Future Energy Systems

Mr. Abhilash Gopalakrishnan
Electrification - Distribution Automation, India Development Centre
ABB Global Industries & Services Ltd. Bangalore-560048,
abhilash.g@in.abb.com

Abstract: One eighth of the world population is still living without access to electricity. Energy supply chain majorly based on electricity is in focus. The shift from centralized to more distributed styles is evident in Smart Grids, Industry 4.0, Industrial internet and IoT, Society 5.0. With integrated communications being major party to smart grids, the information and communication technology integration in energy sector is a necessity. While in the US most of the discussion revolves around Smart Grid, the EU FINSENY project focuses on building the Internet of Energy. More than ever these systems seem to show convergence with ongoing technological developments. Technologies include power electronics on one hand and Information and Communication Technologies on the other. What really matters is the resulting customer value. In Energy systems the value is in integrating Distributed Energy Resources (DER), Energy Storage planning and implementation, interfacing with transmission systems and building a resilient grid. The purpose of this paper is to discuss the challenges, opportunities and standards worth watching.

Index Terms Energy System, Electricity, Cloud, Internet of Things, Control Systems, Industrial Internet.

I. Introduction

Energy plays a major role in global economic landscape. Electric Power systems are considered part of this critical infrastructure due to the significant role these play in human lives by providing energy to meet home and industrial needs. The fact that power systems involve human lives and expensive infrastructure such as turbines, generators and transformers etc. make their automation mission critical in nature. As per world energy outlook nearly one eighth of the world population is still living without access to electricity [1]. The key drivers of change include de-carbonization, reliability in the face of growing demand, electrification of transportation, empowered customers, market designs and regulatory paradigms. The enabling factors include technology advanced, policies and standards [2]. The electricity supply chain considers, generation, transmission, distribution and consumption aspects. The shift from centralized to more distributed architecture is evident in the evolution. The supply chain consists of primary equipment like turbines, generators, circuit breakers, switches, transformers and so on. The secondary equipment includes power system protection and control equipment, sensors, communication switches, Supervisory Control and Data Acquisition (SCADA), Distributed Control Systems (DCS) which constitute the automation elements.

The protection functions perform voltage and current measurements and application functions act based on these measurements. Power systems require microsecond reaction times and is based on open loop control to isolate the faulty section. The control aspects involve a closed loop control including feedback. These require actions in milliseconds. In the age of Industry 4.0, energy efficiency, electricity supply and sustainability are important [3]. The provisioning of energy subject to increasing resource usage and scarcity and environment concerns point to sustainability. Developing countries like India and China show growth figures up to 25%. The four key trends include, electrification of energy distribution, an increase in energy consumption, more dynamic electric loads and an increase in distributed generation.

The focus of this paper is to present the initial landscape and evolution to future of electricity-based energy systems and have a look at trends observed as future.

II. Initial landscape

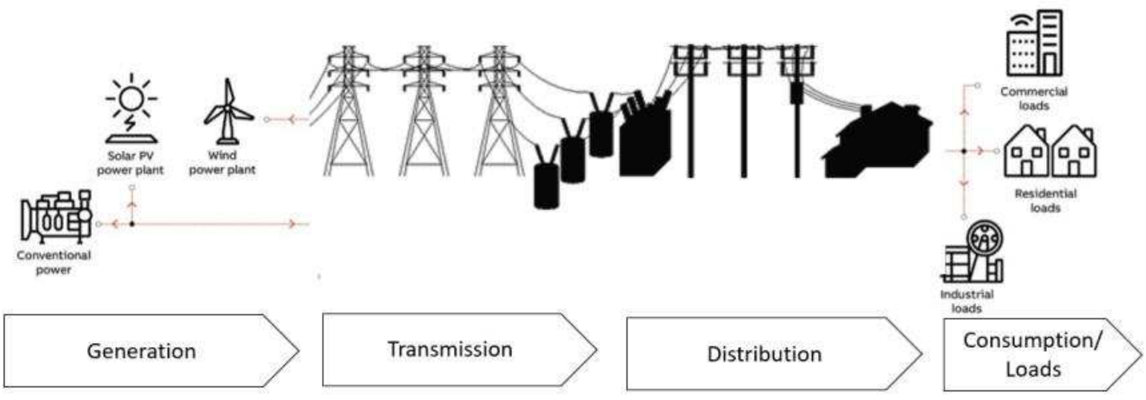

Fig. 1. Electricity Supply Chain.

As in Fig.1, in a traditional landscape, the electricity system is composed of a chain of generation, transmission, distribution and consumption with flow of electricity happening from generation to consumption. Across the world this is highly regulated sector driven majorly by utilities. Major parts of the system are built on Alternating Current (AC). The base loads are served by utilities which perform efficient generation but is less flexible. The traditional electricity supply chain is demand driven. For handling peak load in this system, we normally reserve some generation capacity. The voltage levels vary across the system.

For example, in Europe, the dominant standard generator voltage and frequency is11 kV and 50 Hz, while in North America, 13.8 kV and 60 Hz is the dominant standard generator voltage and frequency. India uses the 50Hz frequency. Voltage generation is economical at 11 kV and 33 kV. Mostly the voltage generated is 11Kv. It can be stepped up and stepped down for example 11 kV to 33, 66 or beyond according to requirements. The nominal voltage generated at Indian power plants range from 11kV to 33kV. When it reaches homes it is 220 volts, alternating at 50 cycles (Hertz) per second. The transformers play an important role stepping up and down voltage across the system. Transmission voltage in India (highest) is 750kV AC and these lines are erected by Power Grid Corporation for interstate connections throughout India. High Voltage DC (HVDC) is also used for transmission at voltages of 500 kV. The primary systems are well supported by automation, including substation automation for transmission and distribution substations including electrical relays, Remote Terminal Unit (RTU), switches and SCADA for local operator. Load Dispatch Centres are located in various parts of the country. The sector is highly standardized by bodies including IEEE, IEC, ANSI and BIS for India and categorized as electrotechnical standards. The system is many decades old and primary intention is to avoiding blackouts. Still major blackouts including the one in India in 2012, and recent incident in U.S, indicate deficiencies in the system. Taking a cue from Albert Einstein's famous quote– 'We cannot solve our problems with the same thinking we used when we created them'.

III. Evolution

There are two major initiatives one driven by Smart Grid in the U.S and another by Future Internet of Smart Energy by EU. The Smart grid vision generally describes a power system that is more intelligent, decentralized and resilient, more controllable and better protected than today's grid. The five key technologies include Sensing and Measurement, Integrated Communication, Advanced Components, Improved Interfaces and Decision support and Advanced Control [4]. The challenges include the need for:

1. Increase the efficiency of power plants.
2. To reduce stress on the grid resulting from higher demand peaking.
3. Facilitate large percentage of renewables with a stable grid and reliable supply.

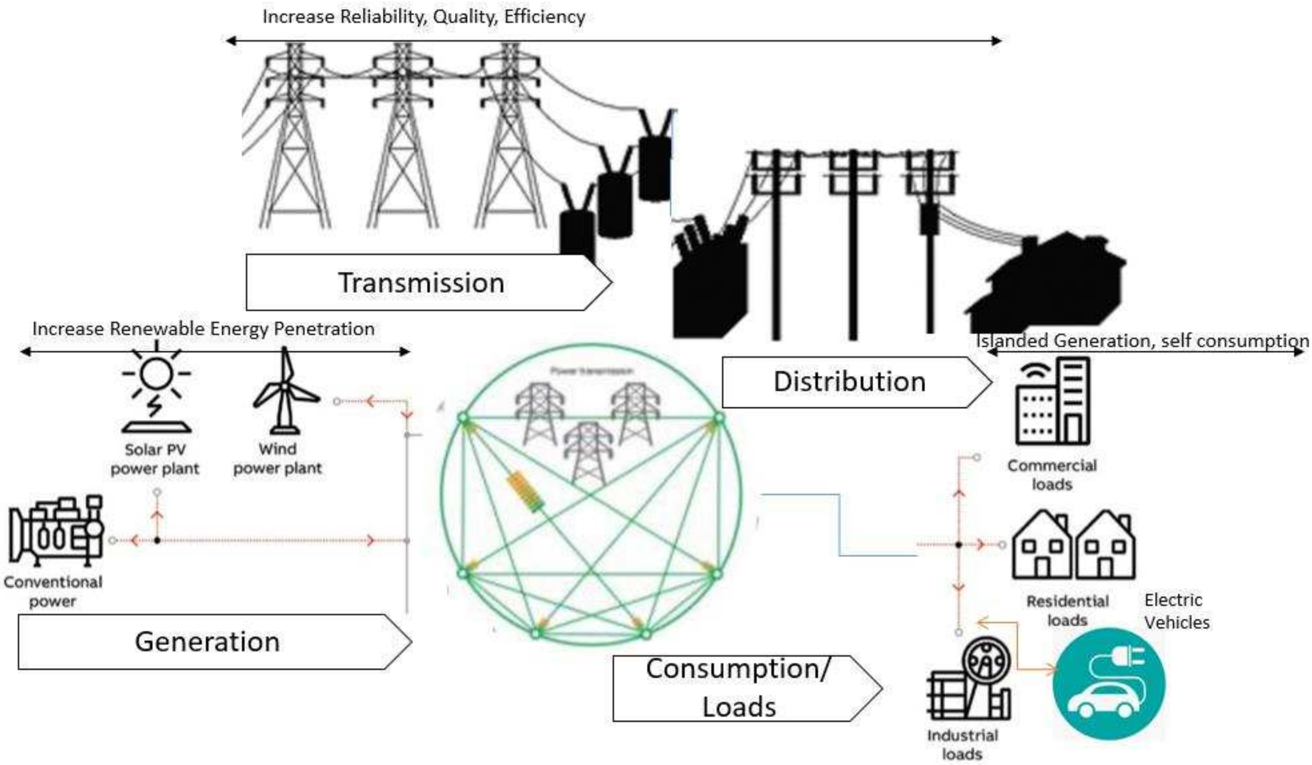

Fig. 2. Distributed/Mesh view of Electricity Supply Chain.

As in Fig. 2, the most important shift is from central to distributed generation. Next is impact of Information and Communication Technologies. These changes render the system in the form of a mesh network, reminding us of contemporary communication networks. Implications to customer include more flexibility, microgeneration, smart devices like smart fridge that switch off when idle. Implications to transmission and distribution includes grid capacity and need for large investments. With electric vehicles and stress on the grid – Stability, Reliability, Fault Tolerance are more important. Implications on generation include shift to sustainable energy supply (future without coal) but also considering reliability of sun/wind (renewables) a challenge. The traditional grid built on demand-based approach needs to be augmented with the right kind of automation systems to be able to take advantage of these advancements. This also necessitates the convergence of Information Communication Technologies (ICT) and Operational Technologies (Control). While control systems see availability, integrity and confidentiality as priorities, the information technology systems see confidentiality, availability and integrity respectively as priorities. The new philosophy focuses on a more distributed approach instead of completely relying on a central grid. On domestic level this would mean:

1. Distributed Generation
2. Distributed Storage
3. Demand Side Management (DSM)

The invention of rogowski coil (non-conventional) based current and voltage transformers enable significant flexibility in placing and measuring current and voltage. Another consideration is the Intelligent Merging Unit (IMU) which take input from sensors and stream the values enable significant digital capacities like functions of relays be more distributed. Today's fault detection, Isolation and Restoration Strategies requires methods like IEC 61850 GOOSE over ethernet. Wide Area Early Warning Systems (WAMS) using Phasor Measurement Unit (PMU) is another advancement. The resulting measurement from a PMU is termed synchro phasor. A typical PMU can report measurements with very high temporal resolution in the order of 30-60 measurements per second. This helps engineers in analysing dynamic events in the grid not possible with traditional SCADA measurements that generate one measurement every 2 or 4 seconds. The system needs time synchronization as to be able to maintain the sequence of events. New solutions on Demand Side Management (DSM) stand for the modification of consumer demand for energy through various methods such as financial incentives and behavioural change through education. Today, a number of utilities are implementing Advanced Distribution Management Systems (ADMS), that integrates many utility systems and provides automated outage restoration and optimization of distribution grid performance. ADMS functions include automated Fault Location, Isolation, and Service Restoration (FLISR); conservation voltage reduction; peak demand management; and volt/volt-ampere reactive (volt/VAR) optimization.

A large number of stakeholders are part of the system including governments, regulators, consumers, generators, traders, power exchange, transmission and distribution companies, power equipment manufacturing and ICT providers. To consider customer indices The Customer Average Interruption Duration Index (CAIDI) and System Average Interruption Duration Index (SAIDI) are significant.

FINSENY project envisions, a sustainable energy system combining critical infrastructure reliability and security with adaptive intelligence enabled by future internet. All sectors of economy rely on energy sector [5]. In order to maintain sustainability Europe has committed to 20/20/20 which stands for 20% reduction in greenhouse gas emission 20% renewables and 20% primary energy use reduction. The major challenges on the path include integration of DER, smart buildings and microgrid , engaging and empowering commercial customer to take more active role in energy markets, active shaping of the demand curve, support for EV charging infrastructure with mobile loads and enable new trading and information services in marketplace. Distribution is at the heart of the customer and to make distribution grid smarter it requires:

- A decentralized control monitoring structure across MV and LV Network
- Automation of grid operations
- An autonomous detection of fault condition and mitigation of restoration actions
- Dynamic adaptive mechanisms for active and voltages management of grid constraints
- Improved forecasting of generation and demand for more efficient operations and decision making.

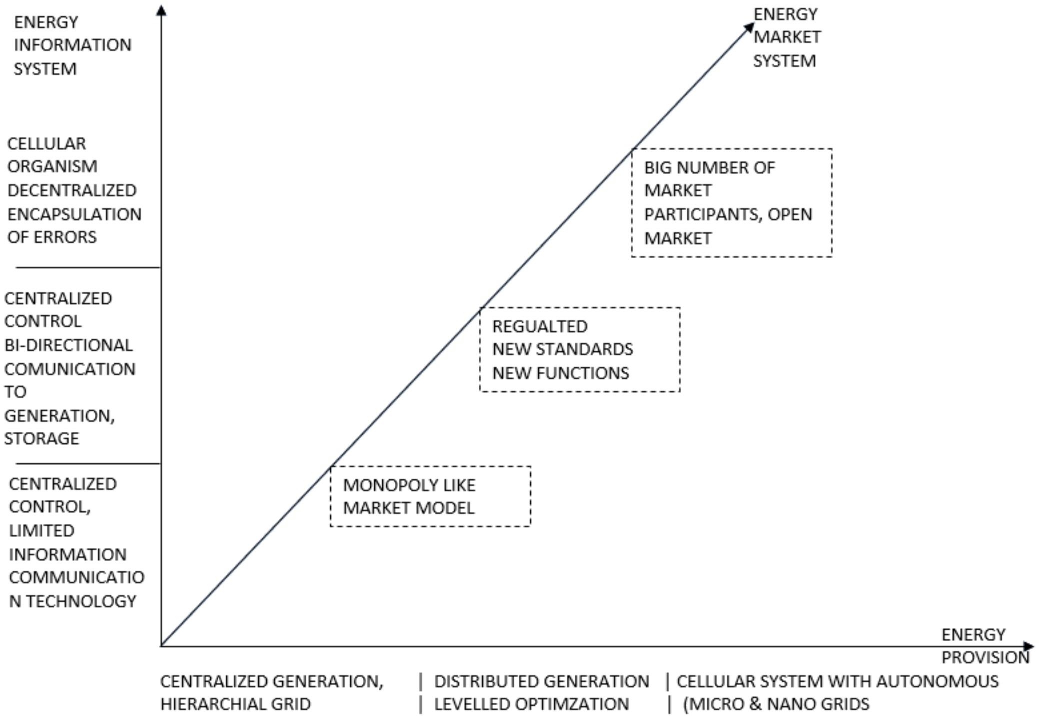

Fig. 3. A representation of trends and characteristics.

Fig. 3, presents a high-level view of evolution from information systems and markets perspective. The critical factors in energy Information, market-and power systems evolution include; Reliability, Safely, Security, Adaptability, Utilization and Intelligence. Reliability stands for minimum interruption to supply at all levels. Safety in this context stands for protection from dangerous occurrences. Security and compliance protect from intrusions. The adaptability aspect considers the wide energy sources, and a grid which is capable of self-healing through decision making as local. Improved utilization of assets by monitoring and control, gathering information of relevant customer assets such as to deliver the features are relevant as well. The ICT landscape consists of the evolution of communication networks including Internet of Things (IoT), Internet of Services, Cloud Computing, Fog Computing, coupled with connectivity management, service enablement, security and privacy considerations. Limitations of current internet to perform mission critical applications include the lack of priority guarantees, potential security gaps, and ability to satisfy short and deterministic latency requirements. The considerations in distribution network include microgrids, smart buildings, electric mobility, marketplace for energy. The evolution is also due to aging infrastructure and technology innovations.

The challenges are more apparent in the distribution systems where it is complex to plan, operate and maintain. In these systems, the considerations include integration of renewable energy sources and electric vehicles, energy storage, demand side management, use of power electronic equipment for lighting and drives and response to recent extreme weather events [6,7]. The utilities focus is on customer service, system reliability and operational resiliency. Certain percentage of load support can come from energy storage. This necessitates additions of metering equipment, system monitoring capability and more advanced control and protection technologies. The challenges include:

A. Integration of Distributed Energy Resources (DER)

Rooftop solar PV is becoming very popular. Wind Turbines and Fuel cells are other major alternatives. These may or may not be connected to grid. Utility owned DERs might be configured for minimum impact. As such DERs are largely non-dispatchable and do not to contribute to system capacity. These are not available for frequency control, but still contribute to capacity deferral.

B. Energy Storage Planning and Implementation

The approaches include chemical, thermal and mechanical. Energy storage decouples generation and delivery by time shifting energy in terms of min, hours, days. The benefits include load shaping, peak load deferral, supplement/ backup power, power arbitrage, voltage control and frequency regulation.

C. Interfacing with Transmission Systems

Historically transmission and distribution are two different systems. With bidirectional power flow, the borders are blurring. The lines between Medium Voltage (MV) and Low Voltage (LV) are seem as converging.

D. Natural Disasters and their influences

Extreme weather events like tsunami, monsoons destroy equipment and lead to blackouts. Modern weather forecasting provides advance warning letting utilities and operator to plan for infrastructure and redesigns to prevent damage. Underground feeder circuits, building redundant /direct communication paths helps in improving system reliability and minimize service interruptions.

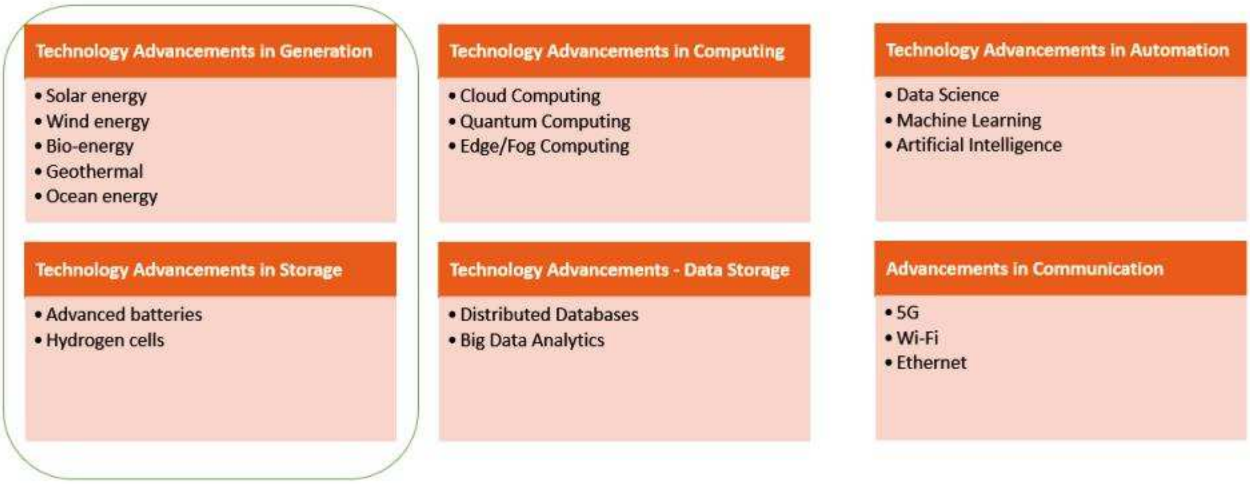

Fig. 4. Microgrids Architecture.

One of the approaches which is involved distributed control and also discusses autonomy is Microgrids [8]. As in Fig. 4, microgrids are electricity distribution systems containing loads and distributed energy resources, that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded. Microgrids closely resemble a hybrid car, where the car is partially driven by electricity and possess storage in form of battery, thereby enabling a continuous supply. Since renewable sources like sun are intermittent, it is important to integrate a reliable source which is not dependent on environmental conditions.

Lessons learnt from deployments across the world include the need of major sensing capability addition, a reliable and secure communication system, interoperability based on standards, data management, visualization, archiving, bad data detection, time synchronization, data confidentiality and sharing. McKinsey reports only 20% of potential usage of data in industrial systems. A distributed intelligence is as well needed. Cyber Security for distribution system and protecting privacy are necessary as new technologies are adopted.

III. FUTURE

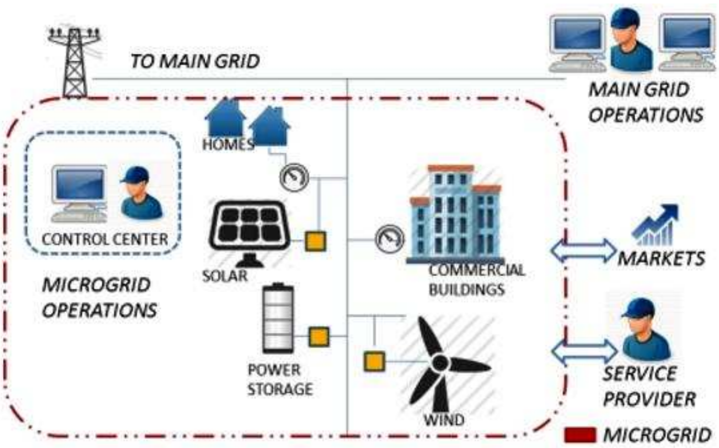

Fig. 5. Technology Advancements relevant in Energy context.

Fig.5, represents some of the advancements relevant to energy context. The two key technology considerations include power electronics which plays a significant role in power flow and stability, while automation mainly driven by significant use of software and electronics or embedded systems. A resilient grid requires intelligence which is achieved using data to insights approach. The compensation systems like Static Synchronous Compensators (STATCOM) using power electronics to control power flow and improve transient stability on power grids is important. Here the Information Communication Technologies like Cloud computing, which provides distributed processing, storage and availability is going to play a major role. Wide are warning systems necessitate the needs for Big Data Analytics since the data coming from PMUs is big [9]. The data consists of both operational data and non-operational data. The need for analytics includes data analytics on available data for root cause analysis and streaming analytics based on real-time data. Cyber Physical Systems with their significant capabilities of analysing 'What If' scenarios may also play a major role in the evolution of these systems. Cloud lets data collected to be processed elsewhere, Internet of Things lets us reach every nook and corner unravelling data, while Machine Learning lets us find patterns and relations leading to insights using analytics [10,11]. Artificial Intelligence lets us perceive the environment and perform actions to achieve goals. What really matters is the resulting customer value. In energy context, safety and reliability is also major consideration in customer value. We follow Steve Job's quote; 'You have to start with the customer experience and work backwards towards technology'.

IV. EMERGENCE OF STANDARDS AND FRAMEWORKS

Standards include Distributed Generation aspects of IEEE 1547, Substation Automation considerations in IEC 61850, NIST Smart Grid Framework and EU Framework [12,13,14,15]. The major focus is around interoperability and resilient grid. More than smartness the system requires to be resilient so that it can survive the new situations created due to the changes. A major element in this experimentation is the Micrograids. These distributed concepts and the control approaches followed could be scaled to bigger systems. The entire effort can be seen in the context of three aspects of Customer Experience, Handling Uncertainty and towards autonomy. For example, standards like IEC 61850 focuses on interoperability across multiple vendors and enables significant digital capabilities in relays. Another set of standards NERC-CIP and IEC 62351 focus on the Cyber Security Considerations while IEC 62351 focuses on redundancy aspects for reliability and availability in these systems.

V. INSIGHTS, OPPORTUNITIES AND APPROACHES

Based on Three Layer Product model by Jan Bosch [16], Fig. 6 provides a representation of technologies and methods. Those which are standardized and stable are becoming a commodity. The differentiation includes latest technologies including big data analysis, virtual generation using power electronics. Experimentation layer involves modelling and simulation and Cyber Physical Systems which will enable faster experimentation and evolution.

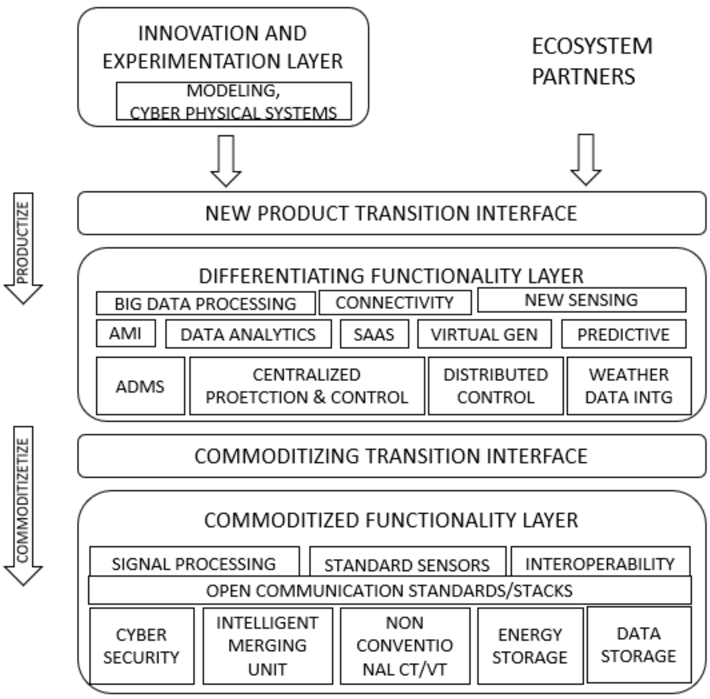

Fig. 6. Energy System Advances seen in Three Layer Product Model.

The capabilities of latest technologies including connectivity would play a major role in the ability for faster experimentation. Power System Standards of IEC 61850 and maps the same to Web protocols like HTTP. Approaches like blockchain are considered in energy trading.

The major improvement involves the theme of sustainability. Sustainable electricity supply chain consisting of clean energy systems and thereby decelerating climate change is in focus. In this context Blockchain technologies are considered to support smart contracts, consensus, encryption and data storage [17]. These systems enable tracking of the energy systems towards clean energy [18].

VI. Summary

Customer value in the in-energy context includes, safety and reliability in addition to key considerations like interoperability, resilience. The two key technology considerations include power electronics which plays a significant role in power flow and stability, while automation mainly driven by significant use of software and electronics or embedded systems. The systems focus on customer experience, handling uncertainty and creating a path to autonomy. The experimentation in these systems consider factors like Microgrids and also usage of Cyber Physical Systems, Blockchain etc, thus enabling delivery of innovative experiences to customers and enabling sustainability.

References

[1] World Energy Outlook 2018. https://webstore.iea.org/download/summary/190?fileName=English-WEO-2018-ES.pdf
[2] IEEE Vision for Smart Grid Controls: 2030 and Beyond. http://amfarid.scripts.mit.edu/resources/Books/SPG-B02.pdf
[3] Klaus Schwab,"The Fourth Industrial Revolution", Jan 2017.
[4] Krzysztof Iniewski, 'Smart Grid Infrastructure & Networking', ISBN-13: 978-0071787741, McGraw Hill.
[5] FINSENY project publications. http://www.fi-ppp-finseny.eu/publications/
[6] Ratan Das and Working Group K15, 'Looking into the Future Protection,Automation and Control Systems'
[7] Ratan Das, Vahid Madani, Farrokh Aminifar, John McDonald, S. S. Venkata, Damir Novosel, Anjan Bose and Mohammad Shahidehpour, 'Distribution Automation Strategies: Evolution of Technologies and the Business Case'
[8] C. Nayar, "Innovative remote micro-grid systems
[9] Reza Arghandeh et al, Big Data Application in Power Systems
[10] Kai Hwang, Jack Dongarra, Geoffrey C. Fox,"Distributed and Cloud Computing: From Parallel Processing to the Internet of Things", 2012.
[11] P. Mydra and K. Donahoe, "The true vision of automation," IEEE Power & Energy Magazine, vol. 5, no. 3, pp. 32–44, May/June 2007.
[12] IEEE 1547 and 2030 Standards for Distributed Energy Resources Interconnection and Interoperability with the Electricity Grid. https://www.nrel.gov/docs/fy15osti/63157.pdf
[13] Core IEC Standards. https://www.iec.ch/smartgrid/standards/
[14] NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 3.0. https://www.nist.gov/el/smartgrid/nist-framework-and-roadmap-smart-grid-interoperability-standards-release-30-draft
[15] India - Country Report on Smart Grids. http://dst.gov.in/sites/default/files/India%20Country%20Report%20on%20Smart%20Grids.pdf
[16] Jan Bosch,"Achieving Simplicity with the Three-Layer Product Model", IEEE Computer, Nov 2013.
[17] Jiani Wu 1, and Nguyen Khoi Tran , "Application of Blockchain Technology in Sustainable Energy Systems: An Overview", Aug 2018.
[18] Tracking Clean Energy Progress. https://www.iea.org/tcep/energyintegration/smartgrids/

About the Author

Abhilash is Principal Engineer in Electrification Division- Distribution Automation R&D at ABB based in Bangalore, India. In Product Development for over 20 years, he has been majorly focusing on Architecture and Design of Software Systems. He completed his Bachelors in in Mechanical Engineering in 1998, Master's in Software Systems from BITS, Pilani in 2010 and Architecture and Systems Engineering Professional Certificate from MIT Professional Education in 2017. Passionate about building world class systems and products, his interests include Decision Support Systems, Cyber Physical Systems and Innovation and Technology Management. He has 3 granted patents and over 10 publications to his credit. He is a Senior Member of IEEE and Member of ACM.

"The challenge of leadership is to be strong, but not rude; be kind, but not weak; be bold, but not a bully; be thoughtful, but not lazy; be humble, but not timid; be proud, but not arrogant; have humor, but without folly." – Jim Rohn

"A leader is one who knows the way, goes the way, and shows the way." – John C. Maxwell