

## Chapter 2

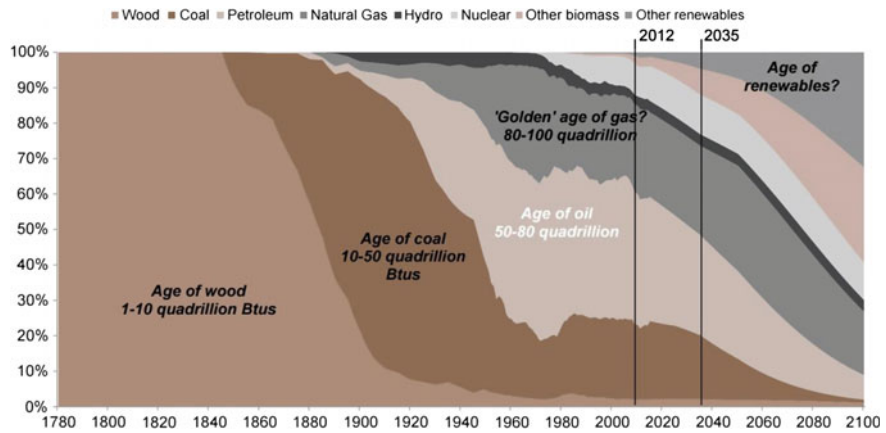
# Grid Revolution with Distributed Generation and Storage

### 2.1 Distributed Energy Resources

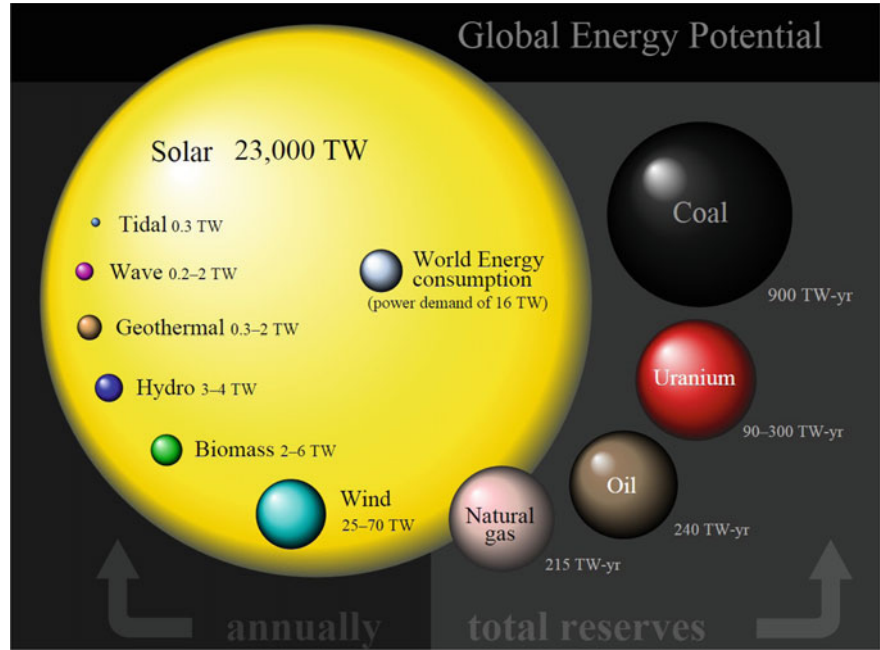
The evolution of the US primary energy mix over two centuries is illustrated in Fig. 2.1. This interesting figure shows that, until around one and half centuries ago, wood was the only energy source. Coal was explored and gradually became the dominant source of energy by the first half of the 20th century. The age of coal continued until oil and gas joined the mix. Gradually, along with these energy sources, hydro, nuclear, and renewables diversified the energy portfolio. With sometime variations, Fig. 2.1 could be extrapolated to the global energy history. Figure 2.1 also makes a projection for the energy mix based on business-as-usual (BAU) assumptions, highlighting that the future will be the “Age of renewables.”

Figure 2.2 illustrates the global reserve of conventional fuels and the annual energy potential of renewable energies. Despite the optimistic view that it may take a few more centuries for conventional fuels to deplete, there is no doubt that fossil or mineral (e.g., nuclear) fuels will deplete one day and that ultimately renewable energies are the main hope of future human survival. The climate change crisis has created more recent alarm that the BAU trend in energy transformation may lead to significant natural disasters. It has necessitated finding alternative approaches to the BAU as shown in Fig. 2.1, to move the world toward renewables in the shortest time frame. There is an insightful argument today that the Stone Age did not end due to depletion of stone, and fossil fuel age should not end due to the depletion of fossil fuels. The promising element here is that renewable energy sources are generally abundant, as is obvious in Fig. 2.2.

A list of renewable energy sources is presented in Fig. 2.3. Generally, not only are they the most sustainable alternative route to addressing climate change problems, but also they have a few other critical advantages, including abundance and relatively scattered geographic distribution. As such, it has been a matter of economic benefit and security for energy-importing societies to explore the utilization of their local (renewable) energy sources. Nevertheless, combinations of reasons,

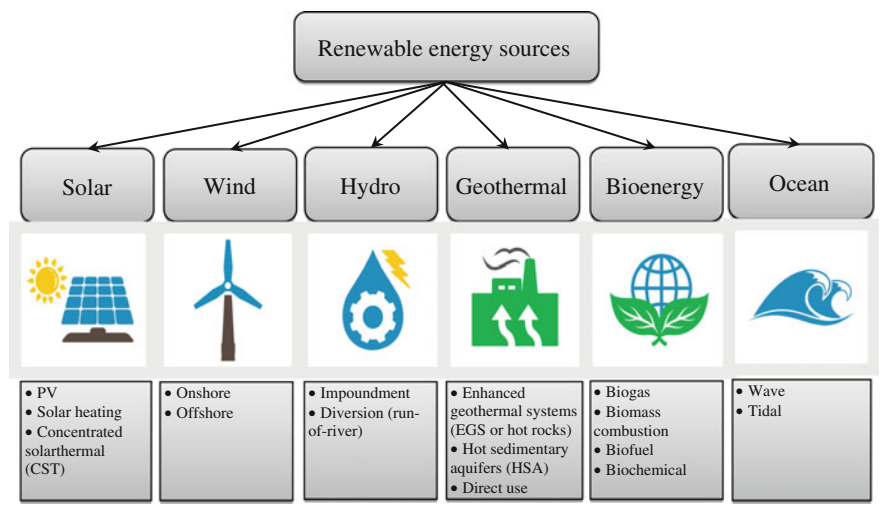


**Fig. 2.1** Evolution of the US primary energy mix from 1780 to the present and the business-as-usual projection out to 2100 [1]



**Fig. 2.2** Global energy reserves and availability [2]

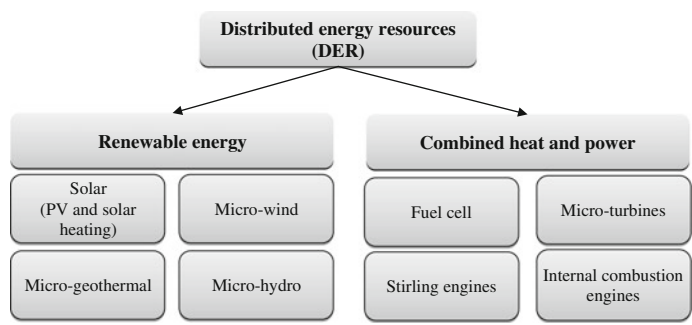
including their intermittency and limited availability, have made distributed energy resources (DERs) among the most expensive energy sources. These constraints first result in a low-capacity utilization factor and thus high investment costs (though negligible subsequent operation costs). Secondly, because of the unavailability of



**Fig. 2.3** Various renewable energy technologies

the energy source (solar radiation, wind, biomass, etc.) at particular times (day, week, season, etc.), either an auxiliary power source (such as other types of generation or connection to the grid) or energy storage is required. Without this consideration, energy security and autonomy with renewables are almost impossible at both macro- and microlevel.

One of the key issues in climate change mitigation is energy efficiency. Earlier we discussed that grid centralization has generated considerable distances between the supplier (generator) and the consumer. The transmission of electricity over the network at various voltages results in the loss of a non-trivial amount of energy. Therefore, the possibility of generating energy at the demand side, termed distributed generation (DG), has many advantages in terms of energy efficiency, as it can reduce the power losses due to network transmission, the network footprint, reserve generation capacity, etc., as well as utilize any coproduced heat.



**Fig. 2.4** Common types of small-scale distributed energy resources

DG and DERs have wider definitions. In fact, both DG and DER can be defined as any type of “electric power generation within distribution networks or on the customer side of the network” [3]. Figure 2.4 categorizes DER into two groups of renewable and non-renewable combined heat and power (CHP).

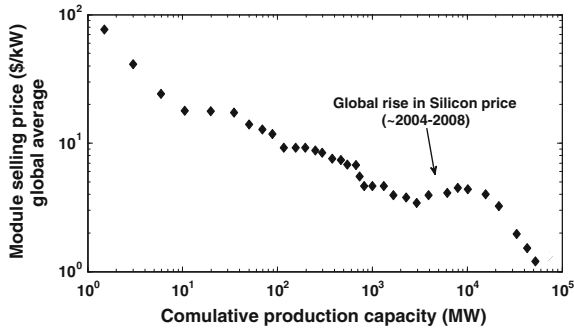
## 2.2 PV as the Pioneer DER: History and Role in Microgrids

The sun has ever been a source of inspiration for humankind, and there have been times in history when it was worshiped as the basis of divinity. It is the direct and indirect source of life on Earth, and mankind has always tried to utilize its energy for a better life. According to some documents, the first incidence of solar energy utilization has been traced back to the 7th century when magnifying glasses were used to make fire or kill ants. One and half hours of solar sunlight reaching the Earth’s surface (at the rate of 122 PW and average intensity of  $170 \text{ W/m}^2$  [4]) is enough to satisfy the entire energy consumed (570.12 EJ in 2012) by all fuel types [5]. It is rational, therefore, that humankind has thought of ways to convert this abundant source of energy into other energy sources and/or to store it for later consumption at times of need. Excluding solar heating, the most revolutionary advancement in solar energy utilization has been the development of PV cells. Solar PV cells directly convert solar radiation into electricity using the PV effect.

It is almost two centuries since the 19-year-old Edmond Becquerel discovered the so-called photovoltaic effect in 1839 [6]. This was followed by the discovery of photoconductivity by Willoughby Smith in 1873 [7] and the discovery of the photoelectric effect by Heinrich Hertz in 1887. The work of Philipp Lenard [8] on the photoelectric effect and questioning the wave theory of light inspired Albert Einstein and led to the discovery of light quanta or photons [9] that won him the Nobel Prize.

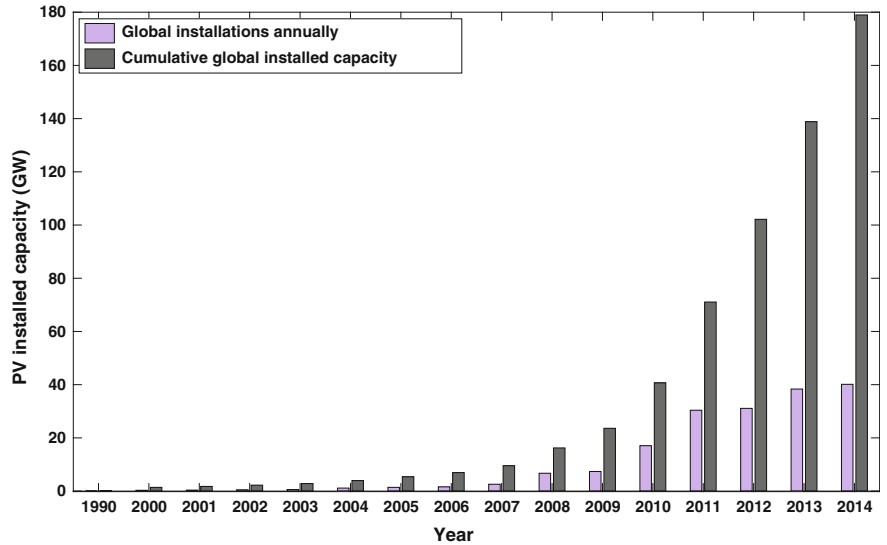
Russell Ohl, from Bell Laboratories, discovered the first silicon solar cell in 1940 by accident, a phenomenon that was later theorized as the PN barrier or P-N junction [10]. This discovery led to the Nobel Prize-winning invention of transistors in 1947 and the development of the first PV technology product (using silicon semi-conductors) in 1954, both at Bell Laboratories. This technology was used in 1958 to power radios of the US Vanguard 1 space satellite. Since then, PV technology underwent steady and slow development until the oil crisis of the early 1970s. From that time, renewable energies including PV technology received increasing attention (though still from the economic/security, and not sustainability aspect) in developed countries. For instance, the Solar Research Institute (later renamed the National Renewable Energy Laboratory, NREL) of the US Department of Energy was formed in 1977. Though the expedited research and development work improved the efficiency of solar PV cells and significantly reduced the CAPEX of PV cells (from  $>\$70/\text{W}$  in 1977 to  $\sim \$10/\text{W}$  in 1990, see Fig. 2.5), with the industrial learning rate of 18.4 % [11], the technology was still distant from

**Fig. 2.5** Learning curve of PV module price [12, 13]



commercial competitiveness. As such, PV cells had only niche applications and their total installed capacity by 1990 was as low as 0.1 GW (Fig. 2.6).

Another turning point in the history of PV technology (and other renewable technologies) occurred in early 1990s when international concern about sustainability resulted in some binding agreements (United Nations Framework Convention on Climate Change, UNFCCC) to stabilize greenhouse gas concentration in the atmosphere. PV cells have zero emission during operation and their lifecycle environmental impacts are less than 100 kg-CO<sub>2</sub>/MWh, according to mainstream lifecycle analyses [14]. These factors motivated their development even at the low oil price that existed during the 1990s, due to the projected potential future market. From the 2000s, the multi-fold increase of oil price, together with implementation of a carbon tax in some countries (following the Kyoto Protocol of 1997), significantly fostered the research and market of PV technology.

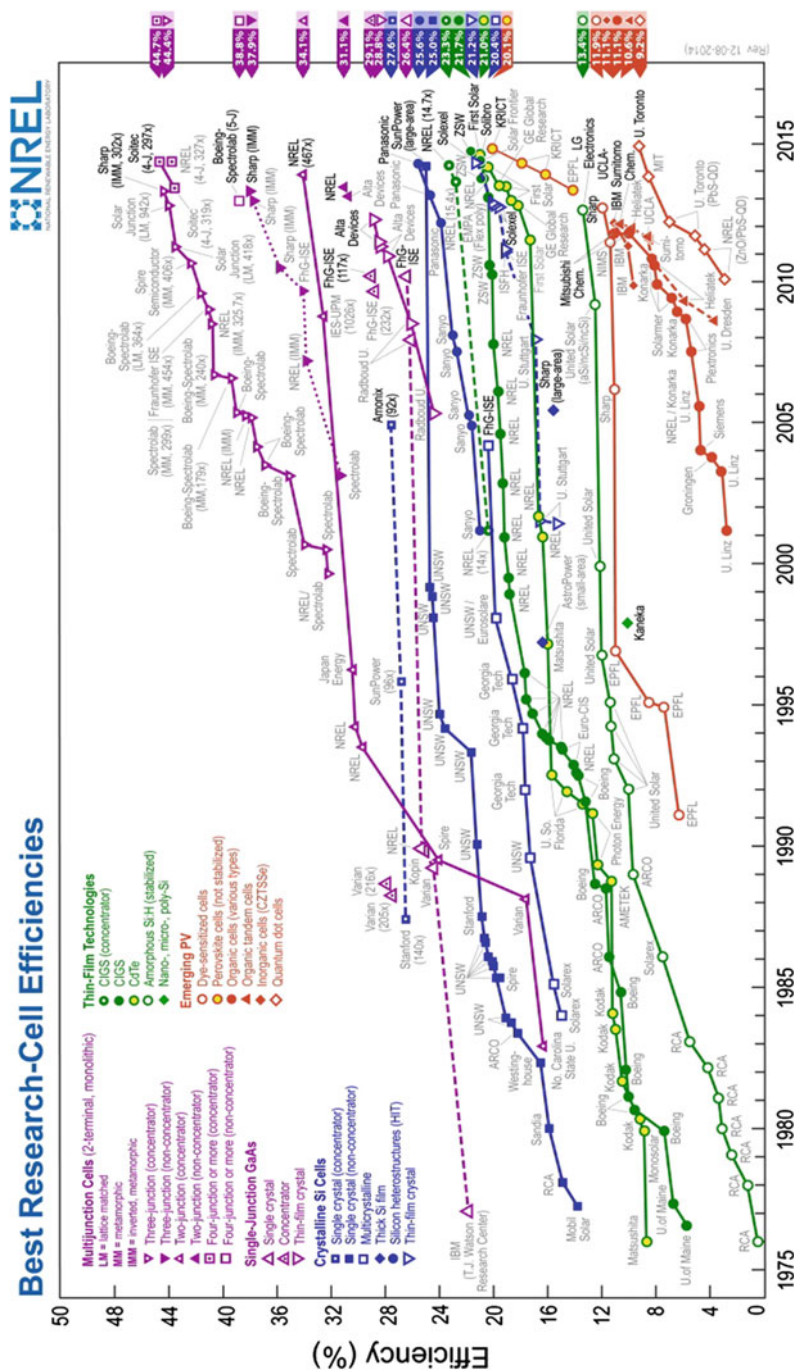


**Fig. 2.6** Global installation of PV modules (data from [17])

The average historical learning rate (i.e., module cost reduction for each doubling of the cumulative installed capacity) for PV modules was about 22.8 % per year over 1976–2003 [15]. From 2004, a shortage of pure silicon resulted in a significant increase in the silicon price (from less than \$50/kg in 2003 to above \$300/kg in 2007) and thus an elevation in the PV price. This caused some aberrations in the PV learning curve, as evident in Fig. 2.5. However, even this issue did not affect the rapid growth in solar PV uptake. While the global PV cumulative installed capacity was 1.4 GW in 2000 and 5.4 GW in 2005, installation experienced a tipping point afterward with a 30–75 % annual increase. In 2012 and 2013, 30-GW PV systems were installed each year globally. With this, the global PV cumulative installed capacity exceeded 100 GW at the end of 2012 (tenfold of that in 2007) [16]. The value reached 138.9 GW by the end of 2013 [17]. By the end of 2014, the installed capacity was almost 180 GW and it hit the value of 200 GW in early 2015 (double of that in 2012).

It is noteworthy that the term “tipping point” or “black swan” for the PV module price from 2010 might be misleading. As evident from Fig. 2.5, the high silicon price (as well as other material prices) during 2004–2008 increased the cost of PV modules and decreased the average historical learning rate of PV panels. Return of the silicon price to around 50 \$/kg from 2009, together with usual cost reductions (due to continuous technology improvement as evident from Fig. 2.7) of PV, resulted in a sharp reduction in the PV price to compensate for the lower learning rate of the preceding years. Candelise et al. [18] have questioned the accuracy of the learning curve for PV price projection, given the dynamics of the PV price/market. They argued, with evidence, that price forecast and policy making using only a simple relationship between historical technology price and installed capacity (experience/learning curves) entail notable limitations. Such a curve does not reflect the complexity of the market, technological breakthroughs, etc. [20]. Followings are some of the main limitations of learning curves for PV systems:

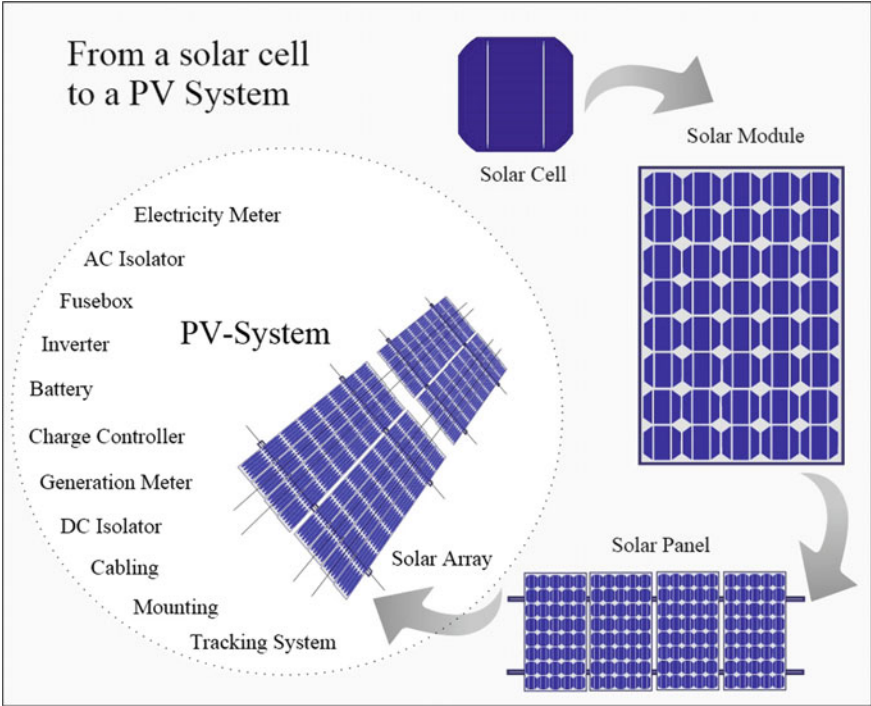
- Experience curves are not based on all PV technologies. There have been three generations of PV technology. The first generation includes the conventional wafer-based crystalline silicon (mSi) technologies (including three types of single-cSi, multi-cSi, and ribbon-sheet-cSi). The second generation is thin-film (TF) technology (including amorphous silicon, amorphous- or micromorph-silicon multi-junction, cadmium-telluride, etc.). Emerging new technologies such as concentrating PV (CPV) and organic thin films and many other novel technologies are considered the third generation [21]. Historically, cSi has been the mainstream PV technology accounting for 89 % of the total market in 2011 [21]. As such, learning curves are based mainly on cSi and do not reflect the newer generation of PV technologies, some of which could disrupt the curve.
- Learning curves reflect only the PV module price. A PV system, however, consists of two components: the PV module and the balance of the system (BOS) (see Fig. 2.8). The latter includes inverter, power control system, racking, cabling, and storage (if any). Except for storage, the other components of



**Fig. 2.7** Historical improvement of PV panels as of August 2014 [19]



- the BOS are almost mature, having a lower learning rate than the PV module, (12.5 % vs. 20 %) [15]. According to the European Photovoltaic Industry Association (EPIA), the cost breakdown of the most common PV technologies is as follows [22]: 50 % (TF)–60 % (cSi) of the cost of a typical PV system is for the PV module, 10 % for the inverter, 23–33 % for installation of the BOS, and 7 % for engineering and procurement. The PV module cost itself includes 45–50 % for silicon, 25–30 % for cell manufacturing, and 20–25 % for assembly into a module (labor costs, etc.). Therefore, even the module production cost is partly technological and partly material/labor costs. Unlike the technical portion, the material price may not be correlated with a learning curve.
- There is a difference between the production cost of a module and its market price. That difference is mainly defined by market demand/supply dynamics [18]. For example, the recent marked increase in PV production capacity, especially in China, has resulted in reduction of the PV cost/price gap due to increased market competition [23]. Overall, the International Energy Agency’s Energy Technology Systems Analysis Programme (IEA-ETSAP) and the International Renewable Energy Agency (IRENA) project that further price reductions of 40–60 % are feasible by 2020, for which efficiency improvement will be a key factor [21].



**Fig. 2.8** Components of a PV system [24]



Overall, the PV price decline has increased the social acceptance of PV technology and, with the commoditization of panels, inverters, and associated components, has made installation on the demand side very convenient. The possibility of generating power on the demand side and converting “consumers” to “prosumers” (producers and consumers) has many advantages in terms of energy efficiency, as reduction can be achieved by some power losses due to network transmission and distribution (T&D), the network footprint, reserve generation capacity, etc. Of course, the extent of these benefits depends on system configuration and penetration levels [25, 26].

### 2.3 Energy Storage: History and Role in Microgrid

Energy storage is an embedded survival mechanism of Mother Nature. The bodies of all plants, insects, and animals, including humans, have arrangements for storing energy to use when needed. Nature has organized a newborn baby to have energy storage equal to 10 % of its weight (in the form of fat in the upper back) to survive the early hours of birth. Babies lose this stored energy within the first few days after birth. This embedded energy storage has obviously inspired intelligent creatures, from ants to humans, to store their essentials at times of abundance to consume during shortage periods.

Civilization was initially formed at locations with an abundance of primary needs (water, food, fuel, etc.). However, as population increased and civilizations spread across broader locations, shortages of some necessity commodities appeared among tribes [27]. This led to the development of trade and supply chains.

In summary, commodities are not always produced at the right time and at locations where they are needed. This also applies to energy. Today, the majority of produced oil and gas is used in locations other than where it is produced. The supply chains of solid (e.g., coal) and liquid (e.g., crude oil) energy sources are well developed. The gas supply chain is also evolving from the traditional pipeline form to other approaches such as liquefaction and transportation. Unlike fuel energies (gas, liquid, or solid form), the management of electron energy (electricity) is very different. From one aspect, electricity can easily be transferred from one location to another, whereas such transfer is very costly and time-consuming for fuel energies. On the other hand, storage of solid/fluid energies during oversupply periods is easier than storage of electron-based energy. With renewable energy sources that are imperfectly predictable and controllable, storage becomes a critical issue. Figure 2.9 shows various types of energy storage. The lifecycle maturity status of some energy storage technologies is also shown in Fig. 2.10.

The easiest and least costly form of storage might be thermal storage, in which energy is used to heat (sensible or latent) or cool a solid/liquid material. The stored energy can then be used for heating, cooling, or electricity generation at later times. Phase change materials play a key role in the development of thermal storage, with special attention to solar energy storage [28, 29].

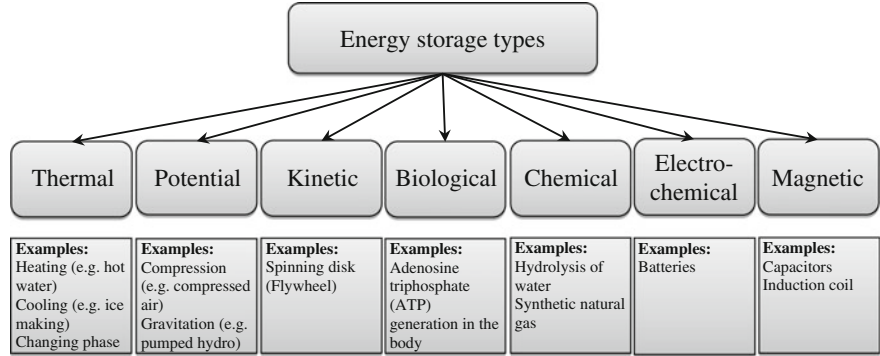


Fig. 2.9 Various types of energy storage

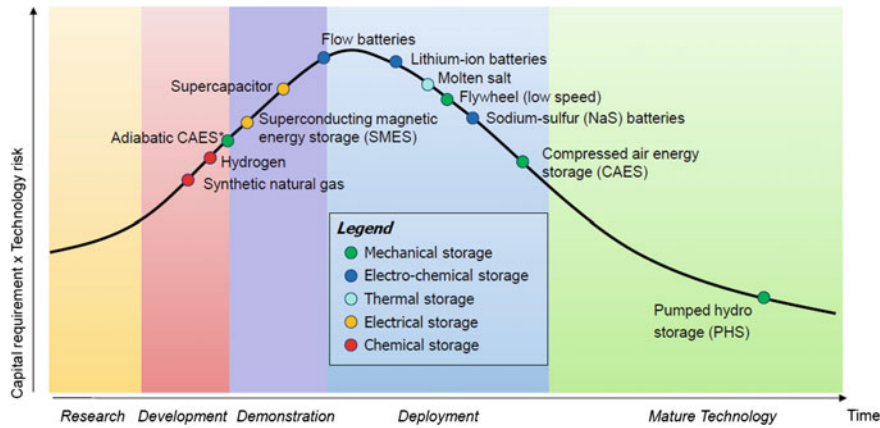


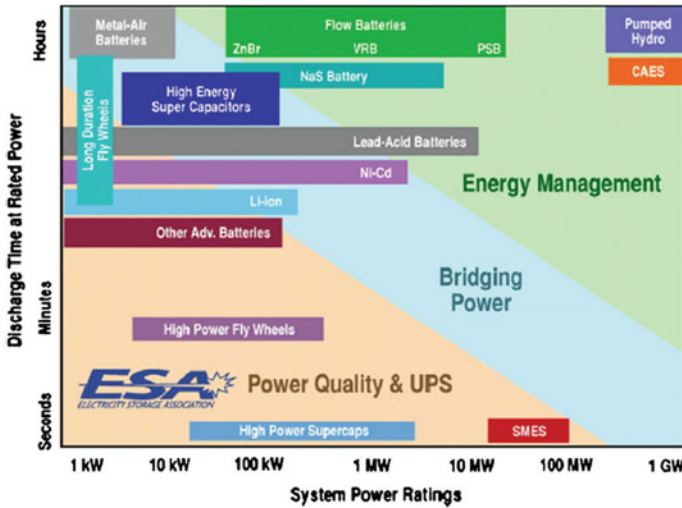
Fig. 2.10 Product lifecycle and maturity status for some energy storage options (Image courtesy of SBC Energy Institute [36])

Potential energy is another form of storage, achieved by introducing pressure or tension to a medium. For instance, compression of natural gas not only reduces its volume and makes transportation easier, but also the pressure can be recovered (subject to some loss) at a later time or another location to generate work. In the electricity industry, pumped hydro has a long history of using storage to generate electricity. Compressed air is also almost a mature technology (see Fig. 2.10), discussed as an economical approach for large-scale electricity storage [30]. The advantage of potential energy storage is its resilience in terms of duration of storage. Unlike potential energy storage, kinetic energy storage is used for temporary energy storage (for seconds or minutes). An example is the flywheel, which is in the deployment phase. The most complex form of energy storage might be chemical and biological storage, which is actually the most accessible, in our own bodies! Batteries are categorized as electrochemical energy storage. Magnetic energy storage is the form of storing energy using an electromagnetic field.

Electrical energy storage (EES) is not a new technology/concept; it has been practiced for over a century. It was 20 years after the invention of rechargeable lead acid batteries, in 1859 [31], that Thomas Edison invented the light bulb in 1879 and developed the first centralized commercial power plant in 1882 in New York City's financial district for lighting the shops and attracting customers [32]. Soon, demand increased and lead acid batteries were found as a solution for storing electricity at times of low demand and selling it to the shops at peak evening times. In 1896, a 300-ton, 400-kWh lead acid battery was used at a hydropower station to avoid outage at equipment breakdown [33].

In the recent years there have been extensive academic and commercial activities around electric vehicles to an extent that a tipping point in EV car uptake is projected in very near future. But, it might be interesting for many people to know that EVs were dominant automobile products in the market in the late 1800s and early 1900s with a peak in 1913 [34]. Afterwards, Henry Ford's success in efficient and cheap combustion cars doomed EV market to an extent that today we can rarely believe their history. The above examples shed light on the long and successful journey of energy storage over one and half century. Through this time, battery storage, along with other energy storage types, has been developed, each with a certain learning rate. The objective of electricity storage has also become far more than the initial intention of peak-shaving or short-term outage prevention [35]. Today, EES is used for many other reasons, such as delaying capacity/network expansion, regulating frequency, and balancing voltage (preventing brownouts) [36]. As such, each energy storage technology is suitable for a given objective. The technologies are usually categorized based on the timescale of applications: instantaneous (less than a few seconds), short-term (less than a few minutes), midterm (less than a few hours), and long-term (days) [37]. A detailed background of the historical development of various energy storage options can be found in the Electricity Storage Handbook published by Sandia National Laboratories [38].

Attention to electricity storage was triggered when several intermittent renewable power sources, especially PV and wind power, emerged in various sizes ranging from a few kilowatts to hundreds of megawatts. These power sources, whether grid-connected or off-grid (stand-alone), require storage (for load-balancing) due to their output intermittency as a result of weather/seasonal fluctuations. Historically, pumped hydro at large centralized power stations has been the dominant option for electricity storage, due to the notably lower comparative cost [33]. However, this popular and mature (see Fig. 2.10) storage option is geographically limited and for obvious reasons is not available/feasible for all levels of grid use, including distribution and community level (e.g., residential and commercial). Batteries (along with super-capacitors and flywheels) are a feasible EES option for short- to medium-term storage (up to a few hours). Today, numerous commercial batteries are available, including lead acid, lithium ion, sodium sulfur, and vanadium redox flow, each with different characteristics such as energy capacity cost, round-trip efficiency, depth of discharge, life, discharge duration, cycle frequency, energy/power density, and environmental impact [31, 39]. Figure 2.11 from the US Energy Storage Association (ESA) shows the place of energy storage technologies based on their power ratings



**Fig. 2.11** Screening of energy storage systems for various applications based on their power ratings and discharge times (*Image* courtesy of the US Electricity Storage Association)

and typical discharge times. Those with lower discharge time are suitable for power quality management and uninterruptible power supply (UPS). Those of large size and very high discharge time are suitable for bulk power management. In the middle are the storage systems suitable for T&D support and load shifting.

Selection of the right battery is linked to many parameters, including the application objective, position in the grid (close to generation, transmission, distribution, and end user, for example), and geographic location, and there are numerous tools for evaluation [40]. Nevertheless, batteries still require further development to improve their round-trip efficiency and lifetime in order to reduce the overall costs [41]. Recent studies project a fast decrease in battery prices. In their paper published in *Nature Climate Change* [42], Björn Nykvist and Måns Nilsson report a learning rate between 6 and 9 % for Li-ion batteries (see also Fig. 2.12).

Some studies support the benefit of subsidizing battery storage cost in the medium term to allow faster uptake of PV technology (at residential level) and meanwhile to prevent grid instability and security [43]. Rapid storage uptake in microgrids is evident in the recent report by GTM Research [44]. According to that report, currently about one-third of the operational grids in North America have EES, 90 % of which were installed during 2011–2014 [45]. The projections by GTM and the US ESA show exponential annual increments in energy storage installations toward 2019 (see Fig. 2.13) [46]. It is also evident from Fig. 2.12 that currently most energy storage installations are by utility companies. Projected to 2019, however, the share of non-utility sectors including residential notably increases.

While we were finalizing this book for print, Tesla (the company famous for its ambitions for low-cost batteries for electric vehicles) surprised the world with the announcement of its 10-kWh Powerwall battery at the cost of \$3500 per unit (see

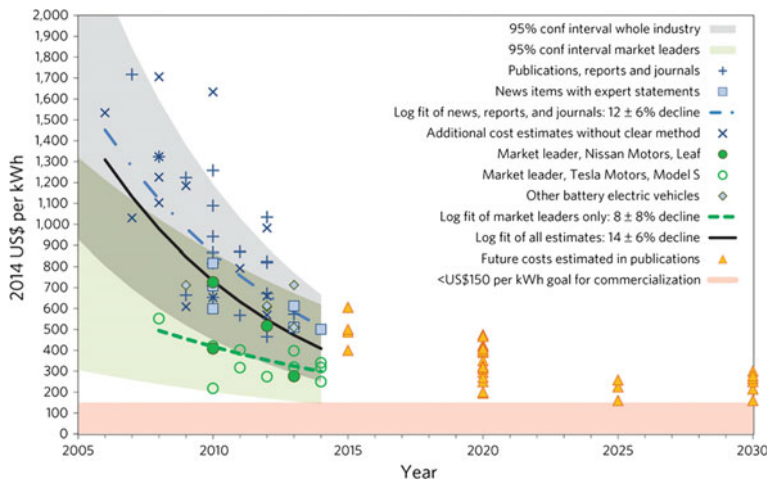


Fig. 2.12 Rapidly falling costs of battery packs for electric vehicles (Image source [42])

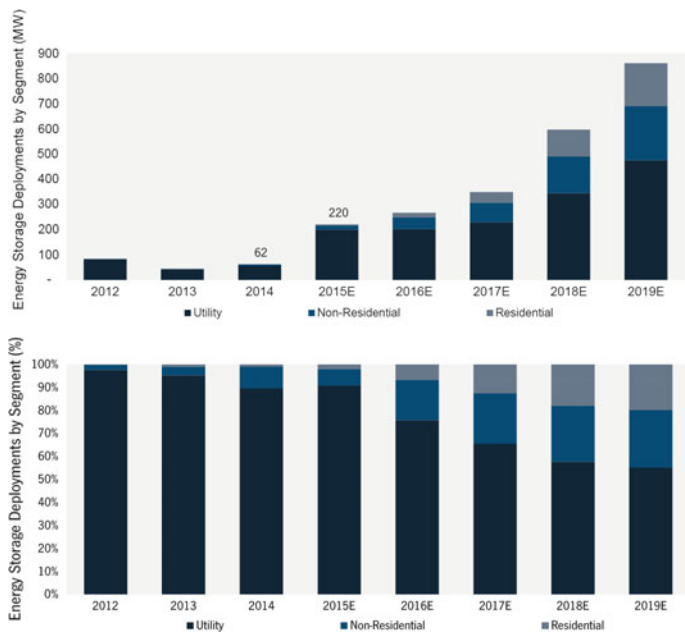


Fig. 2.13 Trend of historical and projected energy storage installations in the USA, by sector (Image courtesy of [46])



**Specifications**

- Technology:** lithium ion battery with liquid thermal control.
- Models:** 10 kWh \$3,500; 7 kWh \$3,000
- Warranty:** 10 years
- Efficiency:** 92% round-trip DC efficiency
- Power:** 2.0 kW continuous, 3.3 kW peak
- Voltage:** 350 – 450 volts
- Current:** 5.8 amp nominal, 8.6 amp peak output
- Operating Temp:** -20°C to 43°C
- Weight:** 100 kg
- Dimensions:** 1300 mm × 860 mm × 180 mm

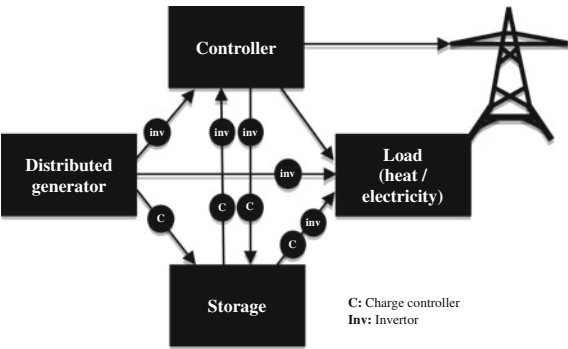
**Fig. 2.14** The revolutionary Tesla Powerwall battery introduced in April 30, 2015 [47]

Fig. 2.14 for the specifications). This technology will undoubtedly revolutionize the structure of energy storage markets and their public and commercial uptake. Thus, along with other forms of DG and battery energy storage for end users, the topology and operation of future electricity networks may become very different from the traditional system.

**2.4 Nanogrids**

A nanogrid is defined as a stand-alone hybrid generation system that uses distributed renewable and non-renewable resources with or without energy storage to supply power to a local load [48]. Its difference from a microgrid is that such a system serves only a single user, while a microgrid supplies multiple users. Figure 2.15 illustrates a nanogrid with a DGS system.

**Fig. 2.15** Schematic of a nanogrid with DGS system



Various combinations of energy generation and storage technologies have been studied for nanogrid and microgrid applications (Table 2.1). For obvious reasons, solar systems have been of the highest interest for small-scale demand side applications. The earliest simple configurations were PV-grid, PV-diesel [49], and PV-Battery. The configurations have diversified over time with the inclusion of various hybrid DGS systems such as PV-hydrogen, PV-diesel-battery, PV-wind-battery [50], PV-wind-diesel [51], PV-wind-diesel-battery [52], and PV-wind-diesel-hydrogen-battery [53]. The list of configurations (Table 2.1) could be much longer if other generation types (e.g., bioenergy, hydro, and gas turbine) and storage (e.g., hydro, compressed air, flywheel, capacitance, and chemical conversions) are included [54].

**Table 2.1** Illustrative list of some generator/storage configurations for nanogrid and microgrid

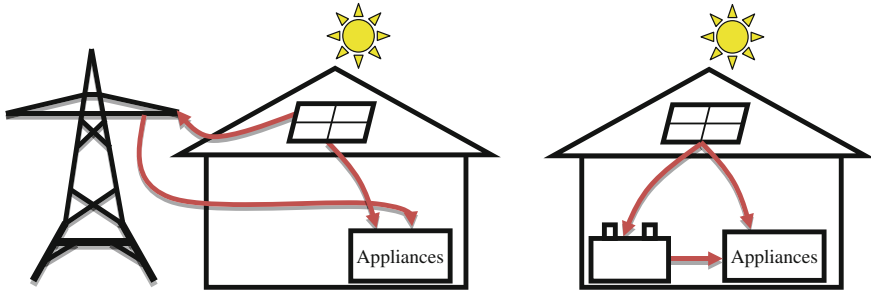
Configuration	Grid dependence	Comment	Sample reference
PV	×	Unable to provide 100 % reliability	[55]
	√	Surplus electricity sent to grid or curtailed	[56]
PV/diesel	×, √	Diesel generally used in the absence of grid. But it could be also used during peak grid tariffs	[49]
PV/hydrogen fuel cell	×	Surplus PV generation used for hydrolysis of water and hydrogen generation to later generate electricity in a fuel cell	[57, 58]
PV/battery	×	Surplus PV output saved in battery for later consumption	[59]
	√	Battery used to shift consumer load. Economic benefit for the user and DSM benefits for network operator	[60]
PV/diesel/battery	×	Surplus PV output saved in battery for later consumption. Shortfall supplied by diesel generator	[61, 62]
PV/battery/hydrogen fuel cell	×	Surplus PV generation saved in battery or used for electrolysis of water and hydrogen generation. Hydrogen generates electricity in fuel cell during high demand periods	[63, 64]
Wind/diesel	×	Surplus wind generation curtailed. Demand shortfall supplied by diesel generator	[65]
Wind/pumped hydro	×	Surplus wind generation stored in water by pumping to higher elevation. When wind unavailable, water directed to lower elevation and generates electricity	[66]
Wind/diesel/pumped hydro	×	As above, except that diesel generator used when water storage insufficient to supply demand shortfall	[67]
Wind/diesel/battery		Surplus wind output saved in battery for later consumption. Shortfall supplied by diesel generator	[68]

(continued)



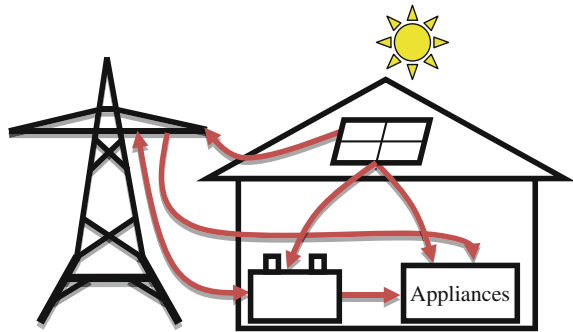
**Table 2.1** (continued)

Configuration	Grid dependence	Comment	Sample reference
PV/wind/diesel	$\times, \sqrt{\phantom{x}}$	Electricity generated with PV and wind when available. Shortfall supplied by diesel generator. When generator not operating as a base load, possible reliability issue without grid connection	[51]
PV/wind/biogas	$\times, \sqrt{\phantom{x}}$	Electricity generated with PV, wind, and biogas from sewage treatment, etc. When biogas generator not operating as a base load, possible reliability issue without grid connection	[69]
PV/wind/battery	$\times$ (with enough battery size)	Surplus PV/wind generation saved in battery. Demand shortfall still possible	[50, 70]
PV/wind/diesel/battery	$\times$	Surplus PV/wind generation saved in battery. Possible demand shortfall supplied with diesel generator	[52, 71, 72]
PV/wind/hydro	$\sqrt{\phantom{x}}$	Surplus PV/wind generation stored in water by pumping it to higher elevation. When PV/wind output insufficient, water directed to lower elevation and generates electricity. As pumped hydro cannot follow load with multiple on/off, reliability issue possible unless there is grid connection	[73]
PV/solarthermal/wind/hydro	$\times$	Surplus PV/wind/solar thermal generation stored in water by pumping to higher elevation. When PV/wind/solar thermal output insufficient, water directed to lower elevation and generates electricity	[74]
PV/wind/hydro/battery	$\times$	As above, but battery helps for faster response to load change compared with hydro	[75]
PV/wind/hydrogen fuel cell/battery/diesel	$\times$	Surplus PV/wind generations converted to hydrogen by water electrolysis and stored in battery. When PV/wind output insufficient, fuel cell or battery used. Remaining shortfall supplied by diesel generator	[53]
PV/wind/hydrogen fuel cell/battery/hydro	$\times$	Surplus PV/wind generation converted to hydrogen by water electrolysis, stored in water by pumping, and stored in battery. When PV/wind output insufficient, one or combination of the three storage sources utilized	[76]



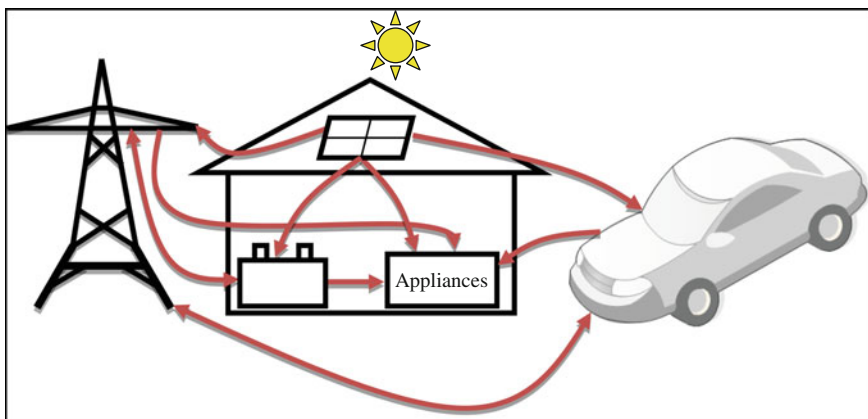
**Fig. 2.16** Schematic of two DG configurations: grid-connected DG (*left*) and off-grid (*stand-alone*) DG with storage (*right*)

**Fig. 2.17** Illustration of a grid-connected DGS system

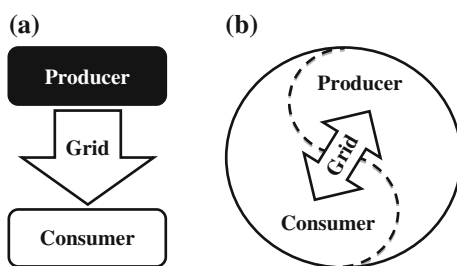


Obviously, a key issue to the success of nanogrids (likewise for microgrids) is the market price parity of electricity generated by DER versus centralized power plants. Traditionally, nanogrids, in simple forms such as PV-diesel or PV-Battery (Fig. 2.16-right), have been used in remote locations without grid access. The recent rapid decline in PV prices has brought grid parity for PV to many countries. There has been an unexpected rate of increase in residential level uptake of PV systems in many countries, including Germany and Australia. Interest in DG has increased even at locations with grid connection (Fig. 2.16 left).

Interestingly, the prices of battery storage systems have also shown a notable declining trend and it is anticipated that battery technology may follow the price trajectory of PV [77]. In off-grid applications, electricity storage is an inseparable part of PV generation if close to 100 % reliability is sought. However, a storage system can provide flexibility for a nanogrid even when the grid is available (by shifting the load to the least expensive tariff periods). As such, the third configuration, the grid-connected DGS system (Fig. 2.17), has received great attention both commercially and academically. The current trend of innovative academic research is toward the modeling of grid-connected DGS systems which are relatively more



**Fig. 2.18** Illustration of a grid-connected DGS system with static and mobile (electric vehicle) storage system



**Fig. 2.19** Conventional one-directional grid versus bidirectional smart grid of prosumers. The electricity community is familiar with the concept of AC as “alternating current.” The new AC is “alternating consumers,” which alternates within the consumer–producer range through the day. **a** Conventional grid with one-directional power flow from producer to customer. **b** Smart grid with prosumers (bidirectional communication of producer and customer)

complex than the former configurations [60, 78–80]. Adding to this complexity is the projected rapid uptake of electric vehicles. When such vehicles also join the nanogrids of small-scale prosumers, the combination of static and mobile storage system will provide better flexibility for operation of the grid, though with considerably increased complexity (Fig. 2.18).

Thus, whereas the conventional grid was a one-directional network of producers to consumers (Fig. 2.19a), the future grid looks to be a bidirectional network of nanogrids which are now “prosumers”: sometimes producers and at other times consumers (Fig. 2.19b).

A grid-connected DGS system is much more complex than its predecessors (off-grid DGS or grid-connected DG). The complexity applies both to the operation of an individual nanogrid and to the macrogrid. The primary goal of any demand side management (DSM) program is to influence consumers to use electricity with

higher efficiency and with a schedule that guarantees security of supply. DSM is expected to have a more complex structure and to play a much more critical role in robust operation of bidirectional networks with a large proportion of prosuming members (nanogrids).

Castillo-Cagigal et al. [81] stated that DSM faces notable challenges due to the increased complexity of DGS systems that require monitoring, communication, and control systems. They highlighted the requirement of active DSM (ADSM) with a combination of DSM and automatic control at residential demand loads. This was also considered by Strbac [82]. A similar requirement was discussed by Tan et al. [83] from Sandia National Laboratories as solar energy grid integration systems–energy storage (SEGIS-ES).

Though some network operators perceive nanogrids as business competitors and behave passively, others have initiated activities toward the management of grids with nanogrids. As an interesting and pragmatic example, a New Zealand electricity network operator, Vector, initiated a program to lease a nanogrid system (comprising a 3.0 kW PV, a 10.7-kWh Li-ion battery, and an inverter) to residential customers with certain DSM terms and conditions. The key condition is that the consumer (now the prosumer) must use all the energy stored in the battery at peak times. According to the company, this scheme not only promotes DGS uptake by households but also benefits the company by reducing/delaying network upgrading investments [84]. Such examples shed light on the thinking about how diverse and complex operation of the future electricity network is likely to be.

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