the efficient and stable operation of power networks. Forecasting [181,182] enables utilities to optimize unit commitment decisions and effectively schedule maintenance, thereby reducing generation costs and enhancing the reliability of energy systems [183].

Significant volumes of data are generated within the smart grid through various sources, including Intelligent Electronic Devices (IEDs). This data encompasses power utilization patterns, Phasor Measurement Units (PMUs) for situational awareness, energy consumption metrics from widespread smart meters [184], pricing and bidding information from Automated Revenue Metering (ARM) systems, and data related to the control, and maintenance of power generation, transmission, and distribution infrastructure. Additionally, operational data such as financial records and other large datasets contribute to the growing data landscape in energy infrastructure [26].

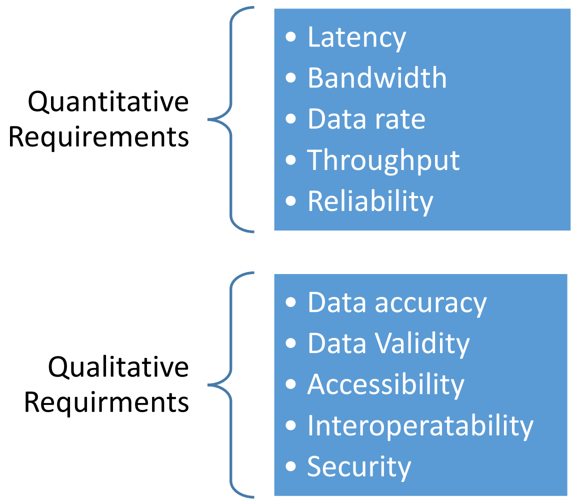
The rapid increase in data volume underscores the critical role of big data technologies [185] in facilitating the energy transition. Traditional data management frameworks, which rely on a consistent, single approach, are inadequate for handling the high diversity and volume of data characteristic of modern power systems [186]. As such frameworks struggle to correlate data from diverse sources across spatiotemporal continuum, making it difficult to integrate this information into a unified power system model. The adoption of big data technologies addresses these limitations, enabling the effective integration and analysis of complex datasets, which is crucial for advancing the energy transition. Big data founds its most common application in cost minimization of energy technologies as in [187] suggested recommender system for a combination of RE resources and electricity demand at random times using Markov Chain [188].

4.4 Cloud Computing and cloud technologies

Automation cloud allows software applications to be deployed remotely via intra/internet connections, enabling easier remote administration and leveraging powerful computing capability, such as parallel computin. This approach facilitates access to solutions as a service, reducing the need for hardware investments and thereby lowering investment risk. Such digital advancements are crucial for supporting the energy transition by enhancing operational efficiency and flexibility. The cloud services supports the integration of technologies, actuators and sensors with software solutions and AI bots [189].

Edge computing, fog computing, and mobile computing are virtualization technologies designed to enhance cloud computing by improving mobility, location-awareness, and latency management. mobile computing boosts network response efficiency by enabling processing closer to devices, with data storage and computing power transferred from mobile devices to the cloud. Edge computing extends fog computing by incorporating analytics, processing, communication, and decision-making at the edge, closer to end devices. For instance, smart meters in the smart grid track real-time power usage, facilitating demand and supply analysis. However, processing large volumes of data for decision-making is challenging. Cloud computing platforms provide a scalable, cost-effective solution, ensuring reliable data management and communication within the smart grid [190,191] .

Fog



Computing, where data is processed closed to its origin with reduced energy consumption [192], a key segment of the Internet of Things (IoT), enhances cloud capabilities such as storage, computation, and networking while enabling low latency, energy efficiency, and location awareness as shown in Figure 9. It can also be integrated with cloud systems in Big Data applications [28,193,194]. Since, a fully RE based smart super grid can only be possible with user response taken into account, prosumers can access Smart Grid services from both local and global utilities via the cloud. To ensure consistent and widespread access for service sharing, the integration of private, public, and hybrid clouds is crucial for Smart Grid applications [190].

Figure 9. Features of data in cloud computing.

4.5. Energy storage and green hydrogen

The growth in RE resources and decrease in fossil fuel consumption are driven by climate change initiatives, sustainable energy systems and energy transition. However, the rapid rise of RE introduces new operational challenges and designs in achieving a 100% RE goal [195]. Energy storage systems play a crucial role in facilitating the transition from hydrocarbon fuels to RE [196,197]. Over the years, as RE based generation gets lowered levelized cost of energy, so does battery storage systems. Thus, combining the RE with efficient storage technology offers even more cost effective solution in the future [36,198]. Battery storage system is essential for vehicle to grid and grid to vehicle mode with bidirectional interface [199].

A fully RE based energy system require to expand storage capacity for surplus energy due to their intermittent nature to increase grid stability, enhance reliability and improve system efficiency. This requires a technology that offers high efficiency and low energy loss in energy storage [200,201]. The objectives of energy storage have expanded beyond just short-term outage prevention or peak-shaving, but also for applications such as voltage balancing, frequency regulation, delaying capacity and network expansion. The energy storage technologies include pumped-hydro, lithium-ion batteries, metal-air batteries, compressed air energy storage, super conducting magnetic energy storage, thermal energy storage, super-capacitors and hybrid energy storage. [202–204].

Digital technologies like cloud computing, artificial intelligence (AI), wireless sensor networks (WSN), edge computing, Artificial neural networks (ANNs), the Internet of Things (IoT), blockchain [205] , and digital twins greatly improve battery management systems by enabling real-time monitoring and optimization [206]. Similarly, machine learning enhance the performance, reliability, and management of energy storage devices by accelerating calculations, capturing complex mechanisms, and making optimized decisions based on comprehensive status data [207]. This is especially valuable for the real-time management of various energy storage systems, including batteries, fuel cell, capacitors and hybrid systems. A digital twin enhances agility, sustainability, and productivity in water electrolysis systems by supporting data-driven decision-making, anomaly detection, optimization and control. This, in turn, contributes to lowering the cost of clean hydrogen production [131]. Hydrogen is produced via electrolysis during periods of excess power and can be converted back using high-efficiency systems like fuel cells when RE resources are insufficient. The hydrogen based energy system involves four key stages: hydrogen production, storing, safety, and consumption. For this purpose, ANNs have been effectively used to predict optimal operational parameters enhancing productivity and reducing costs [208] .

The most advanced energy storage method using RE is hydrogen storage. Power-to-Gas technology supports California's 100% RE scenario to balance energy demand and supply on a large scale [209]. Although as compared to battery storage, power-to-Gas has lower immediate round-trip efficiency, it offers the advantage of independently scaling power capacities enabling massive and long-duration storage [168].

The study's analysis of the California power system indicates that achieving 100% renewable energy will require significant expansions in both generation and storage infrastructure, with hydrogen playing a key role in this transition. However, a study on Germany's electric grid [211] reveals that focusing solely on short-duration extreme events or individual years may lead to underestimating the storage requirements and associated costs in a 100% RE electricity system. A study on US grid having only solar, wind and battery states that Long-duration storage (LDS) reduces system costs more significantly than battery storage, with costs being twice as sensitive to LDS price reductions. Batteries handle intra-day storage, while LDS is used for inter-seasonal and multi-year needs. As optimization spans more years, reliance on LDS grows, improving the affordability of renewable electricity [212].

Extensive experiments in Europe's first Hydrogen Valley (Northern Netherlands) demonstrate the significant financial benefits of hydrogen storage. By incorporating hydrogen storage units and competitive market prices, operational revenues for a 4.5 MW wind turbine could increase by up to 51%, amounting to an additional €126,000 per turbine annually [213]. The findings underscore the critical role of hydrogen offtake agreements in ensuring the success of the energy transition. Figure 10 gives an overview about the role of digital technologies in RE transition.

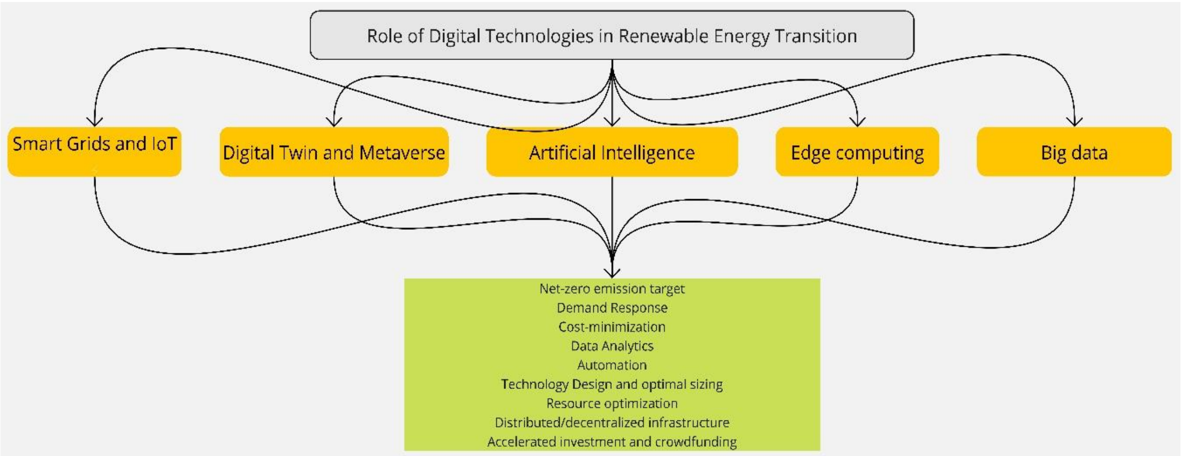


Figure 10. Role of digital technologies in RE transition.

5. Policy Recommendations

Integrating RE sources into the grid, while ensuring grid stability and addressing technical challenges related to energy storage and transmission require careful planning. This rapid transition require corresponding innovations, such as advanced energy storage systems and the smarter grids for better grid management and to enhance flexibility. The demand side management (e.g., responsive load, new tariff models, and advanced smarting infrastructure), and network expansion to connect virtual power plants (VPP), energy trading, increase capacity and link to neighbouring systems as in community microgrids, new business models [214] and market structures to ensure system security such as capacity markets are also equally important.

Governing RE transitions is a complex task due to number of associated uncertainties. It includes ambiguity regarding future energy price, performance and outcome of radical innovations, social acceptance to the innovation, stakeholder interest, cost-benefit analysis, policy support and various disagreements between stakeholders [215]. Policy makers and experts often develop long-term and short-term RE transition policies based on simulating energy scenario of a region to find an optimal transition path. This approach is however correct theoretically, but a holistic policy should also consider socio-technical aspects.

Although the transitions are long-term processes with complex multi-dimensional, policymakers should avoid relying solely on a single policy instrument such as carbon pricing, particularly when it faces significant political challenges. Instead, a comprehensive approach is needed, involving a variety of policy instruments, including financial tools (grants, subsidies, loans and taxes), regulatory measures (standards and laws), and relevant activities (similar projects, public opinion, expert consultations, predictions and roadmaps). The optimal mix of these instruments will likely differ over time and across regions, influenced by specific political cultures and stakeholder dynamics [216–219].

Given the inherently political nature of low-carbon transitions, social scientists should analyze policy dynamics as well as inform policy development. More costly transitions may be more viable if they garner stronger stakeholder support. To assist policymakers, scholars should provide in-depth analyses of the resources, interests, and strategies of various involved stakeholders. Therefore, policy analysts should focus on the intricate dynamics of social acceptance, governance and political struggles, recognizing that these aspects can act as both barriers and enablers of accelerated transitions [220].

Often policymakers and energy analysts emphasize the importance of supporting niche innovations, which can overshadow the equally critical requirement to exclude existing carbon intensive regimes [221]. Effective phase-out policies involve procedures to diminish emissions from specific sector or technologies, modifying market rules to promote low carbon emissions through mechanisms such as carbon taxes or pricing, encourage social dialogue and debate through the creation of new networks and think tanks, and reducing support for high carbon technologies such as tax breaks or subsidies. Countries must review their energy transition strategies to include fiscal incentives. International concessional investment can demonstrate the viability of renewable energy, mitigate perceived risks, attract private investment, and reduce capital costs.

Beyond adequate infrastructure, an innovation-friendly regulatory environment is crucial for the success of digital businesses in the energy sector. Peer-to-peer energy transaction and VPP models [222] can only flourish if producers and consumers are permitted to participate in aggregations, with clearly defined roles for stakeholders within the legal framework. To facilitate the adoption of digital technologies in the energy transition, addressing uncertainties related to compatibility with existing systems and upgrade processes is essential. Rapid technological evolution makes standardization and interoperability crucial. Additionally, social barriers, particularly consumer concerns about data privacy, can hinder the uptake of smart technologies. Policymakers should implement regulations that establish robust safeguards for securing customer data access, thereby enhancing consumer confidence and supporting the widespread adoption of digital solutions in the energy sector.

A future research avenue must be a study that focus on analysing and synthesizing existing architectural efforts for RE transition via smart grid initiatives, in consultation with key stakeholders. The research should identify pivotal points of interoperability across the diverse and deployed smart architectures. This analysis should culminate in the development of a consensus framework document that encapsulates common architectural features. Such a RE transition framework will serve as a valuable resource for both developed and developing countries, enabling them to implement interoperable and scalable smart solutions tailored to the specific needs of the respective communities.

Conclusion

The ongoing global transition towards building green and sustainable societies requires massive reshaping of traditional energy resources. Fulfilling the energy needs of the ever-growing population of the world, demands radical policy interventions and technological development. Despite of the availability of all the natural resources, energy poverty has encapsulated the world and various methods are being introduced by the governments including the shift from fossil fuels to renewable energy based electricity generation. Thus, a thorough and robust strategy is required in the renewable energy that caters to the changing dynamics of the energy markets, using innovative regulatory frameworks, technological advancements, and adaptive economic incentives. This approach will ensure the continued growth of renewable energy sources, promote sustainability, and drive the necessary transition towards a cleaner and more resilient energy future.

Energy and climate policy should integrate financial and regulatory measures while also fostering learning, experimentation, and coalition-building to advance emerging niche innovations and support political efforts. Analysts and policymakers should move beyond single-policy approaches like carbon pricing and consider how a variety of instruments can be combined into a comprehensive and effective strategy.

The increasing investments underscore the growing importance of digitalization in shaping the future energy landscape. Digital technologies are instrumental in overcoming common barriers to energy transition, such as high upfront costs, limited access to finance, perceived risks, distrust in new technologies, competing investment priorities, and lack of awareness. By making clean energy solutions more accessible and affordable, digital business models enhance revenue streams for stakeholders and provide a range of ancillary benefits, thereby driving the energy transition forward. The need is to Implementation of cybersecurity safeguards to protect the resilience of energy systems amidst digital transformation. Also, the use of financial tools to accelerate the deployment of digital solutions and upgrade existing networks with the required digital infrastructure.

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