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TOPICAL REVIEW

An Energy Internet for India: are we ready for a technology leapfrogging?

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Abstract

Globally, national electricity systems are amid aggressive transitions. The shift from large fossil-fuel based power systems to many small-scale distributed renewable energy systems is a favourable paradigm for a transition to the Energy Internet. Relying on wide spectrum of emerging technologies such as information & communication technologies, the Energy Internet facilitates real-time trade of power through bidirectional flows of electricity, communication, and money. Energy transitions in India are at a fast pace and further transformation to an Energy Internet is an achievable dream. Current structure of expedited energy transition is experienced in the form of transformation in business models of energy utility service companies and energy markets. The objective of this paper is to systematically assess the ongoing transitions, the challenges and the opportunities and examine whether India is ready to leapfrog into a new way of energy transactions which will gradually transform the present electricity system to an Energy Internet. Our findings elaborate a reality check on India's current transition pathways and answer the question: can an Energy Internet become real in near future?

1. Introduction

Globally, the national electricity systems are amid aggressive transitions. The shift from large-scale conventional fossil-fuel-based power generation systems to renewable energy systems which are low-cost, efficient and scalable seems to be the preferred choice. Planning and managing an electricity system with a large number of producers as well as consumers where the transactions are expected to be dynamic and real-time would be complex and challenging. Bi-directional communication among producers, consumers, and the utility play an important role in the management of such electricity systems. This communication channel needs to be further developed into an energy trading mechanism, where the price of electricity can be derived in such a way that all participants are benefited. The concept of Energy Internet has evolved from this thought process, where consumers (including residential prosumers) and generators (including captive generators) with varying power consumption and generation levels can participate actively in the power transaction mechanism. An Energy Internet integrates millions of heterogeneous prosumers to the network. Participants of this transaction mechanism are called energy cells. The priorities of such energy cells will vary according to the patterns of power consumption, generation potential, storage capacity, and availability of the dispatchable loads. In addition, there would be technical and resource constraints. This makes an Energy Internet a highly desirable but very complex system to operate. At present, there is no working model of the Energy Internet under commercial operation across the globe and the literature is scarce, making the research in this area novel and timely (Zhihong *et al* 2018).

In this paper, our objective is to study whether the current technological advances, regulatory and policy initiatives and structural changes suggest a possible transition towards an Energy Internet in the Indian context. Towards the realisation of this objective, the authors review the concept of the Energy Internet, analyse the imperatives of energy transition leading to reforms, and present challenges of the Indian power sector for the adoption of an Energy Internet. The motivation for this research is from selected works. In Joseph and Balachandra (2020a), a systematic review of global perspectives on Energy Internet oriented energy transition was performed. The study presented detailed discussions on the aptness of an Energy Internet for a transitioning electricity system, developments in smart grids to enable a smooth transition to an Energy Internet and systematic review of literature on the state-of-the-art Energy Internet. Literature reviews outlined the structure of Energy Internet, its operational features, and energy market mechanism. Findings showed that while the global energy system infrastructure, technologies, and operational strategies are adequately ready for transition to an Energy Internet, hindrances put forth by the government agencies, policies, and regulations need to be addressed. Further, Joseph and Balachandra (2020b) presented an overview of the Energy Internet, an in-depth discussion on network structure and operational mechanism. A significant contribution was made by introducing the concept of an Energy Intranet to bridge the gap in the literature to denote the scaled-down version of the Energy Internet. In addition, four types of energy cells were introduced as the best representation of a transitioning electricity system. The thought process was further strengthened by literature on the business perspective of an Energy Internet in the context of big data was presented by Zhou *et al* (2016) and on the practicality of implementing an Energy Internet by Hong *et al* (2018). However, there are few knowledge gaps in the literature that appear to hinder the realisation of an Energy Internet. They are: (i) strategies for the implementation of an Energy Internet in an existing nationwide legacy grid has not been studied in the past, (ii) transformation of the present legacy grid system to an Energy Internet in a gradual and coexisted manner has not been adequately explored, and (iii) the support of existing policy regime is not rightly identified especially in the context of developing countries. Thus, to summarise a clear understanding of how present national electricity systems can transform to an Energy Internet remains a significant research gap, especially in the context of a country or a nation, and there is a strong need for academic research to address this gap. Given this, the objective of this study is to find whether an Energy Internet can become a reality in an emerging country like India by leapfrogging the technological as well as policy advancements. At present, the legacy grid in India is undergoing a significant transition to incorporate renewable energy sources and systems. In order to study the readiness of the Indian electricity system, in this paper, we have first assessed the significance and need for energy transitions and highlight regulatory changes which would be relevant for the adoption of an Energy Internet. However, there are certain challenges posed by the transitioning electricity system which may hinder its transformation to an Energy Internet. We have analysed and classified challenges into two major categories. Firstly, challenges pertaining to resources and environment, and second, challenges posed by ongoing technology transitions. Despite these challenges, there are certain opportunities in the present system which can fulfill the basic technological requisites for an Energy Internet. This analysis comprises: opportunities provided by the transition technologies, storage devices, emerging technologies like blockchain and an expected boom in electric vehicles (EVs). Thus, the proposed implementation strategy for an Energy Internet is the coexistence of an Energy Internet and legacy power grid, and its gradual scale-up.

2. Energy Internet—an overview

2.1. Key concepts, principles, and actors

An Energy Internet is an energy sharing network that optimally manages the power flow between renewable energy generators, loads, storage devices, and EVs. The concept of an Energy Internet leads to sharing, personalisation, and interaction of energy between generators, consumers, and prosumers (Zhou *et al* 2016). Energy cells, utility cells, and the clearance house are the types of interactive agents in an Energy Internet. Energy cells refer to the consumers or prosumers of various categories, specifically residential, commercial, and industrial, as individuals or groups. A typical energy cell consists of electric loads, storage devices, EVs, and local generation facilities. In an Energy Internet, numerous energy cells are connected to facilitate energy trade. The utility cell provides ancillary services to maintain a stable electricity system. The clearance house determines the market clearance price depending on the demand and supply. Interaction between these agents is depicted in figure 1.

An Energy Internet serves as a platform for trading of electricity for prosumers. Energy cells optimize their energy utilization pattern by managing their consumption and local generation. Utility cells provide efficient infrastructures for energy cells to trade electricity. The Energy Intranet is a concept introduced by Joseph and Balachandra (Joseph and Balachandra 2020b) to address the small-scale network systems with similar Energy Internet characteristics. While the Energy Internet addresses a nationwide network, an Energy Intranet addresses a small-scale network. An Energy Internet is recognised as a network of Energy Intranets.

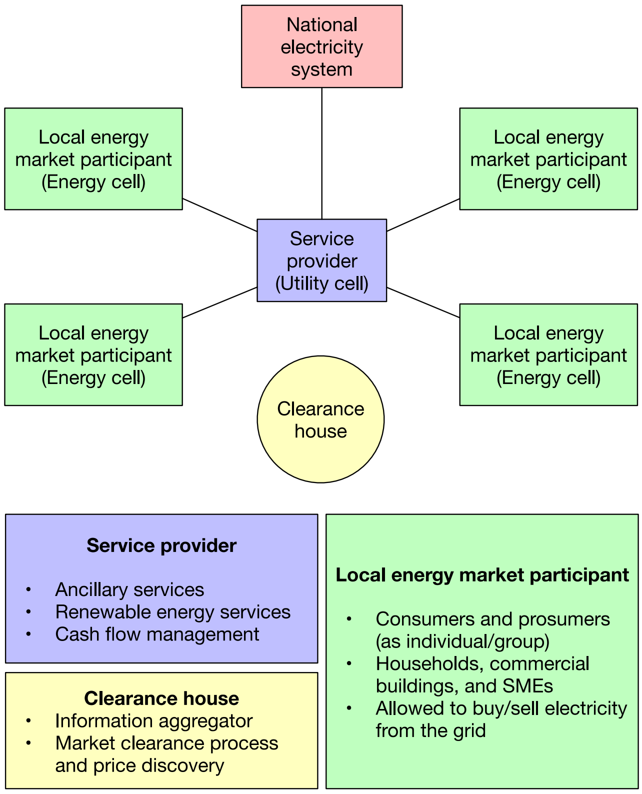

Figure 1. Interactive agents in an Energy Internet.

2.2. Operational principles

The export of surplus energy generated or the import of additional energy required to meet the demand by an energy cell would be performed only through the energy market framework designed for an Energy Internet. Energy cells do not hold permission for bilateral electricity trade by bypassing the energy market. A single household prosumer/consumer or a coalition of multiple prosumers/consumers can form an energy cell. For example, household consumers in an apartment complex can form a single energy cell. The Energy Internet allows energy cells to participate in the energy market autonomously.

In general, the energy market clearance process takes place in two stages. At the first stage, the day-ahead energy market clearance is carried out on the day prior to the actual day of energy trade. Generators are scheduled for dispatch based on the day-ahead energy market process. On the actual day of consumption, if there is any mismatch in the demand and supply, then the real-time balancing energy market would operate during every trading window to balance the demand and supply.

Prosumers commit to buy/sell electricity in a day-ahead energy market through a utility cell. In a real-time energy market, prosumers anonymously interact with each other to facilitate peer-to-peer electricity transactions. The clearance house in the day-ahead energy market computes the optimal dispatch schedules for the renewable energy resources owned by the prosumers and other generation facilities connected with the Energy Internet. Participants of the day-ahead energy market transact electricity based on the dispatch schedule on the actual day of consumption. Any deviation in the demand or supply would be balanced by the real-time energy market. The presence of EV and local storage devices in the Energy Internet helps in managing the surplus and deficits in electricity supply by optimally charging/discharging the batteries. For instance, if the electricity price is high, then storage devices can be discharged to meet the demand and they can be charged when the electricity price is low. It is desirable to effectively utilize the storage devices and EV batteries for electricity transactions in the real-time peer-to-peer electricity markets or during the actual day of the consumption. The benefits of managing the real-time variations in the power demand using storage devices are: (i) power traded in a real-time energy market is a fraction of power traded in the day-ahead energy market. Thus, the overall utilization of the battery remains low, which reduces the degradation of the battery, (ii) day-ahead energy market dispatch schedule prefers generators with a high availability ratio. Availability of electric vehicle depends on the usage pattern of the owner which could be highly uncertain, and (iii) costs associated with battery's replacement, operations and maintenance are expensive, and it would escalate the cost of electricity. Therefore, storage devices and EV batteries are suitable for real-time energy markets.

3. Imperatives of transitions leading to electricity system reforms

3.1. Significance of electricity system transitions within and outside India

As stated earlier, the Indian electricity system is going through significant transitions at different levels to overcome many underlying challenges. The good news is that all these transitions are favourable to a future system that is likely to be evolved into an Energy Internet. In this section, few of the most important transformations that appear to support Energy Internet transition are discussed. Energy transition from over the dependence on fossil-fuel based conventional energy sources to renewable energy sources is a promising development in the recent past to achieve the goal of low-carbon energy supply (Ketter *et al* 2015). Two major benefits of renewable energy technologies made it plausible for low-carbon emission energy supply. First, they are zero greenhouse gas (GHG) emission technologies during their operations and they can be installed as decentralized small-scale energy systems (Robyns *et al* 2012). While it is generally known that renewable energy technology does not have any GHG emissions, its ability to supply electricity in a decentralized and distributed manner has not received the attention it deserves. Surprisingly, the term 'energy transition' became known to the public through decentralized electricity systems like solar rooftop PV installations, which were used by households for self-consumption and cutting electricity bills (Braun *et al* 2009). Further, it moved to a diverse industry, which led to a democratization of energy supply to bring a new form for the energy markets.

In this study, India's national electricity system is considered as a reference to elaborate our findings in a realistic manner. The Indian electricity system is undergoing significant transitions in recent years. To provide better insight on the significance of transitions occurring in the Indian electricity system and their relevance in the context to present research on the Energy Internet, we have discussed the synthesis of the related literature in the following paragraphs.

Research by Balachandra (2011) studied the Indian energy system and its policy failures which left a huge population of the country without energy access. The study proposed a public–private-partnership model as an implementation framework with innovative regulatory, institutional, financing, and delivery mechanisms to address this challenge. The framework involves creation of rural energy access authorities and energy access funds to design, lead, and manage the rural energy interventions by adopting renewable energy-based distributed energy systems. In brief, this study proposes a strategy framework for a rural transitioning energy system.

Amrutha *et al* (2017) studied the impact of targeted policies such as renewable energy certificates (RECs), renewable purchase obligations and feed-in tariffs for achieving renewable energy transition. To study the impact, the authors have developed various scenarios and analysed them using a mixed integer programming model. The study identified the inadequacy of the present policy framework and argues the importance of the induction of market-based incentives to expand the trading of RECs.

Further, Sharma and Balachandra (2018) proposed a study to verify whether energy transitions lead to a sustainable electricity system measured through economic, social and environmental dimensions. A study has been carried out by adopting an integrated framework, which establishes a relationship between the indicator-based multi-hierarchical and multi-dimensional model of electricity sustainability assessment (developed by Sharma and Balachandra (2015)) with generation expansion planning (GEP) and the scheduling of generation. The study is performed by choosing scenarios by varying the national electricity system sustainability index (NESSI) from 0.481 to 0.510. The results show that Indian electricity system is at a transition state towards achieving more sustainable state. Further, this study has been extended by Sharma and Balachandra (2019) by developing and validating a novel approach to represent resource-supply-demand dynamics in evolving GEP models. Towards this objective, the study has discussed the development of the GEP model with detailed operational strategies, the development of representative load curves to model annual wind and solar profiles to analyse dynamic nature of renewable energy resources. The model is validated with Indian electricity system data to study the implications of varying levels of renewable energy resource integration. Important insights from the study shows that large penetration of renewable energy resources while bringing climate change benefits creates redundancy of electricity generation capacity leading to lower capacity utilization of the electricity system. The study also suggests the need for adopting demand response strategies to ensure viability and reliability of conventional and renewable energy generation. In summary, our present study is the continuation of our efforts from the past to fulfill our vision to realise an Energy Internet-oriented renewable energy resource dominant in the national electricity system while enabling small-scale energy prosumers to take part in the electricity system decision-making along with the large-scale generators and prosumers.

One of the recent ongoing developments in the energy transition and energy market, which is driven by the civil society is the renewable energy cooperatives (Fridgen *et al* 2018). Renewable energy cooperatives provide opportunities for individual citizens to become energy producers and to participate in the cooperative energy consumption. Witnessing the remarkable success of cooperative energy consumption, Hentschel *et al* (2018), studied how renewable energy cooperatives significantly impacted the CO_2 emission reduction, including cost cutting and possibilities of setting up renewable energy cooperatives within an industrial cluster. The study has proposed the characteristics needs to be confirmed and rejected for the new renewable energy cooperative of industrial cluster and it has provided the directions to integrate industrial consumers/prosumers to an Energy Internet-like system. In addition, an action plan is also proposed, which has contributed towards drafting the technology roadmap to implement Energy Internet in our study.

While renewable energy cooperatives are a representation of a typical model of energy transition which push the frontiers in energy modelling, there are other modelling frameworks. These frameworks are capable of representing interdependencies between market behaviour, energy security, environmental impacts, energy policies etc (Granado *et al* 2018). These frameworks are represented through three approaches. First, a top-down approach, which is a macroeconomic modelling approach focused on an aggregated economic-wide view. The emphasis on technology is less and focus is given to the macroeconomic system. The second, a bottom-up approach, focused on a technology-rich energy system with less emphasis on interaction between the energy system and the economic system. The third, hybrid approach integrates the essence of top-down and bottom-up approach to formulate a detailed energy technology representation that interacts with the economic system. The hybrid model of a top-down and bottom-up approach is followed by an Energy Internet which is the proposed transition model in this study. An Energy Internet integrates distributed renewable energy systems to the network. The interconnection between the small energy systems and loads facilitates a power transmission at a wide electricity grid network scale. The most prominent distributed renewable energy conversion technology is solar photovoltaic (SPV). The modular structure of SPV turned into an advantage for its fast adoption on small-scale rooftop applications as well as large-scale solar park applications.

At present, Indian states have identified numerous initiatives to promote solar rooftops and small-scale plants. Some of the initiatives include net-metering regulations, state wise solar policy, and an online window for approvals. In addition, a continuous decrease in the cost of solar panels has increased the willingness of the consumers to install and utilize the rooftop space (BloombergQuint 2018, Deloitte 2014). The installation of rooftop solar plants enables self-consumption and an opportunity to sell surplus power through Energy Internet-like energy sharing networks.

India is in pursuit of integrating large-scale renewable energy systems to the grid. There are certain initiatives from the Government of India (GoI) to facilitate the integration of renewable energy systems. Transmission system strengthening at interstate and intrastate level, upgradation of existing control centres, establishment of Renewable Energy Management Centre, deployment of phasor measurement units, and big data analytics are some of those initiatives (Soonee *et al* 2017). These initiatives are favourable for the implementation of an Energy Internet on a nationwide scale. On the other hand, the recent trends in power procurement through competitive bidding of large-scale solar and wind power, the prices were plummeted to a record low level of 2.44 ∗/kWh for solar and 2.43 /kWh for wind respectively (PIB 2018a). These prices are cheaper than the newly built imported coal-based supercritical thermal power plants. This trend in declining the cost of power generation represents the future of renewable energy in terms of its large adoption. However, aforementioned initiatives by GoI, which are meant to build a resilient grid to support the integration of large-scale renewable energy systems may not facilitate the low-voltage distribution grid to support integration of small-scale systems such as rooftop solar, small wind turbines, and energy storage devices (Hirsch *et al* 2018). Power distribution networks in India are not digitalised to meet the specifications required to integrate millions of distributed renewable energy resources (DERs) to the grid (Kumar 2019). However, digitalisation of the power distribution infrastructure is a key process for the development of an Energy Internet.

By 2022, India has set an ambitious target of installing 40 GW of grid connected rooftop solar capacity (PIB 2018b). By 2040, the country has set a target of generating 1663 TWh of renewable energy in the estimated total generation of 4773 TWh (Kumar 2019). In addition, 50% of the estimated total electricity generation (4773 TWh) is expected to be generated by non-fossil fuel sources (renewable energy source, hydro, and nuclear) (Kumar 2019). The plausible ways of achieving this proposal by the researchers and other experts are smart grids and an Energy Internet (Su and Huang 2014). In this context, our motivation is to analyse and present the Energy Internet as the attainable future electricity system of India. This model of energy transition is the continuation of energy transition occurring in the present electricity system in the form of deployment of smart grid infrastructure for renewable energy integration to the national electricity grid.

3.2. Policy and regulatory transitions in the Indian power sector

Though renewable energy systems integration into the grid and the energy transition are relatively new, the time policy and regulatory changes occurring in India have favoured such constant innovations. In this section, the discussion presents the transitions in the policy and regulatory regimes of the Indian power sector and how these transitions can favour the future development of an Energy Internet.

In the pre-liberalisation era, the Indian Electricity Act 1910 (Government of India 1910), which was rolled out in 1910, was the first ever electricity act in the country. The objective of the act was to provide a basic framework for the supply of electricity in the country (Mishra and Singh 2016). Further, the act came up with the idea of private licenses issued by the state governments. First, the legal framework for laying down the transmission wires was also part of this act (Mishra and Singh 2016).

Next was the introduction of Electricity (Supply) Act (Ii *et al* 1998) in 1948. The act led to the formation of State Electricity Boards (Mishra and Singh 2016). Later, the Electricity Regulatory Commissions Act of 1998 (Ii *et al* 1998) led to the formation of electricity regulatory commissions at central and state levels. In addition, this act rationalized the electricity tariffs and brought more transparency to the disbursement of subsidies (Mishra and Singh 2016).

The Electricity Act 2003 (Central Electricity Authority 2003) replaced all the existing legislation in the power sector and geared up competition in the sector (Singh 2006). The act ushered competition through open access in transmission, multiple licensees, the introduction of power trading and various other provisions (Shukla and Thampy 2011, Singh 2006, 2010). The major objective of this act was to attract more investment to expedite the deployment of generation and distribution infrastructures. The provision of non-discriminatory open access in transmission and distribution is another major step in the act. Open access facilitates generators that transmit power through the carriers owned/operated by other parties.

The key objectives of this act are (1) the rationalisation of the tariff, (2) the constitution of Appellate Tribunal and Central Electricity Authority, and (3) to promote the competition (Mukherjee *et al* 2017). Competition is expected to provide cheaper electricity with improved reliability (Singh 2006). Some of the ways through which this act promotes competition in electricity include provision of multiple licensing for distribution in the same geographical location, and introduction of power trading as a distinct activity.

The recent electricity amendment bill of 2014 raised the expectations of the power system stakeholders. The bill is expected to thrust next-generation reforms in the Indian power sector. It advocated the bifurcation of the distribution business into carriage and content to promote competition. However, the bill does not cover certain practical aspects related to the guidelines of implementation, and the treatment of cross-subsidy and prevailing losses (Agrawal *et al* 2017). Therefore, it is imperative to devise a strategy to remove cross-subsidies and to arrive at a framework for the real-time pricing mechanism in future to switch to an Energy Internet.

The objective of a comprehensive electricity policy is not to promote competition among the consumers but to provide a platform for the consumers to be energy efficient and to take appropriate decisions based on the optimal management of local demand and domestic power generation. While surplus power is expected to be traded through power market, deficient power is obtained from the power market. The existing electricity act needs to be modified to adapt to bidirectional energy flow facilitated by an Energy Internet. The major modification in the act is to accommodate the new real-time electricity pricing mechanism based on the demand and supply with an objective to maximize the benefits of all the stakeholders. The policies describing the present three-part tariff, Bhattacharyya and Ganguly (2017), and cross-subsidy (Mukherjee *et al* 2017) mechanisms need an alteration to respond to the Energy Internet pricing structure. The major impact of the cross-subsidy removal is the resultant food inflation and reduction in disposable income by households, especially in the rural area (Bhattacharyya and Ganguly 2017).

An amendment for the electricity act was floated in 2020 after earlier revisions in 2014 and 2018. The electricity (amendment) bill 2020 (PIB 2020) is anticipated to initiate a major reform in the electricity sector. Objectives of the amendments in the act are: (i) to ensure consumer centricity, (ii) to promote the ease of doing business, (iii) to enhance sustainability of the power sector, and (iv) promote renewable energy resources. Bill expands the scope of privatization in the power sector. Privatization in the form of distribution franchisees and sub-licensees would ease the flow of investments. In addition, the adoption of efficient financial and operational plans by the private investors would enhance the overall system efficiency. Further, provisions for penalising the non-fulfillment of renewable energy obligation, the progressive reduction of cross subsidies, establishment of payment security mechanism etc. supports the national electricity system to move closer to the Energy Internet.

The National Electric Mobility Mission Plan (NEMMP) 2020 was launched in 2013 to promote sales of EVs in India. The NEMMP targets the addition of 6–7 million hybrid and EV vehicles every year from 2020 onwards (MoHI 2012). In addition, GoI launched a scheme called faster adoption and manufacturing of (hybrid &) electric vehicles (FAME India) in April 2015 under Nthe EMMP to push early adoption and manufacturing of hybrid and EVs. The first phase of the FAME India scheme has four focus areas, namely the development of technology, creation of demand, pilot projects, and deployment of charging infrastructures (PIB 2016). The objective of the first phase of FAME was to incentivise all vehicle segments to create a market for EVs. Direct incentives for the buyer in the form of price reduction and promoted investments for charging infrastructures are the major highlights. Further, FAME phase II aims at the deployment of EVs for public and shared transport services (MoHI 2019). Energy sharing networks such as an Energy Internet are capable of optimally using the storage capacity of EVs through vehicle-grid-technologies (Joseph and Balachandra 2020b). In this aspect, the adoption of EVs in the country proportionally increases the option for energy storage. However, existing charging infrastructures need to be upgraded to bidirectional chargers. In addition, private EV owners shall be given an option to opt in for bidirectional residential chargers to participate in the energy sharing mechanism controlled by an Energy Internet.

Another government scheme, the National Energy Storage Mission (NESM) launched in 2018, aims at enabling the policy framework to encourage manufacturing, deployment, innovation, and cost reduction of storage technologies. The mission is expected to incorporate cumulative storage capacity of 3500 GWh by 2030 (equivalent to total daily generation of India on Sep 2018) (PIB 2018c). In addition, this huge capacity of storage would enable the Energy Internet-like energy sharing network-based electricity system to provide stable operation with variable and uncertain renewable energy sources such as wind and solar. Initiatives on building charging infrastructure for EV vehicles, storage devices, and other policies give confidence to the end-consumers to invest more on technology infrastructure for their own purposes. As a result, the development of infrastructure from the end-user side contributes to the adoption of an Energy Internet at a faster pace.

4. Energy Internet for India: challenges and opportunities

India is a developing country with ambitious goals set for high economic growth. Electricity, being the most versatile and preferred energy carrier, is the key to driving the Indian economy to achieve these goals. Commensurate with these targets, the Indian power sector is growing at a fast pace and witnessing an aggressive capacity addition by renewable energy systems. In the past decade, the installed capacity of 72.8 GW has been added to the national electricity system (CEA 2010, 2020). The solar PV systems account for 36 GW and wind turbines for 38 GW (CEA 2020). In addition, there are off-grid solar PV systems and solar mini grids of approximately a 485 MW size deployed in the country (IRENA 2019). This suggests that the national electricity system is moving towards providing a conducive environment for the development of an Energy Internet-like system.

The present energy transition occurring in India has focused on the deployment of both large-scale renewable energy systems and a large number of small-scale renewable energy systems. While large-scale systems are installed through solar parks and wind farms, the small-scale systems are deployed through rooftop solar systems, backyard systems, and other forms of stand-alone systems. This energy transition driven by renewable energy resources enables the transformation of pure electricity consumers to electricity prosumers, who produce/sell as well as buy/consume electricity. Such prosumers would be aware of the technology know-how to make better decisions. In this section, we have discussed various challenges posed by the present Indian electricity system and the opportunities provided by the ongoing electricity system transitions that have provided a conducive environment for the transition to an Energy Internet.

4.1. Challenges posed by the present Indian electricity system

4.1.1. Outcomes of ongoing electricity system transition

4.1.1.1. Uncertainties associated with renewable energy resources Uncertainties associated with the renewable energy sources affect the power system in multiple ways. Primarily, it affects the unit commitment of the power plant that determines the start-up and shutdown schedule of units, which are assigned to meet the required demand (Zaman *et al* 2016). In addition, it can affect the economic dispatch plan where ramping up thermal power station is required to meet the unit commitment by neutralising the effect of unexpected significant deviations of renewable energy sources, which may also complicate the demand and supply management (Bahmani-Firouzi *et al* 2013, Lee *et al* 2011). Another aspect to be considered is the transmission infrastructure maintenance and expansion for power evacuation from renewable energy systems are two major aspects to be considered in this study (Loureiro *et al* 2018, Roldán *et al* 2018). The transmission system under uncertainty is prone to instability of the system in terms of electricity grid synchronisation. Future transmission system expansion needs to account for this uncertainty and the cost of infrastructure expansion may cause additional expenditure. In addition, optimization of renewable energy portfolios under uncertainty is also a challenge that can lead to conflict in various aspects of decision makers' preferences (Hocine *et al* 2018).

4.1.1.2. Variabilities associated with renewable energy resources Variability in the renewable energy resources negatively contribute to resource adequacy (Zhou *et al* 2018). Resource adequacy refers to meeting the energy demand with sufficient generating capacity by ensuring the target level of reliability (Tuohy *et al* 2016). Variability of renewable energy resources, especially wind and solar, may lead to deficient or surplus generation. Variability can occur in multiple temporal scales. It can be seasonal variations, or it can be hourly variations throughout the day. The management of this variability of renewable energy source is a challenge that can lead to instability in the systems and renewable energy curtailment in extreme cases (Castro and Crispim 2018). This also leads to further challenges in optimally designing and sizing renewable energy systems, especially standalone systems. Further, additional expenditure on storage devices is another challenge associated with addressing the variability of renewable energy resources (Amusat *et al* 2017).

4.1.1.3. Dispersed and less concentrated renewable energy resources Integration of dispersed and less concentrated renewable energy resources to the national electricity system has posed challenges with respect to the addition of new models of network elements for the planning and operation (Buchholz and Styczynski 2006). Besides the challenge of interconnection of dispersed renewable sources through highly expensive transmission infrastructures (for example offshore wind farms), there are certain other challenges to be solved at the distribution level. These challenges can be broadly classified into three categories, namely conformity, reliability, and dispatchability. Conformity refers to ensuring network conformance according to the technical standards (voltage quality, equipment overloading, etc) in low voltage distribution networks (Elektrizit 1998). Reliability refers to providing power at high availability and network support to recover after the event of faults. Dispatchability refers to compensation of fluctuations and dispatch of power balance in clusters of DERs, storage units, and controllable electric loads (Buchholz and Styczynski 2006). The envisioned Energy Internet model focuses on the dispatchability aspect of the disperse electric loads.

4.1.1.4. Need for storage technologies and associated challenges Albeit, energy storage is a solution for the aforementioned challenges such as uncertainty, and variability (Zerrahn *et al* 2018), there are certain challenges curbing the development of storage technologies towards its large-scale deployment. Most important challenges are related to its economic viability. That means its high cost and need for its periodic maintenance and replacement cycles (Parra *et al* 2017). This is not only the case with common lead-acid household batteries but even with other technologies such as hydrogen-based storage (Kousksou *et al* 2014), or lithium storage. In addition to the economic viability, storage devices pose certain technological challenges with respect to reaction times, charging/discharging efficiency curves, life time, operating/dead zone, and self-discharge (Beaudin *et al* 2010, Haas *et al* 2017, Ibrahim *et al* 2008). Finally, there is the environmental aspect where deployment of large scale energy storage impacts the environment in terms of harming the ecology (inundation of land due to pumped storage) or the expulsion of toxic materials from batteries while recycling (nickel cadmium and lead-acid batteries) (Beaudin *et al* 2010).

4.2. Opportunities for transitioning to an Energy Internet

4.2.1. Electricity system transition

The primary energy source in the envisioned Energy Internet is renewable energy. Thus, renewable energy sources are expected to occupy a major share in the installed capacity as well as electricity generation, and small-scale renewable energy generation systems are the most suitable for the topology of an Energy Internet. Small-scale energy networks embody the transition towards an electricity system that is self-resilient through distributed generation (Bou Ghosn *et al* 2010, Domínguez-Garcia *et al* 2012, Li *et al* 2011). That means that an electricity system that integrates distributed generation systems can recover from the shocks in the main system through the isolation and islanding of electricity networks. Thus, distributed small-scale systems based on renewable energy sources are apt for energy sharing networks that integrate small-scale prosumers with local generation facilities such as solar rooftop PV or backyard solar PV or wind turbines and their storage devices (back-up battery and/or electric vehicle battery).

Decentralised and distributed small-scale power generation is becoming acceptable due to its inherent characteristics such as versatility, ease in operation & maintenance, comprehensive technological know-how, short gestation period, and flexibility for capacity expansion. Though solar, wind and biomass are widely used as decentralised systems, solar technologies appear to be the most prominent among small-scale decentralised power generation systems, especially, for rooftop applications. Practically, for solar, O & M costs are very low, technology is simple, installation process is fast, and future capacity addition is effortless as the size of the plant varies according to the number of PV array modules assembled together. Technologies like solar PV and small wind turbines for the domestic and small-scale energy consumption are not very strange in developing countries now. But a question arises: how do the decentralised power generators working as standalone systems utilize their maximum generation potential at times when the demand is low? Possible answers are generation curtailment and energy storage. The curtailment of renewable energy is not an acceptable way of dealing with the problem due to the negligible marginal cost of production and resultant under-utilization of the resource. Therefore, storage is a widely acceptable solution to manage the surplus production for standalone systems. However, the deployment of storage devices is a costly affair and requires periodic maintenance. This insight has driven technology enthusiasts towards the formation of a network of decentralised energy sources, electric loads and storage devices for optimal energy sharing and management (Huang 2010). Electric vehicles (EVs) can also contribute to this optimal energy management system by plugging-in the battery for charging and discharging according to the demand supply conditions.

4.2.2. Recent boom in electric vehicles

The torage of energy is an important aspect of energy-sharing system models using distributed renewable energy systems. Prosumers can own storage devices and EVs to store surplus energy. The widely accepted strategy is to charge the EVs with power from the renewable energy systems. Further, present-day EVs, which possess batteries in the order of 60 kWh and more, would provide a medium for energy storage which is transportable. The advantage of exploiting vehicle batteries for the energy storage is tied with its mobility. That means that the storage device is not static at a particular location, and energy can be drawn from the battery whenever the vehicle is sufficiently charged and plugged-in to the point of power demand. The optimization aspect of energy storage using EVs, and stationary storage technologies are academically celebrated topics in the recent past, especially the optimal sizing of stationary storage devices which is used in tandem with vehicle-to-grid programs and its energy dispatch scheduling. Studies by Mortaz and Valenzuela (2017), (2018) on the optimization of the electric vehicle battery for a microgrid without any stationary storage device is a notable study in this area. First, the study proposes an energy scheduling problem and second, the study proposes an optimized size of an electric vehicle parking lot without incorporating any stationary storage devices in the micro-grid under study. The proposed model can be further developed with an objective to minimize the investment on stationary storage devices by choosing batteries in the EV for energy storage. By doing this, an investment made for the storage device can also be minimised by optimally utilising the vehicle battery. In addition, other innovative business models that can provide monetary benefits like free parking for feeding power to commercial buildings can be promoted. The recent boom in EVs opened up wide possibilities for the proposed energy sharing model. Several studies have reviewed these opportunities and challenges (Cheng *et al* 2014, Haidar *et al* 2014, Hota *et al* 2014, Mwasilu *et al* 2014). For instance, Mwasilu *et al* (2014), have presented an intensive review on the interaction of EV in the smart grid infrastructure. The study shows that it is imperative to have information and communication infrastructure (ICT), and metering to utilize the energy storage capability of the electric vehicle. The major challenge that hinders the large adoption of EVs in the energy market is the low penetration of embedded vehicle2grid (V2G) functionality. Therefore, the proposition in the study is to manufacture EVs with vehicle-to-grid technology in-built, which may cause extra cost, but it will entice more EV owners to integrate their vehicles to energy markets. Similar studies were categorised and discussed in Hota *et al* (2014). Studies are categorised into four aspects: (1) charging and scheduling of plug-in hybrid electric vehicles (PHEVs), (2) application in reducing intermittence of renewable energy production, (3) PHEV participation in electricity markets and (4) infrastructure facilities and energy management schemes. In the first aspect, studies related to coordinated charging of EVs through game-theoretic models have been analysed (Gerding *et al* 2011, Ma *et al* 2010). The participation of PHEVs in the electricity market is another aspect that is relevant for this study. Studies on multi-agent-based game-theoretic models (Kamboj *et al* 2011, Schill 2011, Vandael *et al* 2011, Wehinger *et al* 2010, Wu *et al* 2012), V2G mode of operation (Al-Awami and Sortomme 2012, Chukwu *et al* 2011, Hamrén 2010, Kempton *et al* 2008), and scheduling of PHEVs in parking lot (Kempton *et al* 2008, Saber 2009, Saber and Venayagamoorthy 2010, 2012) are the important categories of research we have found relevant for this study.

4.2.3. Emerging technologies

4.2.3.1. Information and communication technologies (ICTs) The modernisation of the electric grid is nearly impossible without the support of information and communication technologies (ICTs). This paradigm shift can relate to the recent similar innovation by Uber Technologies Inc. Uber demonstrated how ICT-based mechanisms can enable the establishment of a virtual mega enterprise to aggregate and manage virtually distributed assets (cars owned by individual entrepreneurs) with a centralised intermediary (mobile application) to provide on-demand mobility services. The proposed Energy Internet mechanism will have similar characteristics where ICT would enable the prosumer-owned power plants (distributed real assets) to trade electricity with the Energy Internet (centralised virtual intermediary). A similar concept has been reviewed in Mengelkamp *et al* (2018) on how prosumer-owned power generation systems can directly sell electricity even without a centralised intermediary using ICTs and blockchains. Further, emerging technologies like energy cloud and blockchains are backed by ICT infrastructures. Energy cloud platforms such as distributed renewable energy systems, V2G, prosumers, neural grid, and smart cities should develop and deploy their technology infrastructure in a coordinated manner. The objective of this platform orchestration is to move away from the persisting siloed asset-focused mindset of the utilities (Lawrence 2018). The gridlock created in the mindset of utilities by current binary thinking between renewable energy and fossil fuel can be eased by transitions in energy systems. The focal point of such energy transition would no longer emanate from centralised power generation and legacy grids. Rather, organisations will bring coordination between the energy networks that will compete with each other to widen and deepen the energy cloud (Lawrence 2018). Organisations in an energy cloud shall explore new business opportunities by incorporating enterprises that provide forecasting services, renewable energy infrastructure leasing, etc.

4.2.3.2. Blockchain technology Blockchain technology can emerge as the backbone of the energy market in the future. Woodhall (2018) presented four assertions in his study on the democratisation of global energy supply: firstly, the overwhelmingly centralised power supply projects less of an energy democracy and magnifies the inequalities in the system. The consumers' ability to generate electricity from a renewable energy system at their backyard is not promoted. Secondly, the internet is a paradox with decentralised participation and centralised authority (through giants like Google Inc.). Internet users are worldwide, but users are obliged to agree to the terms and conditions put forward by the centralised authorities to use their services and benefits. Thirdly, the application of blockchains in energy shall ensure decentralised participation and authority to fulfill the democratic promise. Lastly, the present electricity system is ready to leapfrog into democratization by blockchains. These assertions explain why blockchain technology can induce the shift from centralised energy supply to decentralised systems and retail energy markets. This idea of the formulation of the energy market for distributed energy systems with renewable energy sources using blockchain is a niche area and not explored in the academic research domain. Noor *et al* (2018), have presented a demand side management model with peer-to-peer energy transaction using storage devices and blockchains for a microgrid with residential consumers. A game-theoretic model has been developed with an objective of flattening the load curve. The study concludes that the model implementation can help bridge the continuously growing demand and supply gap, and minimize events of load shedding though seamless and secure transactions facilitated by blockchain. Power trading over blockchains makes the micro-grids more resilient. This resilience is established on the trust between the agents on the financial and energy transaction aspects (Green and Newman 2017). In addition, the internet of things (IoT) along with blockchain can have applications in future energy systems. The IoT can perform management and analysis of energy data to provide energy-aware services (Baker *et al* 2017, Terroso-Saenz *et al* 2017) and can provide energy management platforms (Wei *et al* 2016).

4.2.4. New policy regimes and transforming energy markets in India

The energy sharing model (Energy Internet) envisioned in this study is proposed to operate through an energy market framework. At present, India has two power exchanges, namely Power Exchange India Limited (PXIL) and Indian energy exchange. These power exchanges function under the provisions made in the 2010 Power Market Regulations. Services offered by these power exchanges are the day-ahead spot sale of electricity in the deregulated wholesale electricity market (Girish *et al* 2018). The proposed energy market can avail the computational infrastructure from the existing power exchanges in the country. The future of the energy market is expected to utilize the experiences from the present energy market framework and by mimicking its operational characteristics to formulate a modern retail energy market for the small-scale prosumers with the support of emerging technologies like blockchain in the Energy Internet platform. While power exchanges facilitate the energy trade, actual transfer of energy takes place through distribution infrastructures established by electric service companies. Electric service companies ,which are also known as the utility companies, are undergoing a transformation phase. Utilities previously focused on power sales, billing, and collection of revenue, and now are transforming into promoters of energy efficiency. Utilities can engage their customers by transforming the consumers to 'prosumers'. Recent policy changes in the Indian states to promote net metering have provided a conducive environment for the consumers to invest in own power production technologies and sell surplus electricity to the grid by transforming themselves to prosumers. Another major development in current policy regime is the proposed enactment of the electricity (amendment) act 2018. The aim of the amendments in the act is to bifurcate the distribution business into a distribution license and supply license to introduce competition in the electricity distribution. It is similar to the facility available to change the cellular service provider by retaining the same cell phone number (known as mobile number portability). Likewise, energy end-consumers can change their service provider for better service or cheaper tariff. Implementation of such policy is an opportunity where the energy infrastructure for such a facility is supportive for the upgradation to an Energy Internet.

While electricity system transition is fostered by energy policies, and amendment acts, there is a vast opportunity bestowed by the policies and government schemes proposed with the objective of transition towards electric mobility (e-mobility) in India. With this goal, the National Electric Mobility Mission Plan (NEMMP) 2020 was launched in 2013. The NEMMP targets the addition of 6–7 million hybrid and EV vehicles every year from 2020 onwards (Saber and Venayagamoorthy 2010). That means, roughly 150 GWh of storage capacity is added every year (assuming balanced mix of hybrid and EV scooters and cars). The NEMMP is expected to cut expenditure on crude oil worth Rs. 620 billion (9.5 billion litres). In addition, GoI launched a scheme called faster adoption and the manufacturing of (hybrid &) electric vehicles (FAME India) under the NEMMP to push early adoption and manufacturing of hybrid and EVs in India. The FAME India scheme has four focus areas, namely, thedevelopment of technology, creation of demand, pilot projects, and deployment of charging infrastructures (PIB 2016).

Another notable government schemes proposed to be launched is the NESM. NESM for India aims at providing an enabling framework to encourage manufacturing, deployment, innovation, and cost reduction of storage technologies. The mission is expected to incorporate cumulative storage capacity of 3500 GWh by 2030 (Equivalent to total daily generation of India on Sep 2018) (PIB 2018c). The addition of this huge capacity of storage would enable the electricity system to provide stable operation with variable and uncertain renewable energy sources such as wind and solar. Aforementioned initiatives provide a conducive environment by giving investment confidence for the end-consumers to invest in EVs, storage systems, and renewable energy systems, which can result in the faster integration of an Energy Internet into the national electricity system.

5. Realisation of an Energy Internet: strengths and weaknesses

An Energy Internet as a futuristic electricity grid has enormous potential to transform the energy utilization philosophy. The Energy Internet promotes energy sharing between the prosumers and consumers. The robust energy trading platform that can be provided by the Energy Internet has been explored in various studies (Hussain *et al* 2020, Perera *et al* 2021, Zhang *et al* 2015). Realisation of such energy sharing platforms is expected to aggregate the scattered renewable energy resources of large- and small-scale capacities. Technologies such as the plug-and-play mechanism and vehicle-to-grid are anticipated to ease the integration of various renewable energy systems and EVs. In addition, from a prosumer's point of view, an Energy Internet opens new arenas of opportunities for energy sharing. In the meantime, for investors, various innovative business models can be implemented, which are beneficial for both prosumers and energy consumers.

However, the present policy and regulatory regime of the country requires modifications to adapt to the Energy Internet. Policies concerning tariff settings, subsidies, power purchase agreements, etc, require modifications to reflect the Energy Internet's real-time pricing mechanism. The realisation of such a pricing mechanism could also lead to apprehension over the price volatility among the consumers. Besides, the investor's confidence also needs to be protected. Next, emerging technologies such as smart meters, protection devices and energy management software are expensive for developing countries. The procurement and integration of such technologies would impact the operational cost, which would be reflected in the per unit cost of energy. Further, the present electricity industry structure may require a revamp where energy markets function in a decentralised manner to provide energy market clearance solutions for local energy markets.

The deployment of a nationwide Energy Internet requires the participation of prosumers and consumers from rural areas as well. The adoption of an Energy Internet in rural areas could be through an approach linking to the socio-economic systems of territorial planning. The concept can be elaborated on by taking cues from Japan. Smart energy community projects such as NEXT21 and Yokohama smart city projects focus on the development of collective housing and the adoption of urban architecture (Lendt and Lindner 2009). Such approaches promote energy sharing in the forms of electricity, heat (CHP plants and absorption chillers), and other fuels (such as hydrogen). In addition, the adoption of EVs and effective control over the vehicle-to-grid infrastructure results in better energy sharing (Ceglia *et al* 2020). A similar example can be found in Juhnde (Germany) where the CHP bio energy plant combined with a district heating system that is owned by a corporative with investments from 75% of the village members (Simcock *et al* 2016).

Therefore, the infrastructure updates required would not be confined in terms of electricity infrastructure assets. The infrastructure updates required include township planning, the deployment of other energy infrastructures, and landscaping of the business environment for energy sharing-centric developments.

6. Discussions and conclusions

The Indian electricity system is fast developing, and an Energy Internet is the best suited electricity system that the present system can evolve into. The aptness of the Energy Internet for the transitioning Indian electricity system is assessed in this paper and is the novel contribution of this paper which is the first study in the area. Various policy initiatives of GoI such as targeted 175 GW of renewable energy integration by 2022, the National Electric Mobility Plan (NEMMP) and National Storage Mission (NESM) have expedited the current form of energy transition. This ongoing transition relies on emerging technologies such as information and communication technologies (ICTs), the internet-of-things (IoT), and blockchain. The above policy initiatives and energy transition relying on emerging technologies have major significance in the adoption of the Energy Internet. However, few factors such as cost of technologies, technical know-how of the human resources, public acceptance of the policy regime, prevailing national political agenda etc. are a few factors that influence the process of transitioning to an Energy Internet. Therefore, to answer the question asked in the title of this paper, we hope that, with the current pace of energy transitions and advancements in the electricity systems established so far at a state, this will help to leapfrog India to the Energy Internet-oriented electricity system in the medium-term.

In future, researchers can explore the possibilities of providing a mathematical framework for the realisation of local energy markets for instantaneous peer-to-peer energy trading. This framework can be tailor-made for the Indian context by considering prevailing cost mechanisms, treatment of losses, power flow, etc. Next, a roadmap to implement the Energy Internet in India by transforming the present legacy system is a key area of contribution through extensive research. Finally, so far there is no study that has explored the financial feasibility of the Energy Internet. A socio-techno-economic study is essential to understand the cost dynamics of an Energy Internet, especially in the context of a developing country.

Data availability statement

No new data was created or analysed in this study.

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