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Internet of Things in Sustainable Energy Systems

Abdul Salam

Purdue University, salama@purdue.edu

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Chapter 6
Internet of Things in Sustainable Energy Systems

Abstract Our planet has abundant renewable and conventional energy resources but technological capability and capacity gaps coupled with water-energy needs limit the benefits of these resources to citizens. Through IoT technology solutions and state-of-the-art IoT sensing and communications approaches, the sustainable energy-related research and innovation can bring a revolution in this area. Moreover, by the leveraging current infrastructure, including renewable energy technologies, microgrids, and power-to-gas (P2G) hydrogen systems, the Internet of Things in sustainable energy systems can address challenges in energy security to the community, with a minimal trade-off to environment and culture. In this chapter, the IoT in sustainable energy systems approaches, methodologies, scenarios, and tools is presented with a detailed discussion of different sensing and communications techniques. This IoT approach in energy systems is envisioned to enhance the bidirectional interchange of network services in grid by using Internet of Things in grid that will result in enhanced system resilience, reliable data flow, and connectivity optimization. Moreover, the sustainable energy IoT research challenges and innovation opportunities are also discussed to address the complex energy needs of our community and promote a strong energy sector economy.

6.1 Introduction

The United Nations seventh sustainable development goal (SDG) is targeted to eliminating energy sector poverty [105]. The continuous and sustained efforts are required both at the strategic and governmental level to realize global access of energy [54, 122, 133]. Thus, the development of technologies and systems, coupled with policy making, governmental practices, and social transformation, is needed to enhance afford-ability and rapid global, regional, and local access of energy resources to the people [132, 134]. To ensure energy access at this scale, decentralized grid systems approach with resources distributed at the lower tiers will bring significant changes. The energy related SDGs are shown in the Fig. 6.1.

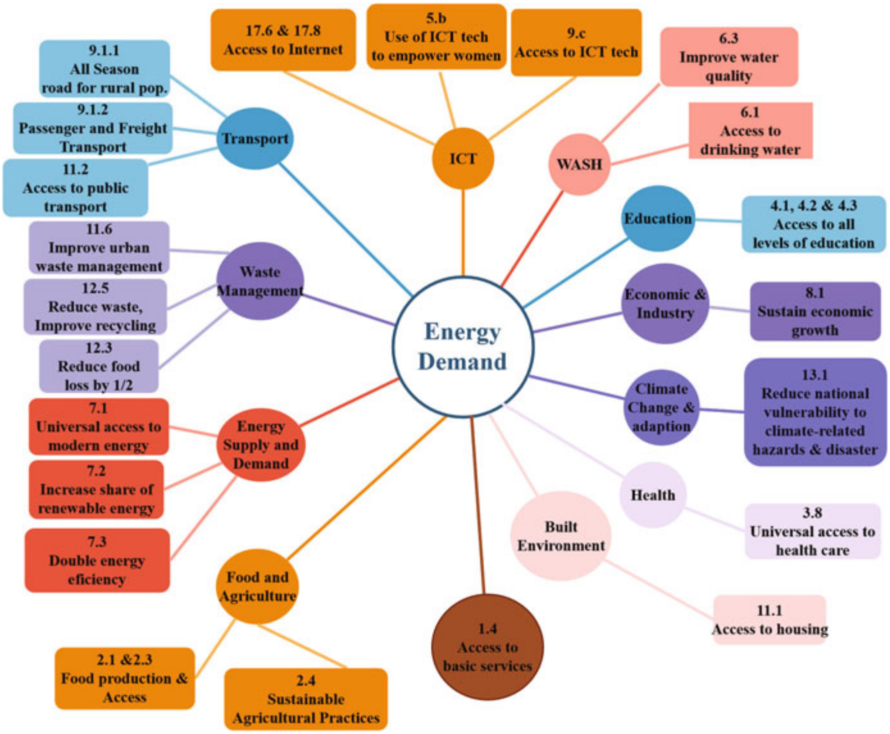

Fig. 6.1 The SDGs related to the energy [105]

It can be observed that energy demand has a strong connection with almost all of the UN sustainable development goals (SDGs). The energy access is highly correlated with the quality of life and plays a vital role in following sectors:

- The health and education sectors rely on dependable energy infrastructure [23, 119, 137]
- Provision of clean water needs energy [8, 54, 104]
- Energy drives the agricultural irrigation systems [121]
- Transportation sector cannot function without energy
- Household heating, cooling, cooking, and electric lighting require energy
- Industrial sector also relies on energy

6.1.1 Energy and Sustainability

The energy access [92] has the potential to reduce energy inequalities. The International Energy Agency (IEA) has defined the energy access as:

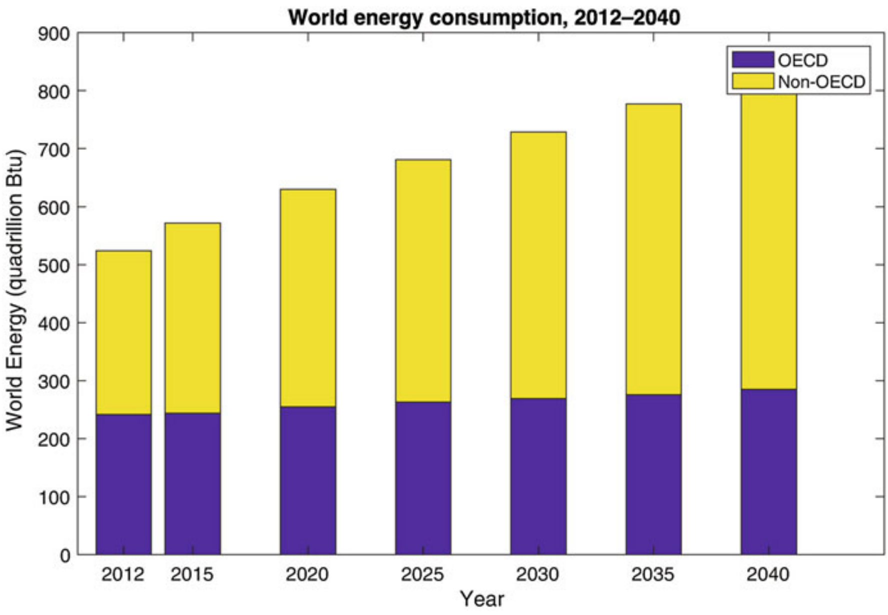

Fig. 6.2 The projected growth in energy demands of the world up to 2040 [88]

> A household having reliable and affordable access to both clean cooking facilities, and to electricity, which is enough to supply a bundle of energy services initially, and then an increasing level of electricity over time to reach the regional average.

Currently, approximately more than one billion people have no access to electricity. The absence of energy access is impacting more to the poorest regions such as Sub-Saharan Africa (SSA) [19].

The increase in world population is predicted to outrun the present outlay of the supply of the novel energy access [88]. The projected growth in energy demands of the world up to year 2040 is shown in Fig. 6.2. The current expansion of the grid will play an important role to meet this demand; however, there is a strong need to discover new sources. The realization of inexpensive techniques for clean energy [47, 54, 104] is also pivotal for economic and agricultural growth, energy enfranchisement of the poor and to reduce the population mobility to the developed countries which is caused due to poverty lack of energy. The energy access is also useful to reduce gender inequality in developing countries where women spend their diurnal energy to collect firewood due to lack of adequate energy resources [92]. It also causes mental and physical health stress in girls and women [17, 74]. Therefore, in addition to being the fundamental requirement, the sustainable energy access has tremendous socio-economic benefits to the community in terms of improving eradicating poverty and gender inequality. The UN's sustainable energy for all [103] program is flag-bearer for this vital cause.

Likewise, the advanced nations are also in need of continuous provision of energy. The energy is required for the functionality of businesses, high priority infrastructure, public safety, healthcare, and other industries. Moreover, potable water and wastewater treatment systems are dependents on energy access, where failure in one area can trigger cascading effects in urban utilities management. Therefore, achieving the energy resiliency is becoming the top priority of the city planners and managers [10, 23, 80, 93, 118, 119, 133, 136, 137].

6.1.2 Energy Related Challenges

As the modern advanced energy technologies are developing, there are emerging challenges that the future energy systems should address by using these advances [50, 128]. The current and future energy related challenges being faced by the community are discussed below. These challenges impact the capacity of power generation and also result in energy distribution disruptions.

- Current energy system depends heavily on water. However, with the variations in availability of water (short-term and droughts), novel techniques for energy production are needed [144].
- The high-voltage transmission lines lack security measures. These are also overloaded are being used afar their predetermined purpose. Moreover, transmission loss is also major issue which leads to power outages and blackouts [130].
- Many energy facilities are located in coastal zones due to high availability of water. But, rising sea levels and high tides, heavy downpours, and flooding from storm surges events are impacting coastal infrastructure and energy facilities and infrastructure [26, 62, 81, 106, 134]. The long duration energy outage in urban and industrial areas results in productivity loss that is also associated with business and economic loss.
- The extreme heat waves and summer temperatures are also causing high energy demands and corresponding increase in electricity usage. Due to peak loads the energy demands are projected to increase [135].
- The energy production and transportation infrastructure are also being impacted by extreme weather events [1]. Therefore, the frequency, duration, and intensity of these events cause energy disturbances which are occurring at different scales.
- One challenge associated with energy consumption is increase in greenhouse gas emissions [3, 138]. These emissions include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) [36]. These emissions are second highest following the majority emissions from the transportation sector.
- The energy consumption by information technology, mobile and computing devices is increasing [107].

- With more and more electric vehicles (EV) are being manufactured, the energy demand is increasing to fulfill EV needs [76].
- Other challenges related to energy infrastructure include a discrepancy between the demand and capabilities of energy systems, and the complex energy needs of industry and community [50].

6.2 The Sustainable Energy IoT

From the discourse of the energy and sustainability, it is evident that global energy access cannot be attained in the absence of technology adoption. Through application of technology the robust solutions for reliable low-cost energy access can be developed that can enhance the performance and operation of the current energy systems. Therefore, by using the next generation sensing and communication technologies, the need of affordable energy can be met for the community (see Fig. 6.3). The IoT technology that can efficiently provide the affordable energy services is necessary to address this basic human need of energy.

The IoT in sustainable energy systems is envisioned as the interconnection of the energy things in the entire paradigm grid system, services supply chains and human capital using state-of-the-art technologies with the ability to meet future needs and clean energy access challenges of the current century. This paradigm with its potential to produce next-generation energy systems is useful to connect various energy technologies and innovative solutions at the global scale. The sustainable energy IoT has the tremendous potential to attain sustainability and resiliency of prevailing energy infrastructure. It also has the ability to reduce future energy

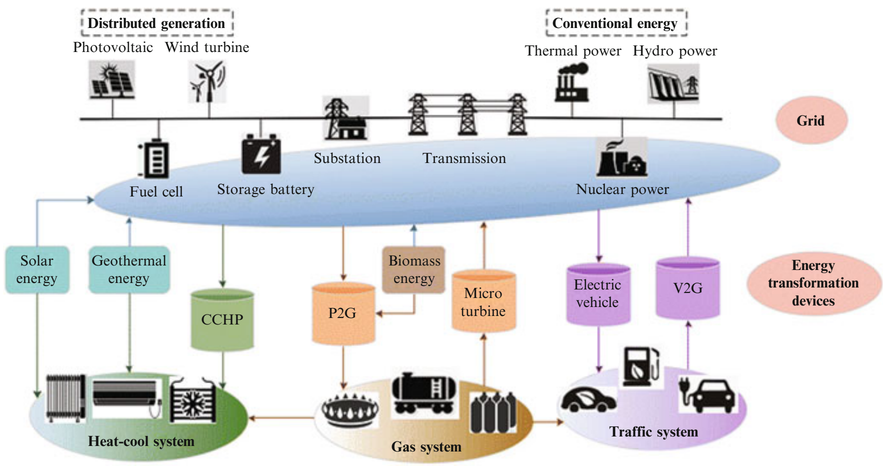

Fig. 6.3 An overview of the sustainable energy IoT

risks through development of secure, novel, and efficient energy infrastructure and technology. The IoT in sustainable energy systems enables various methods and pathways to global energy access through commissioning of clean and renewable energy methods with large-scale availability and scalability for sustainable provision of low-cost energy sources.

6.2.1 Sustainability Energy Things

The sustainable energy IoT carries a huge value for efficient energy value chain. Yet, the main value of the sustainable energy IoT lies in the smart grids, which is a significant achievement of the 21st century. The sustainable IOT paradigm with IoT autonomous and efficient management of the grid has a tremendous potential to bring benefits in consumption and generation. The sustainable energy IoT through its real-time monitoring of the renewable energy generation resources coupled with environmental monitoring can enhance the efficiency in the area of solar and wind power generation. Accordingly, these can be integrated into the grid to maximize the supply. It will also reduce dependence and pressure on less efficient, high demand, pollution causing fossil fuel based energy sources by using the distributed and low loss smart microgrids. The sustainability things are outlined in the following:

- Smart meters, net zero energy homes, green energy, and smart industry
- Generation, wind, solar, natural gas, water, renewables, and coal
- Transmission, phasor measurement unit, and transmission SCADA
- Distribution, smart and microgrid, and voltage control
- Billing, SAP, CRM, and work order management
- Customer, markets, retail energy provider, wholesale, and service provider
- Plant control, electric vehicles, and distributed intelligence
- Load, bulk, and outage management

6.3 Communication Technologies for Sustainable Energy IoT

The communications technologies are vital to provide connectivity in sustainable energy IoT. These form the integral part of the energy control systems are considered the backbone of the sensing and monitoring in energy systems. The most of the communication systems discussed in the first chapter of this book are being utilized in the energy sector. However, the advanced communication technologies pertaining to the sustainable energy IoT are discussed in this chapter. An overview of these technologies is provided in Fig. 6.4. These technologies are the driving force of the innovation in the energy sector and bring efficiency to all aspects of energy system.

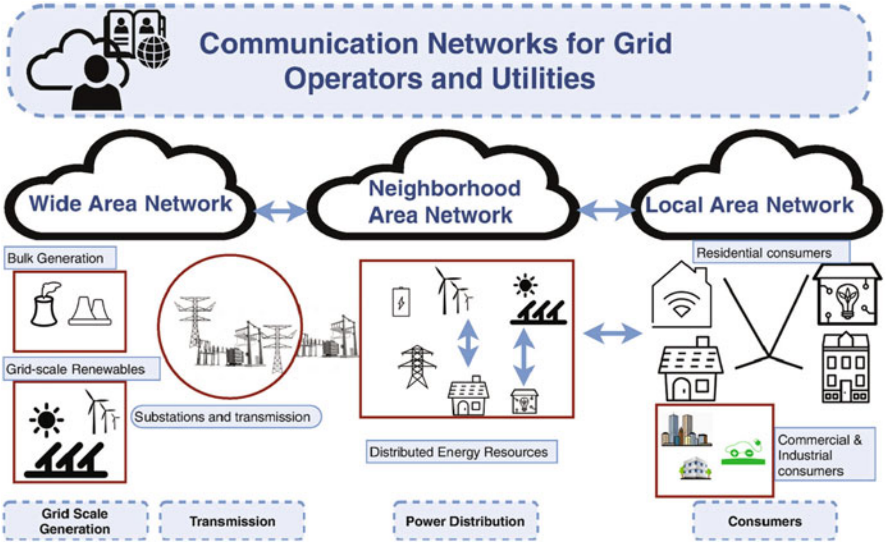

Fig. 6.4 Smart grid communications [38]

6.3.1 Wi-SUN

The Wi-SUN wireless smart utility (ubiquitous) network is a field and local area mesh networking standard supported by Wi-SUN Alliance [56]. It follows IEEE 802.15.4g and has its own physical and data link layer protocols. Its biggest advantage is that it can operate with multiple vendors.

6.3.2 Wide Area Monitoring Using SCADA

The supervisory control and data acquisition (SCADA) was developed in 20th century to collect power data from various geographical locations of the grid. It is main medium of communications between the substations and utility control stations. The SCADA has the capability to interface with large area monitoring systems and Internet, accordingly, robustness and efficiency has increased with this feature [6].

6.3.3 Neighborhood Area Networking

A neighborhood area network (NAN) [82] is an extension wireless LAN to multiple blocks of a neighborhood for the purpose of connecting to utility backbone network and also to the Internet. A NAN can connect multiple smart meters to the grid. These networks are utilized for billing, energy load planning, and demand response on neighborhood basis. In these networks energy consumption is low and data rates are in the order of few kilobits per second. WiMAX standards can be used to extend the range of NAN and can provide data rates of up to 70 Mb/s. A design of the wireless NAN design for advanced metering infrastructure (AMI) in the smart grid with self-sustainable capability is presented in [141].

6.3.4 Power-Line Communications

In the power-line communication, the power cables are utilized as a channel for data transmission. Since, the electric energy companies already have a vast infrastructure to meet the needs of electric power supply, the advancements in the power-line communications will be beneficial for smart grid control and monitoring applications. These communications are divided into four types [112]:

- Ultra-narrow band (UNB) power-line communication (PLC): These communications are based on the use of ultra-low frequency (ULF) spectrum from 300 to 3000 Hz and also in 0.03 to 0.3 kHz.
- Narrowband power-line (NB) communication (PLC). These use the frequency band of 120 kHz using amplitude modulation. These also have low data rates.
- Quasi-band (QB) power-line communication (PLC). These communications operate in frequency spectrum of 1–10 MHz and provide high data rates of more than 2 Mbps. This is long-range communications approach for advanced metering infrastructure networks.
- Broadband (BB) power-line communication (PLC). These use frequency band of 1.7–250 MHz and support high level modulation schemes such as orthogonal frequency-division multiplexing (OFDM).

6.3.5 Other Communication Technologies for Grid

The advancement in power-line communications technology will also enable digital subscriber lines (DSL) over these power carriers. The DSL is able to achieve attain data rates of 1 to -100 Mb/s and classified into following types [99]:

- Asymmetric digital subscriber line (ADSL)
- Very-high-bit-rate digital subscriber line (VDSL)
- High-bit-rate digital subscriber lines (HDSL)

6.3.6 *The Advanced Metering Infrastructure*

The advanced metering infrastructure (AMI) consists of the following components [42]:

- Smart Meters. A two-way communication device which is used to measure the energy consumption of various appliances (e.g., electricity and gas heater). The smart meters are discussed in more details in the sensing section of this chapter.
- Home Area Networks (HAN). A communication and information network formed by the various appliances running within the home to support various distributed applications.
- Neighborhood Area Network (NAN). Network of multiple HANs for collecting and sending data to data concentrator.
- Telecommunications Network. A data communications network used to carry the metering data to control centers.
- Gateway. A device that collects data from the HAN's member (also from entire home as a whole) and transmits to next level.

6.4 Sensing in Sustainable Energy IoT

In this section, the sensing in various energy systems is presented. First, the sensing in nuclear power reactors is discussed.

6.4.1 *Sensors on Nuclear Power Reactors*

The nuclear power generation is a pivotal element of the sustainable energy IoT systems. Due to hazardous nature of nuclear environment to humans, reliable and autonomous sensors can reduce contamination hazards to humans. The sensors used in nuclear power reactors are discussed in the following section.

6.4.1.1 Vibration Sensing

The vibration sensing in nuclear power reactors is carried to monitor and avert environmental radiation discharge [9]. The vibration sensing also ensures the health and safety of plant equipment and employees for unhindered power generation. The nuclear power plant failures lead to negative financial and environmental impacts. The piezoelectric ceramic sensors give electrostatic charge signal based on the application of acceleration [9]. These sensors do not contain electronics based signal processing elements due to the high temperature nature on the environment. Accordingly, external signal processing is required for producing output. On the hand, the use of smart sensors can mitigate this problem where signal processing, networking, and communication capabilities such as analog-to-digital conversions are done on board.

6.4.1.2 Temperature Sensing

The temperature sensing in nuclear power reactors is done both in control systems and also in safety and performance analysis systems [63]. For this purpose, chromel–alumel (thermocouples) and resistance based thermometers are used. Various types of temperature sensors are surface sensors and pool sensors. Currently, there is need of advancements in high temperature physical sensors technology for nuclear energy reactors such as in pebble bed reactors, where high drift is observed in thermocouples at high temperatures. Other temperature measurements approaches include [100]:

- Ultrasonic-guided wave thermometry. There are challenges in propagation of ultrasonic-guided wave [98]
- Johnson noise thermometry. It is susceptible to electromagnetic (EM) interference [18]
- Bragg thermometry. Susceptible to photo bleaching at high radiation [70]
- Optical sensors. The implementation of optical access ports to these sensors is challenging [24]

6.4.1.3 Pressure Sensors

The pressure sensors in nuclear plants are electro-mechanical instruments to determine pressure. These sensors can also measure the differential pressure, level, and flow [5]. These pressure sensors work by measuring the displacement of its mechanical parts which is changed to electronic form. There are also challenges in this conversion due to the high temperature. However, they suffer from leaks. The impulse line techniques suffer from salt contamination. The piezoelectric pressure sensors (Fig. 6.5) can also be utilized to sense dynamic pressure on short-term basis. Moreover, pressure sensors are also needed for higher reliability chloride salt and liquid fluoride environments. The polymer-derived ceramic materials are being investigated to fabricate pressure sensors, however, like temperature sensors, their interfacing to external circuits is challenging.

6.4.1.4 Liquid Level Measurement Sensors

The fluid level sensing is very important in reactors. The microwave techniques are used to sense levels of liquid salt. The other water level sensing approaches include ultrasonic using wave guides and impedance matching, pulsed neutron, neutron

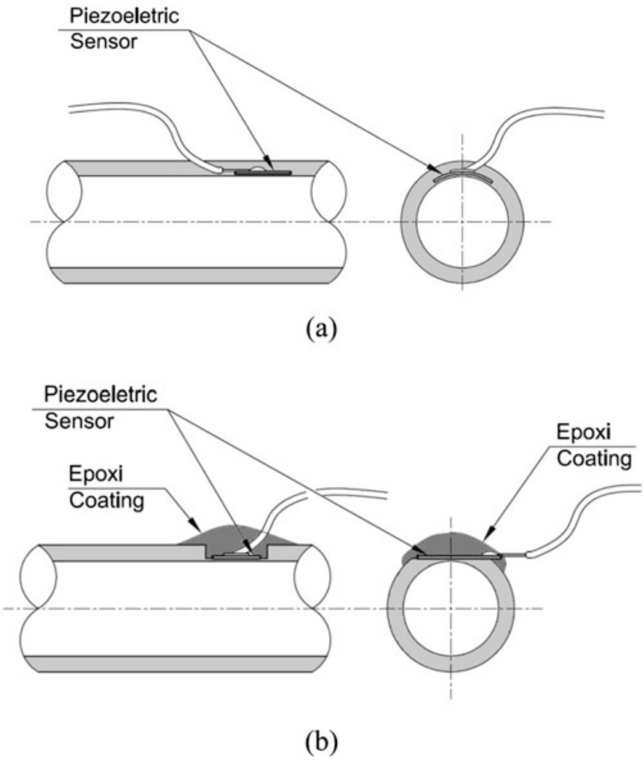

Fig. 6.5 Pipe with embedded piezoelectric sensors, (**a**) installed during fabrication of plastic pipes and (**b**) installed in fabricated pipes [72]

detectors, gamma thermometers, displacer float, conductivity, gamma horoscope, optical, and microwave [44]. However, these approaches are used as a short-term solution. The development of non-insertion (contact less) sodium level sensors is important for real-time monitoring.

6.4.1.5 Flow Sensors

The flow sensing can be either single phase or multi-phase is based on acoustic and ultrasonic methods [125]. The ultrasonic and acoustics are further divided into three types:

- Time-of-flight. In the time-of-flight sensing, 1 MHz frequency wave is transmitted to the pipe at an acute angle, propagates through the pipe, and is received at the other side of the pipe. The wave velocity in the pipe is impacted by the flow of liquid. Accordingly, the travel time of the wave is used for flow measurements.

- The Doppler flow meter. In this approach, the wave reflection is measured in contrast to the propagation (time-of-flight) measurements, where the shift in the reflected frequency in comparison to the transmission frequency is used to measure the flow [90].
- In contra-propagation transmission, the acoustics transmissions are alternated between the transmitter-receiver (TR) pairs installed on both sides of the pipes. The frequency difference is converted to the flow rate.

Based on the physical contact, these sensors can be categorized into two types:

- Intrusive sensors. These work inside the flow stream (e.g., head-type, segmental wedge, drag-type, and impedance sensors)
- Non-intrusive without penetration into the flow stream (e.g., acoustic, electromagnetic, microwave, optic, and nuclear)

The ultrasonic sensors are unable to sense at high salt temperatures and can also cause salt freezing to the heat absorption characteristics the waveguides. Therefore, for nuclear power plants, the development of ultrasonic sensors with capability to operate at higher temperatures (750 °C) is needed.

6.4.1.6 Corrosion Sensing

For the corrosion sensing, it is important to identify which corrosion causing processes. Currently, no techniques exist for in situ monitoring of corrosion and samples are analyzed off-line in laboratory environment. In this regard there is need of sensors technology in tritium sensing. Moreover, the water content monitoring is done to avert imprudent oxidation of reactor materials [29].

6.4.1.7 Radiation Sensors

The sensing of neutron flux is vital for nuclear reactor safety and operation and also for radiation monitoring [21]. For this purpose, the neutron flux and gamma flux sensors are used which can work in three different modes [61].

- Pulse mode during start-up
- Direct current ion chamber mode at full power.
- Variance mode for wide-range coverage

6.4.1.8 Water Coolant Chemistry

The water plays an important role in all power plants as the coolant. The production of energy uses water. Then impaired non-traditional water can be used as cooling with the advanced water recovery and reuse. The water chemistry sensing plays an important role in water quality and its cooling ability monitoring [94].

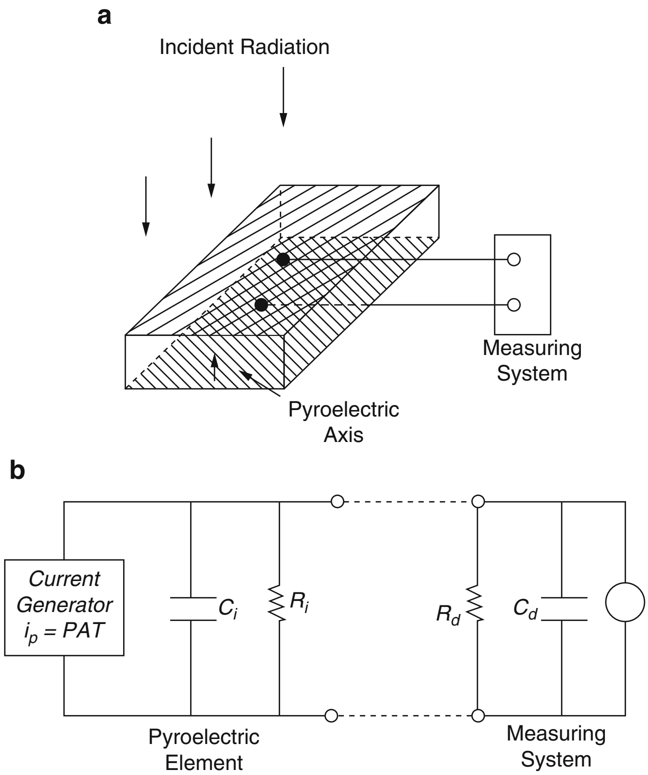

Fig. 6.6 (**a**) An experimental arrangement for infrared radiation detection and (**b**) the equivalent circuit [61]

6.4.2 Sensors for Coal-Fired Power Plants

The coal-fired power plants are another important component of the sustainable energy IoT systems due to their ability to provide flexible energy. In these plants, the monitoring is done to improve the efficiency of the combustion process and for sensors-based autonomous optimization. The coal-fired power plants sensing coupled with advanced stoichiometric control systems has the potential to improve the performance efficiency of these plants. These sensing approaches include coal, flame, carbon, and oxygen, and air flow sensing in various parts of the furnaces [126]. The sensors used in coal-fired power plants are discussed in the following section (Fig. 6.6).

6.4.2.1 Oxygen Sensing

The oxygen sensing is important for combustion monitoring in fossil fuel-fired power plants and is a good indicator of incomplete combustion [124]. The leftover oxygen is used to control the process by analyzing the use excess air in the combustion process. Accordingly, other firing rate and air intake are regulated. The process is optimized based on the reduction of oxygen set-point while minimizing incomplete combustion [52]. Two types of oxygen sensors are used in this application [131].

- The electrochemical sensors based on zirconia utilized air preheater and economizer. In these sensors, the oxygen ion-conducting (for temperature 300 °C and higher) solid catalytic platinum electrodes are used which have the ability to separate and absorb oxygen into electrons and ions [102].
- Since the strong magnetic field attracts oxygen, the paramagnetic sensors can be used for oxygen measurements. It is based on the usage of two nitrogen-filled glass in which oxygen is displaced resulting in suspension rotation which is sensed by photocells. This approach is less sensitive to other gases of the combustion process [60].

6.4.2.2 Carbon Monoxide Sensing

The carbon monoxide (CO) is another reliable indicator of the incomplete combustion process with optimum concentrations levels of less than 200 ppm. This is also used to adjust the oxygen set-point [97]. The CO sensors are discussed in the following:

- Electronic (Catalytic) Sensing. In this process, a combustion-prone platinum catalyst is used in which on oxidization of CO, the resistance of the sensor is increased. To avoid the catalyst poisoning, the ceramic substrate film thermistor is also used [58].
- Infrared (IR) Sensing. The sensors support both in situ measurements where IR sensor (a transmitter-receiver pair) can be installed along the flue ducts and also for extractive off-line sensing where gas samples has removed from the ducts [33]. For the first in situ approach, the recent advancement in the area of tunable diode lasers for the transmitters has improved the accuracy of these sensors in high temperature environments. In the second approach, one sensor is used which works by detecting the absorption frequency of CO.

6.4.2.3 Flame Sensing

The flame sensing in coal-fired power plants is crucial to the safety of the pulverized coal combustion. These sensors are installed on flame burners and work on optics principles by measuring the infrared, visible, and ultraviolet light frequency of the flames. This data about the flame stoichiometry and temperature used to enhance the combustion process [145].

6.4.2.4 Coal and Air Flow Sensing

The monitoring of the air flow in pulverizer mills and furnace is also used for combustion process optimization [16]. For this purpose, the flow meters are used to assess the pressure reduction when passing through a narrow section of the pipe. The pitot tubes are also employed for pressure measurements.

The coal flow is also sensed by using feeding rate of the coal (gravimetric) to the pulverizer mills that is dependent on the firing rate of boiler and load demand on the plant. The electrostatic approach is also used for this purpose where two electrodes are utilized to sense the charge associated with the flowing coal between two points along the length of coal flow. According, the time of travel based on the coal velocity is used to sense flow.

6.4.2.5 Sensing of Carbon Content in Ash

The carbon ash content is also a good indicator of the combustion process efficiency [34]. The content of less than 20% is generally maintained. The carbon content measurements are generally performed using microwave techniques. Due to high permittivity of the carbon, the EM waves are absorbed by the carbon depending on the dielectric constant. Accordingly, the resonant frequency changes are detected by using the resonance cavity sensors.

6.4.2.6 Gases and Temperature Sensing

The gas sensing [115] at single location is generally not representative of the gas concentration. Hence, arrays of gas (linear and planar) sensors are employed for this purpose to get overall picture. The tunable diode laser absorption spectroscopy is another development for sensing of the flue gas concentrations with very high accuracy. The furnace exit gas temperature sensing is also important for furnace control. The temperature sensing can be done by using some of the approaches discussed in the nuclear reactors section. The nitrogen oxide sensing is also carried out to sense nitrogen oxides in the plant.

6.4.3 Transmission System Sensors

The sensing of the grid transmission systems is vital due to many factors [87]. The smart grid sensing technologies are shown in the Fig. 6.7. These sensing

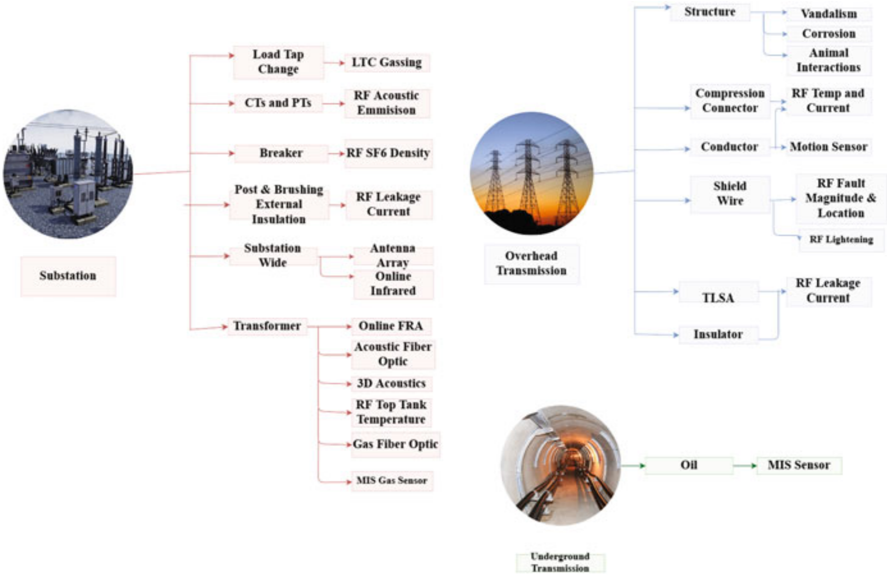

Fig. 6.7 The smart grid sensing technologies [87]

technologies are either fully developed are still in under development. Their applications are discussed in the following:

6.4.3.1 Substation Sensing Methods

The substation sensing methods are discussed below:

- Substation Discharge Monitoring: It is important to monitor potential discharge at substations to avoid catastrophic failures [140]. For this purpose, the antenna arrays are being used to sense, locate, and identify components that are causing discharge. Moreover, the 3D acoustic emissions techniques are also being used for discharge sensing in transformers. The 3D acoustics is also used to sense of bubbling sources and gas sources.
- Video Imaging: In this approach the IR tomographic cameras are used to produce video thermal images of substation components.
- Metal Insulated Semiconducting (MIS) Gas in Oil Sensor: In this approach, an inexpensive hydrogen sensor is used to measure the H_2 and C_2H_2 in transformers head-space and oil. The MIS gas sensor is manufactured on a chip [111]. This sensing approach is also used to sense hydrogen and potential acetylene in cable oil.
- Fiber Optic Based sensing. There are two types of fiber optic based sensing: acoustic and gas. In acoustic, the stress areas of the transformers are monitored for discharge using fiber optics cable. In the second approach, the gas presence

at the tip of the fiber optics is used to identify early failures and degradation in high risk areas [32].

- Frequency Domain Analysis: It works on the principle of frequency domain analysis of the transformers. In FDR approach, the variations in frequency response measurements are used to identify the configuration changes of the transformers. These measurements are done contentiously using natural transients [66].
- Sensing Gas in System Load Tap Changer (LTC): This sensing approach is capable of measuring the LTC gas ratios without the requirement of individual gas measurements [57].
- Radio Frequency. The RF based sensing approaches are used to sense leakages of the current levels to inform insulation washing and flash-over for various types of insulations [114]. These are also able to perform wireless/remote identification of high risk components (e.g., acoustics based internal discharge, current, jaw temperature of disconnect, and density of sulfur hexafluoride). The time and magnitudes of fault currents flowing in the shield wires are utilised for this purpose.

6.4.3.2 Overhead Line Sensing

The overhead line sensing approaches are discussed in the following:

- In overhead transmission, the current and temperature sensing approaches are utilized to sense temperature of connectors, current magnitudes, compression of conductor such as dead ends and splices. Accordingly, a histogram is created to assess loss and to identify high stress components. These sensors are capable of energy harvesting from the abundant magnetic field prevailing in the line environment [71].
- Similar to the substation environment, the overhead insulator leakage and associated currents are measured using RF approaches. The time and current magnitude of the current flowing are also measured in shield wire to identify the exact location of faults. The same measurements are also done for the lighting current distributions [30].
- The surge sensor is used to measure and log surges and total charge detected [40].
- The transmission structure sensing is done using sensing of the environment data and image processing for decision support systems. Accordingly, different incidents such as unknown outage and avian activities can be detected in real-time [65].

6.4.4 Smart Meters

The smart meter is also a type of sensors in sustainable energy IoT. The smart meters are the fundamental components of the advanced metering infrastructure (AMI). These connect customers and service providers via different types of communications links [129]. The smart meters are also used for monitoring of duplex power flow. Accordingly, the dynamic billing, load monitoring, and remote functionality are enabled through the use of smart meters.

6.4.5 *Wind and Solar Sensing*

The reliable integration of solar [68, 73] and wind energy [10, 11, 15] resources in the sustainable energy IoT requires real-time sensing of these environmental parameters for the efficient energy generation process [116]. These environmental sensing is done for solar irradiance and wind speed. This type of weather-related variables sensing in sustainable energy systems has the tremendous potential to bring more multitude of energy sources to the power systems.

6.5 The Case Studies of Sustainable Energy IoT Technologies

In this section, the sustainability IoT case studies are discussed in great details.

6.5.1 *Electric Vehicle Energy Internet*

The basic idea of electric vehicle (EV) energy Internet is to transmit energy from one place to another [35, 142]. The EV transmits, stores, and distributes energy from renewable energy sources (e.g., solar, wind) to the places where needed such as charging stations and houses. EVs are equipped with the batteries and together can form a large network of distributed energy storage system, e.g., if all light vehicles in USA become EVs then the entire power generated by them will be 24 times higher than the entire electric generation grid. In Fig. 6.8, a schematic of EV energy Internet is shown. It divides the EV into two layers [142]. The lower layer is the transportation network of EV architecture. It consists of energy generation from renewable resources, energy transportation from EVs and energy substations, and consumers. The EV, after charging at renewable energy source, travels to a charging station and discharges at charging station. Accordingly, other EV picks up the energy from that substation and move to the next point.

6.5.2 *Combined Cooling Heating and Power System*

The combined cooling heating and power system (CCHP) is a distributed generation system that can provide heating and cooling simultaneously. When compared with

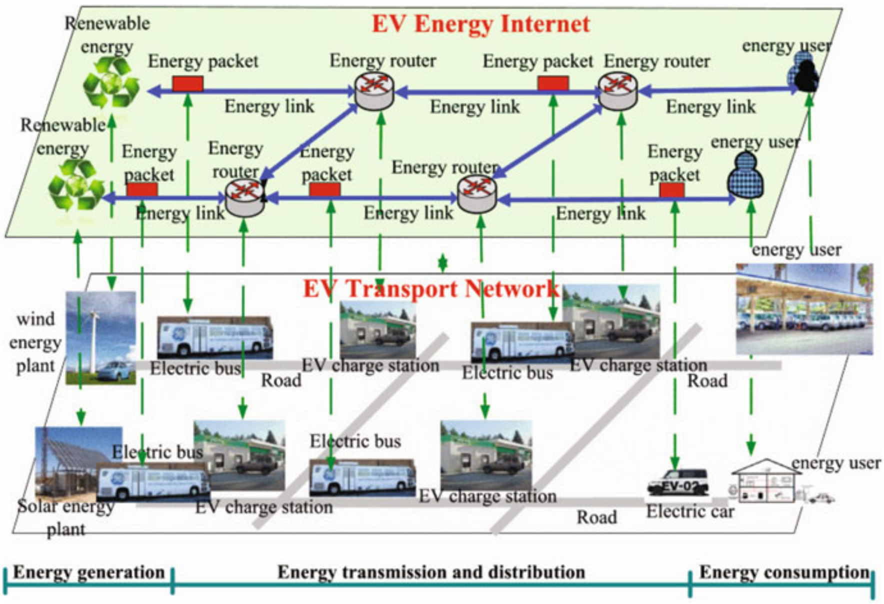

Fig. 6.8 A schematic of EV energy Internet [142]

the traditional alternative, such as separate cooling and heating system, the fuel economy and system efficiency of CCHP are higher. It consists of power generation, heating, and cooling. The CCHP can balance the production and load requirement of electricity, heating, and cooling increasing the overall efficiency from 40% to 70–90%. Moreover, the emission reduction is an added advantage of CCHP system [22].

6.5.3 Power-to-Gas (P2G) Energy Internet

Energy markets all over the world are now focusing shift from fossil fuel-based power generation to renewable energy-based generation. EU has proposed that a target of 20% renewable energy will be achieved, in their mix of energy systems by 2020. This is because of the low emission rate and environmental friendly nature of renewable sources. However, as discussed in the previous sections, the production pattern of renewable sources such as wind and solar is very unpredictable and varying. In addition to unpredictable generation capacity, they may also cause fluctuations in grid. Although, renewable energy has all these challenges, however, they are still considered as future of the energy sources.

One solution to the above problem is to store a large amount of energy when demand is less than the supply and using that stored energy when the demand

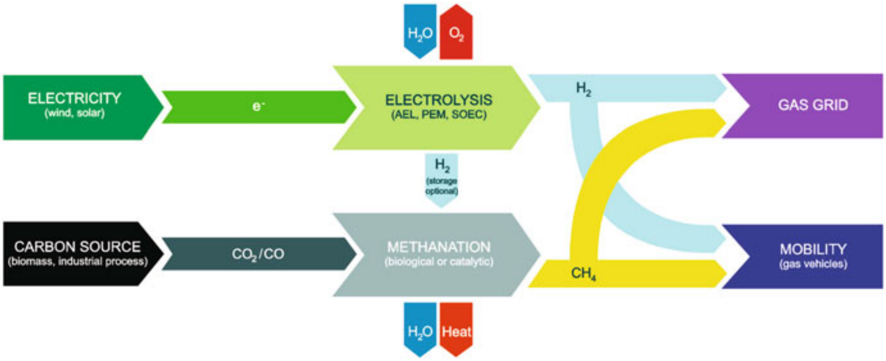

Fig. 6.9 The power-to-gas process chain [48]

increases the supply. This flexibility in the system can be achieved by power-to-gas (P2G or PtG) [48]. As shown in the Fig. 6.9, the P2G is a process of converting water to hydrogen via electrolysis and then conversion to methane. The P2G is a very flexible option for long-term storage of energy produced by renewable energy source-based plant. It adds flexibility to the current energy based system. The P2G offers three benefits in terms of flexibility: (1) time, (2) location, and (3) end-use. Apart from being a long-term energy storage technology, the P2G is also used to balance electric and gas networks [83].

6.5.3.1 Water Electrolysis

The key step of P2G technology is conversion of energy into hydrogen via water electrolysis. In water electrolysis, electric energy is converted into a chemical energy [127]. The conversion process is carried out by electrolyzer. Electrolyzers consist of (1) electrodes, (2) electrolyte, and (3) a diaphragm. Electrodes split the water into hydrogen and oxygen upon supply of electricity. Electrolyte is used to conduct ions and diaphragm act as an isolator to prevent evolving gas streams from flammable mixture. Electrolyzers can be classified into different types based on the type of electrolyte being used. In the following sections, various technical aspects and characteristics of these electrolysis are discussed.

6.5.3.2 Alkaline Electrolysis

Alkaline electrolysis is considered as one of the mature electrolysis processes and it is present in the industry for a decade. They use aqueous alkaline solutions, e.g., KOH or NaOH, as an electrolyte. The highly perforated steel electrodes are separated by insulated diaphragm. It works under atmospherically under high pressure. The atmospheric alkaline electrolysis has higher efficiency than the elevated pressurized one [64]. However, advantage of pressurized alkaline electrolysis is that it produces compressed hydrogen with low amount of input energy. Some of the drawbacks associated with the alkaline electrolyzers are:

- Minimal load capacity of 20–40% PN
- Long start time ranging from 10 min to hr depending upon the purity of the gas
- Long restart times. It takes typically 30–60 min before it can be started again

6.5.3.3 Proton Exchange Membrane (PEM) Electrolysis

It was developed by general electric (GE) in 1966 and was introduced to the market in 1978. It uses polymer membrane as an electrolyte [43]. The nature noble metal is used as a catalyst due to its acidic property. Some of the advantages of PEM include faster cold start, high flexibility, and better coupling with the dynamic systems. However, usage of noble metal as a catalyst makes it a highly expensive option and the life span of a PEM-based system is shorter than alkaline-based systems.

6.5.3.4 Methanation

Hydrogen and carbon dioxide are further processed via Sabatier reaction to produce renewable power methane [127]. The process uses nickel and ruthenium based catalyst. It operates under the temperature of 250–400 °C and pressure of 1–80 bar. Due to exothermic nature of the process, highest conversion is attained at low temperatures leading to low kinetics. Almost 17% of the hydrogen energy is released as a heat limiting the maximum achievable efficiency to 83% provided that no extra heat energy is used.

6.5.3.5 Challenges

P2G is in the developmental stages. Research in P2G is going in two directions. First direction is the improvement of modules like electrolyzer and methanation [127]. The second is the improvement of P2G in systems. The main challenges to explore are:

- Establishment of proper framework for P2G as a system balancing technology
- Lack of precise data results in uncertainty in modeling of P2G technology which makes it impossible to get reliable results
- Lack of case studies to analyze the economic and social impact of P2G technology
- Design of smart management system for P2G

6.5.3.6 P2G Opportunities in Sustainable Energy IoT

The P2G opportunities in sustainable energy IoT are discussed below [2].

Sustainable Energy Systems Sustainable energy systems are the ones which remain operational even during the rapid changes in demand and supply. The response time of P2G technology is fast (typically takes from seconds to minutes). This adds up to the flexibility of energy systems. It also increases the flexibility of the energy systems by significant share of the renewable energy sources.

Reducing Emissions in Energy Sectors The carbon capture and utilization (CCU) technologies are used all over the world to capture harmful gas before it emits to the atmosphere. The CCUs are developed to reduce the adverse environmental effects. Carbon dioxide is necessary for the production of hydrocarbons. It is a very good opportunity to use the CO_2 recovered from CCUs units. Accordingly, there is a possibility of using captured CO_2 for the production of methane via P2G [12].

Congestion Management The high production from the large renewable power plants connected to an electric system can cause congestion in the power transmission lines. Therefore, to avoid the suppression of energy production, it is necessary to install P2G energy storage system in close vicinity to the power plants.

6.5.4 Sustainability and Net Zero Energy Buildings

The sustainable development in energy sector requires the new types of building designs with renewable integration for high energy efficiency [39, 49, 75, 85, 86]. In this regard, the net zero energy buildings (NZEB) is an emerging concept that is being conceived and implemented as a solution to minimize consumption of energy in buildings. There are different technologies for NZEB design [7]. The four different types of net zero energy buildings are shown in Fig. 6.10. These buildings have different sources of renewable energy either on premises in the vicinity to meet energy needs. The NZEBs are also connected to electric grid as well for energy demand in case of low output of renewable sources. However, in favorable conditions for renewable energy (such as solar and wind), the NZEBs are not only able to meet their own needs but also dispatch the excess supply to the grid. Therefore, it balances the demand and supply in terms of the energy consumption.

The net zero energy buildings also has the tremendous potential for environmental sustainability and economic benefits through their net-zero carbon emissions [110]. Because, mostly in buildings gas and other petroleum energy resources are used in fossil fuel boilers and furnaces for heating needs. When replaced with renewable sources (such as air, solar, and water based pump solutions), the carbon footprint is decreased. Moreover, through sustainable IoT's real-time monitoring, sensing, and visualization, the autonomous control can be implemented based on the dynamic needs and conditions of the environment.

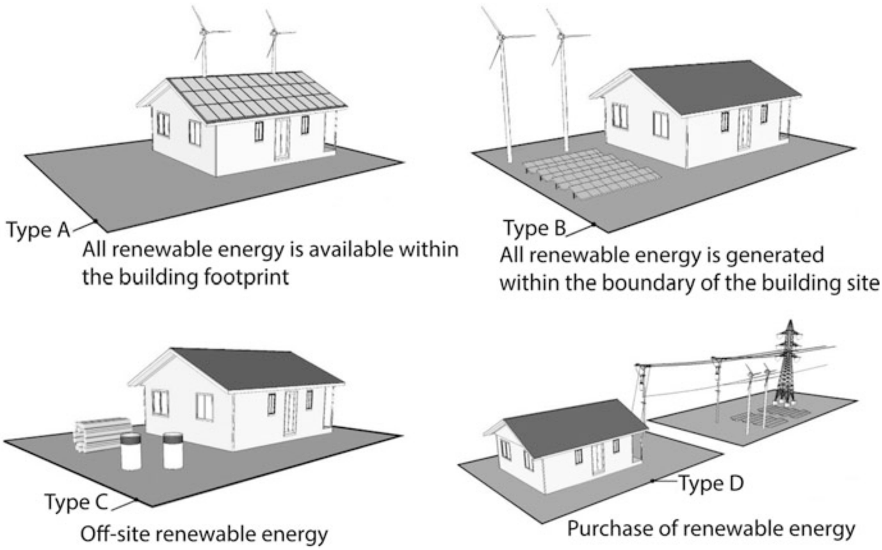

Fig. 6.10 The four different types of net zero energy buildings [39]. Type A: All renewable energy is available within the building footprint. Type B: All renewable energy is generated within the boundary of the building site. Type C: Off-site renewable energy (for example, wood pellets, biodiesel, or ethanol) is used to generate energy. Type D: Purchase the renewable energy which is generated off site

6.5.5 Energy Supply Chain Management

The sustainability energy IoT has many benefits in the areas of energy supply chain management, infrastructure security, and logistics. For example, in fuel depot monitoring applications, various types of sensors provide useful information [13], such as:

- Sensing of temperatures, tank fluid levels, and flow rates is done for accurate and low-cost monitoring
- The leakage can be detected in real-time using water, soil, and air sensing
- The control, usage inventory, and ordering can be achieved through autonomous operation in online or remote fashion, accordingly, the exposure to food related hazards is minimized
- The motion sensors and cameras things connected to the system enable enhanced infrastructure security
- Early detection of failures can be done by sensing of corrosion and cracking in high risk areas

6.6 Sustainability in Energy Generation

With the growth in world population, the fossil fuels are depleting rapidly. Accordingly, due to increased usage and high stress on fossil fuel and other oil based energy resources for transportation and power generation, these is an urgent need of mining energy from renewable sources [25, 55, 78, 79] and exploration of new resources. In this section, the sustainable energy generation from different sources is discussed.

6.6.1 Hydrogen

The hydrogen based energy preproduction is also a good alternative to gas and electricity [113]. It can be produced by using electrolysis, reformation, and gasification. However, there is need of carbon storage facilities for efficient sustainable hydrogen production such as the hydrogen fuel cells. By using polymer electrolyte membrane fuel cell (PEMFC), the hydrogen can also be used to produce electric power with no emissions. The electrohydrogenesis is another biohydrogen production method. It can be considered as an alternative to combustion fossil fuel engine in electric cars.

6.6.2 Biobutanol

The biofuel availability in transportation sector is currently dominated by bioethanol and biodiesel [67]. However, the biobutanol is being considered due to its superior properties as compared to the bioethanol. It can be produced through the fermentation of butanol, acetone, and ethanol [139]. Fermentation and the latest research achievements in feedstock and process development are briefly pointed out. The new ethanol to butanol catalytic approaches are being considered as an alternative to fermentation.

6.6.3 Bioethanol

The bioethanol is alternative to petrol and is obtained through biological techniques. The development of engines with the capability to solely operate on ethanol is bringing innovations in bioethanol production [20]. The steps in production technologies are [51]:

- Microbial fermentation of sugars to ethanol
- Pre-treatment of carbohydrate polymers
- Separation of ethanol by distillation
- Dehydration to fuel-level bioethanol

6.6.4 Biodiesel

The biodiesel is a sustainable and renewable alternative to petroleums. It is produced by using transforming the waste microalgae and cooking oils to biodiesel by using different methods which including lipase preparations [77, 109]. The enzymatic biodiesel has many environmental benefits as compared to the chemical catalytic process. Other state-of-the-art production technologies include metabolic and genetic engineering and biological synthesizes.

6.6.5 Microbial Electricity

The wastewater can be used to produce electricity by using bio-electro-chemical equipment known as the microbial fuel cells (MFC). The electro-active bacterias in the vicinity of electrode transfer electrons during their metabolic process, which are used to produce electricity. The success of this approach is very important for sustainable energy production [91, 117].

6.6.6 Biomass

The biomass [3, 27, 41, 95] (e.g., forest residues, bales and chopped straw, and pellets) has attracted a lot of research focus due to its applications in various energy areas such as power, heat, and in production of biofuels and bioenergy [28, 53, 96, 101, 108, 120]. Different approaches are discussed in the following:

- The biomass gasification is a combustion-free thermo-chemical approach to convert the biomass to fuels. The solid wastes and feedstocks can be converted into energy by using this approach. There is need of innovative development in the area of gasification [69, 113].
- The anaerobic digestion (AD) is another emerging technology to produce renewable energy from solid organic wastes and biomass. It also produces phosphorous, nitrogen, and micro-nutrients byproducts that can be used as fertilizer for soils in agriculture [89].
- Moreover, the synthesis gas (syngas) can be produced from organic biomass by using the supercritical water gasification approach. This results in tar and char formations and currently has low gasification efficiency [14].
- Furthermore, the biomass is also used as co-fired along with coal in various forms. When pelletized, it achieved high energy efficiency in coal combustion. The dendromass (a biomass of roots) is also another renewable energy source from short rotation woody crops [46].

- The woody biomass is also used to produce activated carbon through thermal means that can be utilized for waste treatment and gas purification [143].
- The perennial grasses are also used for energy production. It is species of giant miscanthus, switchgrass, and reed canary grass [59].
- The microalgal biomass and oil crops are other important sources [37].

Other major renewable energy sources are outlined in the following:

- Nuclear. It is a reliable source of energy generation. Currently, the second and third generation reactors are in user. However, the research is on ongoing in fourth generation reactors [31].
- Ocean. Ocean tides and waves are also a good source of renewable power generation [123].
- Hydropower. The run of river, regular storage, and pumped storage are some of the examples of the hydropower plants [84].
- Geothermal. The sustainable energy can also be produced from low temperature heat reservoirs and sources [45].
- Wind. Many configurations of wind energy conversion systems (WECS) are in commercial use [10, 11, 15].
- Solar. The solar photovoltaic (PV) technology is highly scalable and is being used from milliwatt to gigawatt scale production [68, 73]. It is also being used in off-grid solar configurations [4].

6.7 Sustainability IoT Systems and Databases

The sustainability IoT systems and databases are presented in this section.

- Solar Roadmap. A community level solar information database to increase adoption of solar energy.
- BioEnergy Atlas. It is interactive mapping system for BioFuels BioPower.
- RETScreen. A Canadian clean energy software.
- Planning Framework for a Climate-Resilient Economy. A community level framework for climate resiliency and economic vulnerability identification.
- Geothermal Prospector. A tool to map geothermal power resources.
- US Energy Information Administration (EIA) energy mapping system is an U.S. energy infrastructure database.
- The Bioenergy Knowledge Discovery Framework (KDF) contains database for bioenergy analysis, research, and decision-making
- HydroSource. It is an integrated data set for water, energy, and ecosystem sustainability. It has geospatial data sets for hydro-electricity production and water management.
- U.S. Electric System Operating Data. A tool for visualization and analysis of hourly USA and regional electricity demand.

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