Sustainable-Big Data Analytics for the Smart Grid

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The smart grid enables efficient communication between utilities and the end- users, and enhances the user experience by monitoring and controlling the energy transmission. The smart grid deals with an enormous amount of energy data, and the absence of proper techniques for data collection, processing, monitoring and decision-making ultimately makes the system ineffective.

smart grid big data analytics

1. Smart Grid

The smart grid integrates both the behaviours as well as the actions of overall users, such as generators, consumers and generator–consumers in a cost-efficient manner. Due to this integration process, less power loss occurs and high-quality power output is produced, as a result of which the power system remains cost-efficient and sustainable. In addition, the system is secured with safety measures. New products, technologies and services with regards to control, communication, intelligent monitoring and self-healing are nowadays incorporated in smart grids. These entities bring different benefits, such as easy connection and facilitation of operations for generators of all sizes and technologies. Here, consumers play a vital role in the optimization of system operations, while they are also aware of the information about the systems. Further, the load demand can be effectively optimized, which can significantly reduce environmental pollution in the whole electricity supply system. In addition to this, customers can perform appropriate maintenance, ameliorate existing high system levels and ensure reliability, quality and security of supply [1].

Most of the definitions converge at a single element, i.e., the smart grid has digital processing and communications, due to which the data flow control and information management prevails as the crux of the system. The smart grid has different potentials, thanks to the deeply-integrated application of digital technology in power grids. The information which is integrated with the new grid remains the critical issue when it comes to smart grids. Today's electric utilities undergo three levels of transformation, which form the core principles of the smart grid, such as improvement of infrastructure, a strong grid and the addition of a digital layer. Further, business process transformation is required to capitalize on the investments made in smart technology. Electric grid modernization works that have been carried out earlier in substations and distribution automation are now included in the smart grid concept itself. The smart grid corresponds to the complete set of current as well as proposed responses to challenges encountered in power supply. With the involvement of different factors with competing taxonomies, there is no specific universal definition available so far for smart grids. Challenges encountered during the integration of renewable energy resources into smart grid systems are addressed for the virtualization of the projected grid architecture. Both innovative as well as robust modelling of different components are required. The integration of novel technologies into the conventional grid is critical, and the implementation of smart grid architectures with RESs should be incentivized [2].

The flow of power generated from different energy sources into the grid makes the energy system highly robust and adaptive, especially when it comes to matching supply and demand. When global infrastructure needs to be upgraded, a seamless supply of electricity plays a central role. The modern electrical power system bolsters the present as well as future digital economy, and it also buttresses the development of safety, health and national security. Our energy infrastructure encounters a lot of threats, in the form of nature (extreme weather conditions), cyber-attacks (for instance, hackers), physical attacks (terrorism), etc. In this situation, smart grids improve the sustainability of renewable energy resources. These smart grids contribute towards energy conservation and cost-efficient energy management, which finally add value to a clean energy environment [3][4]. Data management systems, sensors, smart meters and appropriate monitoring systems are part of the process of smart grids. Smart grid and, subsequently, the smart metering technologies, is the need of the hour to achieve a sustainable electrical utility. Here, an information system network is required so that it ensembles all substations in coordination with user facilities as well as utilities. However, one should be equipped with high-end system analysis as well as trustworthy communication systems that serve as the pillars of smart grid visibility. Remote communication management among various head-end systems, where the connection is established with smart meters, is one of the primary challenges that require attention. Smart meters are intelligent measurement systems that consist of a smart meter gateway, digital electricity meter and a communication module. In this regard, one can perform real-time estimation of both consumption as well as production characteristics of power, even at individual installations. For instance, an uninterrupted transfer of network status data occurs at the data network, where it is managed, bundled and again transferred to an energy supplier through gateway administrator. Here, the role of gateway administrator is played by meter operator or, otherwise, a local network operator themselves. The smart grid, when implemented successfully, is predicted to solve the confinements experienced in the delivery and distribution of power [4][5]. In the process of achieving this visionary objective, the stakeholders are advised to strategize their utilities and state-level policies.

When distributed energy resources such as energy storage systems, solar photovoltaic and combustion engines are integrated, various advantages can be reaped, which include reduction in system losses and optimized energy consumption as well as economic savings, enhanced resilience, improved power quality and customer participation. In this scenario, the existing grids cannot be coordinated or managed via Distributed Energy Resources (DERs). Electricity flow can be controlled in every household, or even for every smart appliance of the customer. Thus, it can be inferred that the smart grids of the 21st century are set to change grid dynamics drastically, potentially giving rise to the ‘Grid of Things’, similar to the concept of the ‘Internet of Things’.

1.1. Big Data from Smart Grid Operations

Digital transformation enables the integration of renewable energy, sustainable communities and growth of industries, which altogether results in better and more coordinated economic growth. A combination of both grid visualization and grid management aids in making predictive decisions and better situational awareness [6]. Further, smart grids introduce end users into the energy trading system, rather than keeping them as a mere consumer, through demand response, Electric Vehicle (EV) charging, self-produced distributed generation and energy storage. Accordingly, an enormous amount of data gets generated based on the involvement of various stakeholders, which opens multiple data analytics market possibilities surrounding the smart grid [7]. It is important to ensure big data management to leverage the data generated by these processes to gain insights, as shown in **Figure 1**.

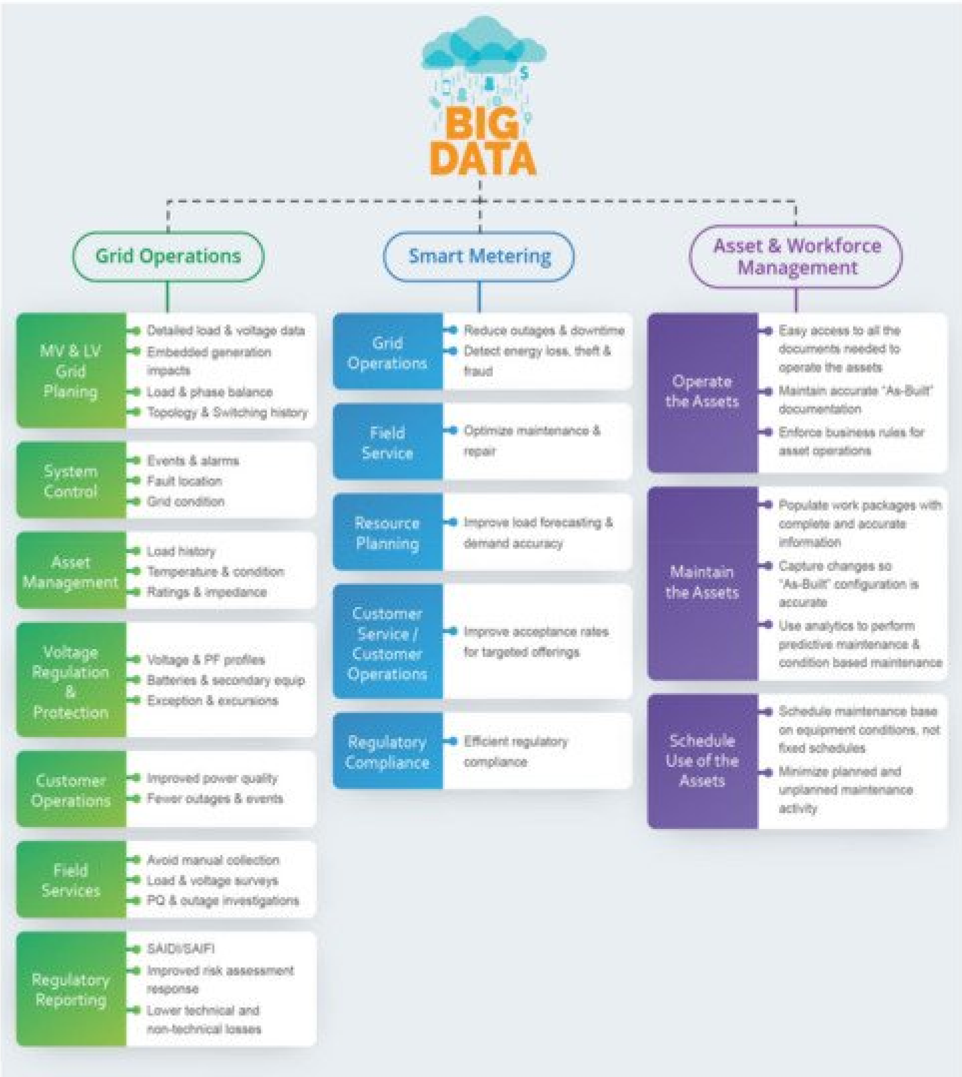

Figure 1. Smart grid big data generated from grid operations, smart metering and asset and workforce management.

1.1.1. MV and LV Grid Planning

At the time of modernizing smart grids, grid planning is crucial, since the grid connection integrates both low as well as high voltage renewable energy sources. When renewable energy sources and electric vehicles are integrated with low voltage grids, it may increase the voltage's volatility [8]. A comprehensive database should be available with information about the cause for voltage volatility. This information would be made available to the distribution system operator for planning. Further, load forecasting should be critically analysed with the available grid transmission and generation data to enumerate a realistic estimate of load distribution. The ultimate goal is to produce sustainable power through load balancing [9].

Impact of Embedded Generation

The networks are designed in such a way that the voltage increases when there is a reverse flow of power from embedded generators. When an embedded generator is connected with a weak network or when power is forced to flow via a weak network, the losses may increase. In numerous cases, there is a positive contribution from embedded generators in terms of reduced volume of network technical losses. During maximum generation using minimal load, the embedded generators may increase the loading levels of transformers and transmission lines. Hence, the generated data can be utilised by control centres for effective grid control [10][11].

Load & Phase Balance

Unbalanced voltage may occur when phases, attached to the grid, are not equally utilized. This grid imbalance may eventually result in impaired control equipment, impaired regulation equipment, uneven loading of the transformers, reactive power costs and uneven motor operation (losses, wear). Grid imbalance occurs due to disruption in the requirements of utility companies [12][13].

1.1.2. Asset Management

When there is an asset management system in place that works according to data analytics and condition-based maintenance, the chance for equipment failure risks is minimal. Further, it also maximizes the equipment's life expectancy. The results of effective asset management can is reflected in reliable service, reduced emissions, lessened costs and increased efficiency for end users [14].

1.1.3. Voltage Regulation and Protection

Across the globe, geographical conditions vary from one country to another. To provide reliable and regulated voltage for the consumer, proper voltage regulation becomes imperative. After integrating with the smart grid, batteries play a crucial role in mitigating the challenges of power quality through electric vehicles. The batteries' selection is an important parameter for better voltage regulation when connected with the smart grid. To construct efficient renewable energy storage systems, attention should be focused on desirable qualities including cycle life, flexible sizing and excellent renewability categorised batteries [15][16].

1.1.4. Customer Operation

Harmonics, voltage sags and power interruptions are predominant power quality issues faced by the consumer, who incurs a heavy economic loss. There are numerous challenges associated with poor power quality in the industry. Software bugs, COVID-19 pandemic outbreak, temperature, radio frequency, equipment EMI, temperature, operator errors, humidity and radio frequency interference are some of the challenges faced by consumers in terms of power quality. It is important to monitor the data for power quality to assess the performance of the network [17].

1.1.5. Field Services

Field services play a vital role in effective operations, investment plans and forecasting maintenance. The data collected from field instruments are collated at the control room to optimize the plants, equipment, people, assets, etc., during the life cycle of every asset.

1.1.6. Customer and Utility Operations

When using smart meters, electricity consumers or end users gain better benefits due to increased accuracy in billing and fast and flexible service. Smart meters receive the data and update them to consumers. Further, it also saves the interval load data to raise an invoice for the customer based on their usage. Customers can save costs by reducing their usage during peak periods based on real-time information. Likewise, the utilities that look for cost-cutting can serve their consumers in a better way and raise their efficiency [18].

1.1.7. Regulatory Compliance

There is a need to establish a legal foundation for data collection as well as the processing of energy consumption data collected from consumers. This is to ensure that the customer’s privacy is respected and protected. According to regulatory compliance, energy consumption data recorded by smart meters are tagged as personal data. There must be regulations for the data collected from the smart grid with regards to the performance of standards for making and keeping appointments, a prompt fixture of faulty meters and reestablishment of supply after the debt is paid off. These regulations help the smart grid system to be efficient [19][20].

1.2. Asset and Workforce Management

Asset and workforce management enhance the operation and maintenance of utilities, while the consumers and stakeholders of the smart grid are invoked to improve the efficiency and economy. In addition to these, it also ensures secure billings, information and subsidy benefits [21].

1.2.1. Operation of the Assets

The smart grid’s assets generate huge volumes of multifaceted data from hardware and software systems. These data are utilized to integrate renewable, transmission and distribution equipment, used for power quality, ICT, storage devices and electric vehicle applications. All these data can be easily accessed to operate the assets. Data collection patterns and plans are important documents and are pointed out as “As-Built” documents that support the functioning of assets, for which verification is important to maintain accuracy [22].

1.2.2. Asset Maintenance

The smart grid involves different operations and measurements in generation, transmission and distribution. These real-time data are acquired completely and accurately from different stakeholders. These data are used in analytics platforms to perform predictive maintenance and condition-based maintenance [23]. Policy makers examine the utilities to formulate business rules for asset operations that successfully handle metering of the data and operations [22][24].

1.2.3. System Control

A combination of both intelligent alarm processors and optimal fault identification provides an overview of defects and their whereabouts. Smart grids can be secured with various factors, such as the optimization of fault location, quick response methods and protective relaying, based on new communication techniques [25][26]. The owner of an asset must proactively take actions to increase the asset’s availability, optimize the costs incurred in asset management and mitigate the risks that potentially threaten the operations. With utility asset management, companies can observe the usage, age and maintenance history as well as other such variables of an asset [27]. One must record the data with regards to voltage, power factor, recharge life rating and battery discharge level to ensure voltage regulation and protection [28].

1.2.4. Regulatory Reporting

When a smart grid is regulated under optimum conditions, it increases the economy of the asset through an efficient electric network. This results in effective management of transmission as well as distribution networks that in turn improve network security. There is a provision available in smart grids to generate regulatory reports, through which serious threats can be identified and prevented. In this way, technical and non-technical losses can be mitigated [29].

1.3. Big Data from Smart Metering

1.3.1. Grid Operations

At the time of using smart meters, the entire grid gains proficiency via accurate meter reading, power outage response and the detection of energy thefts. There is no need to conduct onsite visits to record the meter reading. The energy sector in India faces a common issue, i.e., power theft, which can be minimized or even eliminated with smart meters [30]. When using smart meters, the place where energy is utilized can be tracked and real-time monitoring of power usage ensured. This, in turn, enhances the transparency of the system. Further, power outages can also be reduced by smart meters. These smart meters enable the power distributors to forecast power demand fluctuations and respond quickly and autonomously. In this manner, the distribution and reliability of the energy provider are improved [31].

1.3.2. Field Service

In the case of smart meters, one needs to manage field logistics and a set of reports upon data collection, reporting, processing, configuration, maintenance, installation, meter-reading and outage response daily. The technicians tend to standby round the clock to tackle emergency calls. However, they may not be required to address general repairs and regular maintenance. When it comes to smart meters in the smart grid, both maintenance and repair become easy.

1.3.3. Resource Planning

Smart meters control energy consumption and perform real-time monitoring. These actions produce huge volumes of measurement data that can be utilized in the prediction of load demands. Since smart meters track electricity consumption patterns from time to time, these data are highly helpful in enhancing the load forecasting functions.

1.3.4. Scheduled Use of Assets

Schedule maintenance in the smart grid is based on equipment conditions, and not based on a fixed schedule. Proper scheduling of assets in the smart grid tends to reduce both planned and unplanned maintenance activity, which in turn reduces the cost involved in operations [32].

2. Role of Big Data Analytics in Smart Grids

With the increase in distributed generation, data-based customer interface and alternative energy sources, the utilities are coordinating with each other to produce an information-based digital economy [33]. Today's energy sector faces various challenges such as delayed outage response times, theft of information and cyber security, integration of large-scale distributed energy generation and energy storage, implementation of electric vehicle charging and smart grid business models. The digitized grid allows excellent control and intelligent monitoring capabilities. In addition to the above merits, smart grids can diminish the loss of power and data thefts by altering real-time electrical parameters such as phase, power, current and voltage. It can also identify the source of theft by tracking the location and pointing out the exact source of theft [34][35].

The taxonomy of big data analytics for the smart grid is shown in **Figure 2**. The figure showcases the sources of big data, components of big data analytics, big data-enabling technologies, functional elements in a smart grid and the types of big data analytics.

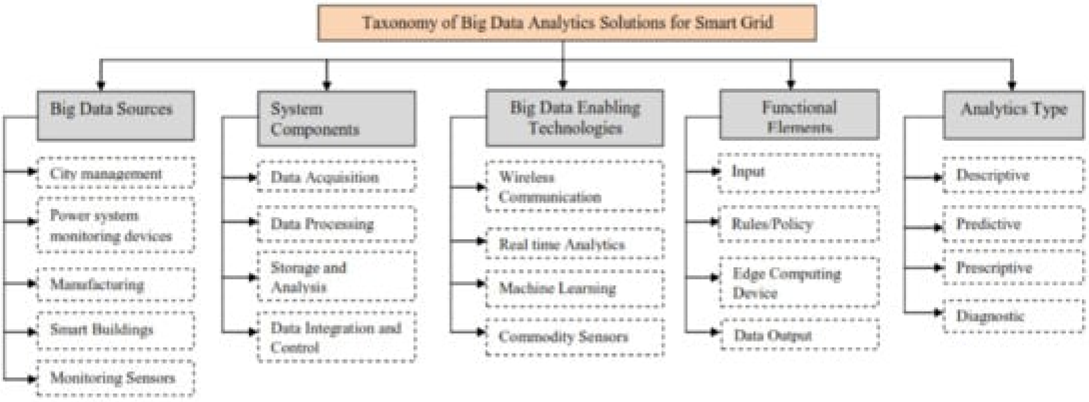

Figure 2. Taxonomy of big data analytics for the smart grid.

2.1. Key Issues in Smart Grids and the Outcomes of Big Data Implementation

Traditional grid systems do not have the facility for data acquisition and monitoring. They also lack the potential to handle real-time processing of huge volumes of structured as well as unstructured datasets in the energy sector, which can confuse analysts.

These copious data can be handled through big data analytics easily, predictive analysis especially can aid in better and faster decision-making, which can be supportive to achieve strategic business objectives, as shown in **Figure 3** [36][37][38][39]. Dynamic and efficient energy management is possible in smart grids, with the help of big data analytics and better grid visualization, as shown in **Figure 4**. This shows that the smart grid, coupled with big data, provides a lot of advantages in terms of power generation optimization in power plants, improvement of customer interaction, optimization of emergency response to outages in domestic coverage, optimization and planning of transmission and smart distribution from transmission and distribution sides, and efficient involvement of DERs as well as electric vehicles, from the commercial side [40]. Efficient energy utilization with greater preference to renewable energy is enabled by close monitoring of data and information that can offer proficient schedules through a smart meter. Further, power quality devices with efficient ICT can achieve suitable power generation and reduce environmental hazards [41][42][43]. **Figure 5** also depicts the involvement of dynamic and modern data analytics coupled with optimum and high-performance computing with efficient data network management for the smooth functioning of smart grids [44][45][46]. This model can also predict the challenges and opportunities present in the energy sector and utilities. It also produces knowledgeable cognizance, good situational awareness and predictive decisions. There occurs a dual-flow transfer of data and power in smart grids, i.e., between consumers and suppliers. This enables power optimization with regards to power sustainability, energy efficiency and reliability. Energy management is directly related to environmental preservation and economic growth. Better optimization and energy management by utilities and consumers contribute towards the achievement of SDGs [47][48][49]. Therefore, both of the stakeholders (consumers and producers) actively participate in energy market trading, which results in dynamic energy management with load forecasting and renewable energy production.

Figure 3. Key issues in smart grids and outcomes of big data implementation.

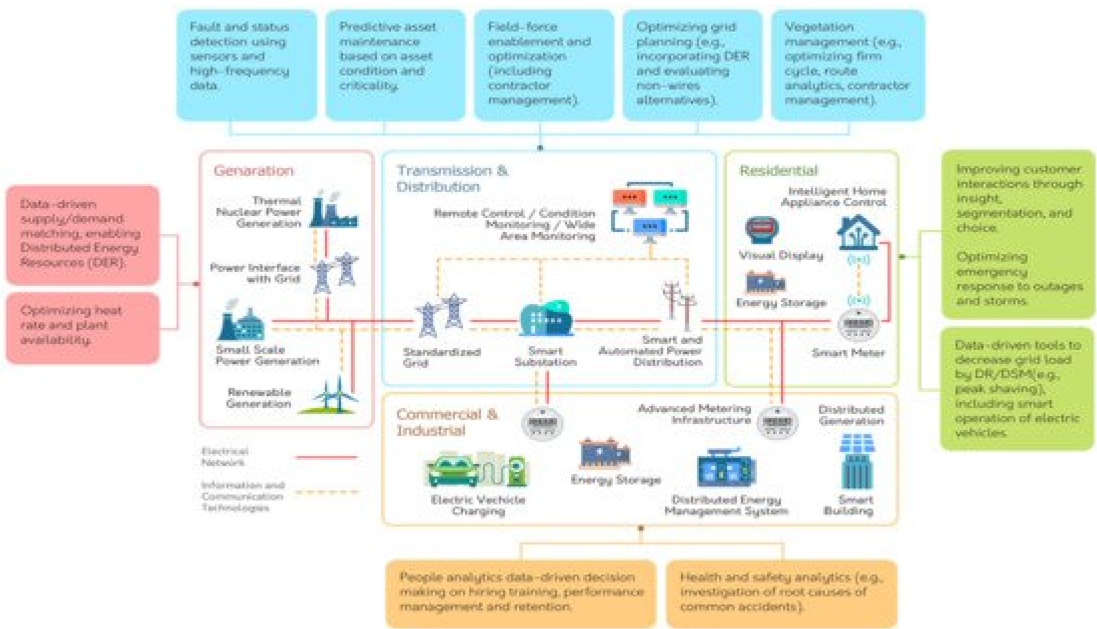

Figure 4. Analytics strategy development model with big data and better grid visualization.

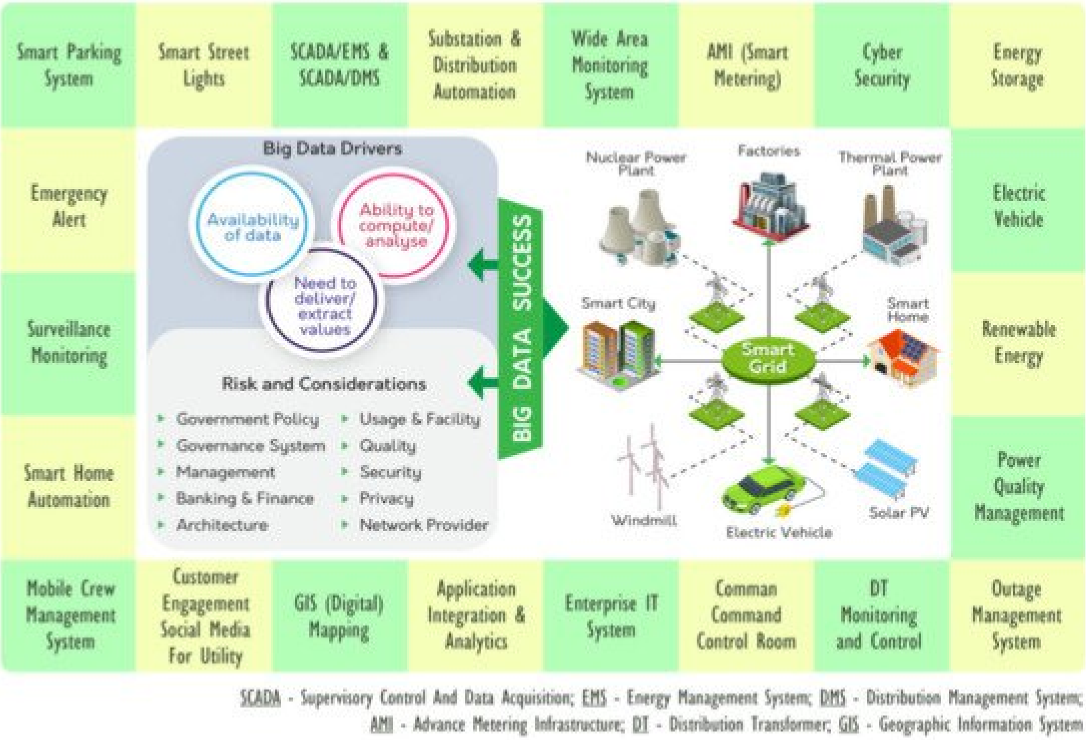

Figure 5. Big data in smart grid management systems.

The achievement of SDG 7 depends on the involvement of socioeconomic and technical aspects of the energy sector. Many perspectives are considered in a big data-enabled smart grid system to attain socioeconomic development. Regulatory and government policies, governing systems, implementation of new architecture and finance are the cardinal factors to be considered while implementing sustainability practices [29][50]. Through big data analytics, efficient energy data management is feasible, which aids in the achievement of SDGs. However, the concerns with regard to electric vehicles, integration of energy storage with existing grid, intelligent metering, cyber security, application of analytical software, surveillance monitoring and digital mapping are under the control of government organizations in most countries. **Figure 5** showcases the outcomes achieved through successful big data analytics in terms of smart grid management with data from Energy Management Systems (EMS), Distributed Management System (DMS), Advance Metering Interface (AMI) and Geographical Information system (GIS). These systems offer better surveillance and data monitoring for analytics and decision making in the smart grid to attain sustainable goals [51][52][53][54][55][56].

Smart grids have different applications installed, such as outage management, energy management system, fault protection, distributed asset monitoring, EV smart charging, integration of weather data, dynamic voltage control, centralized capacitor bank control, automated feed reconfiguration and distribution, as well as substation automation with advanced sensing. In addition to these, provisions such as load forecasting, demand response, shifting and advanced demand maintenance are also installed. The smart grid enables provisioning for the identification of electricity theft, prepaid customer plans, mobile workforce management and remote meter reading [57]. The smart grid system is an automated and self-sustainable electricity network system that can control and monitor the smart meters and can analyse the data in the supply chain. This system can rapidly resolve the issues and reduce the manpower involved in a safe, reliable and sustainable manner. Furthermore, it also provides quality electricity to all of its consumers simultaneously.

This characteristic enables the smart grid to supply power received from widely distributed sources such as solar power systems, wind turbines and hybrid EVs [37]. The smart grid monitors the substations and controls the non-critical and critical operational data, for instance, breaker, transformer status, power factor performance, power status, security, etc., as represented in **Figure 5**. It also shows that Programmable Logic Controller (PLC), wireless, cellular, SCADA (Supervisory Control and Data Acquisition) and Phasor Measurement Unit (PMU) are some of the technologies utilized in smart grid communications to determine the electrical signals travelling in the electricity grid. The time synchronizer enables simultaneous synchronized real-time measurements of multiple remote measurement points on the grid, which results in the collection of a sufficient volume of data for futher analysis [58].

Using big data analytics, the collected data is analysed and the results are helpful in forecasting safety-related issues in equipment connected with smart grids, as shown in **Figure 6**. It showcases a clear process and the role of big data analytics in determining the load limits, power outage and asset management in the smart grid. The information is collected from various sources such as social media, grid operations and consumers and assessed with smart grid information for better load management. Energy demand is forecasted by the smart grid using big data analytics based on the information retrieved from load curves. This information is a collective of energy production and distribution patterns of renewable energy in the grid [59].

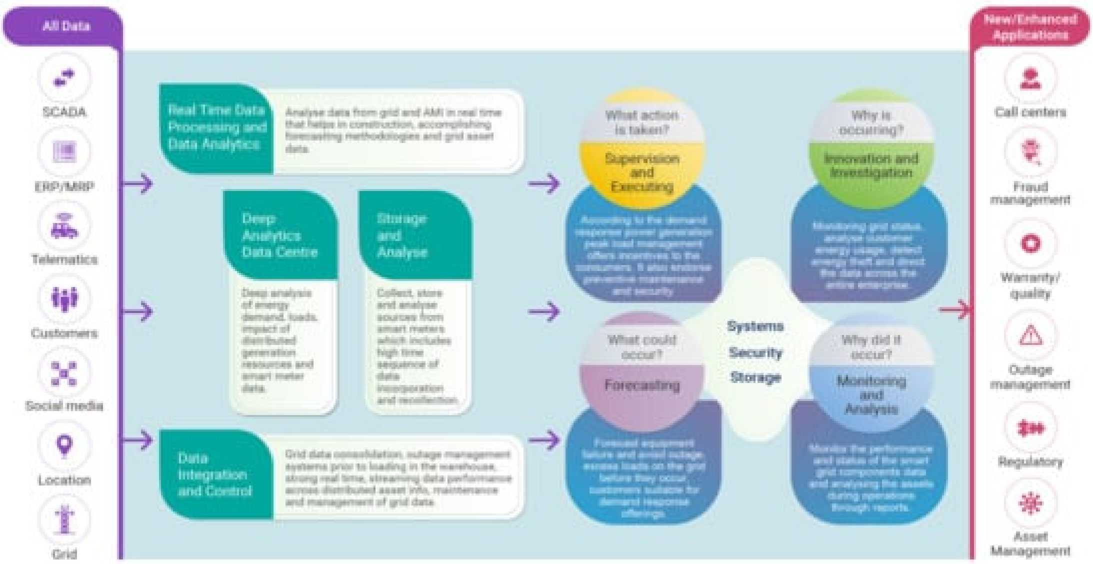

Figure 6. Real-time application of big data and analytics in the smart grid.

2.2. Big Data Analytics Process in the Smart Grid

Figure 6 thoroughly explains the role of big data analytics in the smart grid with four questions. From **Figure 6**, the readers can get a clear view of big data analytics and how it is helpful for the smart grid to have efficient energy management.

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