

## Unit-III

### APPLICATIONS OF EES

In this section an overview of the markets for EES is given by describing existing EES application cases. Applications for conventional electric utilities and consumers are presented as well as near-future use cases, concentrating on storage applications in combination with renewable energy generation.

#### 3.1 Present status of applications

In this section, those cases are described which have already been implemented by electric utilities and consumers. These are respectively time shift and investment deferral for the former, and emergency supply and power quality for the latter.

##### 3.1.1 Utility use (conventional power generation, grid operation & service)

- 1 Reduce total generation costs by using pumped hydroelectricity for time shifting, which stores electricity during off-peak times and provides electricity during peak hours.
- 2 Maintain power quality, voltage and frequency, by supplying/absorbing power from/into EES when necessary.
- 3 Postpone investment needed by mitigating network congestion through peak shift.
- 4 Provide stable power for off-grid systems (isolated networks).
- 5 Provide emergency power supply.

#### **Utility use of pumped hydro storage for time shift and power quality**

Pumped hydro storage (PHS) has historically been used by electric utilities to reduce total generation cost by time-shifting and to control grid frequency. There are many PHS facilities in different countries, and they have the largest proportion of total storage capacity worldwide. A conventional installation cannot function as a frequency controller while pumping, but an advanced variable-speed-control PHS (Figure 3-1) can do so by varying the rotational speed of the motor.



Figure 3-1 | Variable-speed PHS operated by TEPCO (*TEPCO*)



Figure 3-2 | CAES plant in Huntorf (*Vattenfall, IEC MSB/EES Workshop 2011*)

### Utility use of compressed air energy storage for time shift and power quality

Today only two diabatic compressed air energy storage (CAES) power plants are in operation worldwide. In 1978 the first CAES power plant was built in Huntorf, Germany (Figure 3-2). It works as a diabatic CAES plant with a round-trip efficiency of roughly 41 % [rad08]. It consists of a low-pressure and high-pressure compressor with intercooler, two salt caverns (2 x 155 000 m<sup>3</sup> usable volume, 46 - 72 bar pressure range), a motor-generator (60 MW charging, 321 MW discharging) and a high-pressure (inlet conditions: 41 bar, 490 °C) and low-pressure turbine (13 bar, 945 °C). The second CAES plant is in McIntosh (Alabama, USA) and was commissioned in 1991. It has a net electrical output of 110 MW and is also based on a diabatic CAES process, but additionally a recuperator is used to recover heat from the exhaust at the outlet of the gas turbine. Therefore a higher round trip efficiency of 54 % can be achieved. Both systems use off-peak electricity for air compression and are operated for peak levelling on a daily basis.

Worldwide several CAES plants are under development and construction. In Germany for example a small adiabatic CAES plant is scheduled for demonstration in 2016 (project ADELE), which will achieve a higher efficiency in comparison to a diabatic CAES [rwe11].

### Utility's more efficient use of the power network

As one of the examples of EES for utilities, a Li-ion battery can provide the benefit of more efficient use of the power network.

In 2009 the US companies AES Energy Storage and A123 Systems installed a 12 MW, 3 MWh Li-ion battery at AES Gener's Los Andes substation in the Atacama Desert, Chile (Figure 3-3). The battery helps the system operator manage fluctuations in



Figure 3-3 | Li-ion battery supplying up to 12 MW of power at Los Andes substation in Chile (A123, 2009)

demand, delivering frequency regulation in a less expensive and more responsive manner than transmission line upgrades. In addition, because the project replaces unpaid reserve from the power plant, AES Gener will receive payment for its full output capacity by selling directly to the electric grid.

### Utility's emergency power supply

Important facilities, such as power stations, substations and telecommunication stations, need power sources for their control installations with high power quality and reliability, since these are the very facilities which are most needed for power in the case of an interruption. EES systems for this application are mostly DC sources and supported by batteries. Historically lead acid batteries have been used for this purpose.

### Utility's off-grid systems (isolated grids)

In the case where a utility company supplies electricity in a small power grid, for example on an island, the power output from small-capacity generators such as diesel and renewable energy must also match with the power demand. On Hachijo-jima (island), where about 8 000 people

live, TEPCO uses NaS batteries with diesel generators and a wind power station to meet the varying demand. For off-grid photovoltaic systems in the power range (50 W -) 1 kW - 500 kW lead acid batteries for EES are commonly used.

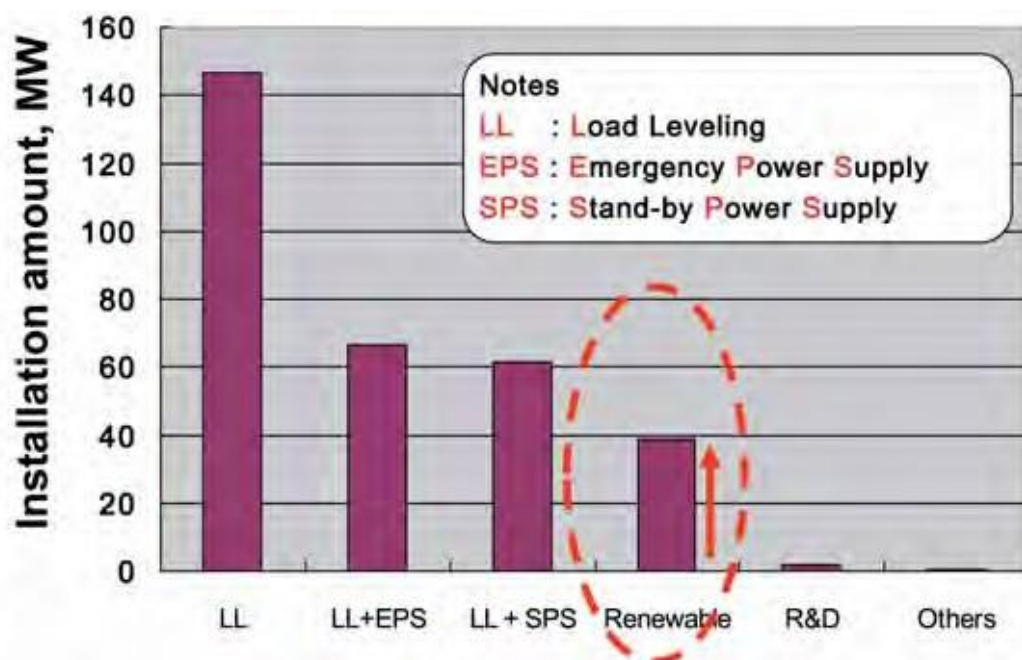
### 3.1.2 Consumer use (uninterruptable power supply for large consumers)

1. Suppress peak demand and use cheaper electricity during peak periods, i.e. save cost by buying off-peak electricity and storing it in EES. The result is load leveling by time-shifting.

2. Secure a reliable and higher-quality power supply for important factories and commercial facilities.

Example: consumers' use of NaS batteries

Figure 3-4 shows the applications of NaS batteries installed in the world with their respective power capacities. The systems used exclusively for load levelling (LL) account for almost half the total, and installations for load levelling with the additional functions of emergency power supply or stand-by power supply represent another 20 % each. However, the need for storage linked to renewable energy, as explained in section 3.2, is growing.



**Figure 3-4 | NaS battery applications and installed capacities (NGK, IEC MSB/EES Workshop, 2011)**

### 3.2 EES installed capacity worldwide

Figure 3-6 shows the installed capacity of EES systems used in electricity grids. Pumped hydro storage (PHS) power plants, with over 127 GW, represent 99 %, and this is about 3 % of global generation capacity. The second-largest EES in

installed capacity is CAES, but there are only two systems in operation. The third most widely-used EES is the NaS battery. As of the end of September 2010, NaS systems were installed and operational in 223 locations in, for example, Japan, Germany, France, USA and UAE (total: 316 MW). However, a large quantity of other EES is expected to be installed given the emerging market needs for different applications, as shown in the next section.

### 3.3 New trends in applications

Five new trends in EES applications are described: renewable energy, smart grids, smart microgrids, smart

houses and electric vehicles. Current use cases of these applications include experimental equipment and plans.

### 3.3.1 Renewable energy generation

In order to solve global environmental problems, renewable energies such as solar and wind will be widely used. This means that the future energy supply will be influenced by fluctuating renewable energy sources – electricity production will follow weather conditions and the surplus and deficit

in energy need to be balanced. One of the main functions of energy storage, to match the supply and demand of energy (called time shifting), is essential for large and small-scale applications. In the following, we show two cases classified by their size: kWh class and MWh class. The third class, the GWh class, will be covered in section 4.2.2.

Besides time shifting with energy storage, there are also other ways of matching supply and demand. With a reinforced power grid, regional overproduction can be compensated for by energy transmission to temporarily less productive areas. The amount of energy storage can also be reduced by overinstallation of renewable energy generators. With this approach even weakly producing periods are adequate for the load expected.

A further option is so-called demand-side management (described under Smart Grid in section 3.2.2), where users are encouraged to shift their consumption of electricity towards periods when surplus energy from renewables is available. These balancing methods not requiring EES need to be considered for a proper forecast of the market potential for EES.

#### Decentralized storage systems for increased self-consumption of PV energy (kWh class)

With the increasing number of installed PV systems, the low-voltage grid is reaching its performance limit. In Germany, the EEG (Renewable Energies Law) guarantees, for a period of 20 years, a feed-in tariff for every kWh produced and a fixed tariff for every kWh produced and self-consumed. To encourage operators of decentralized systems, the price for self-consumed PV energy is higher

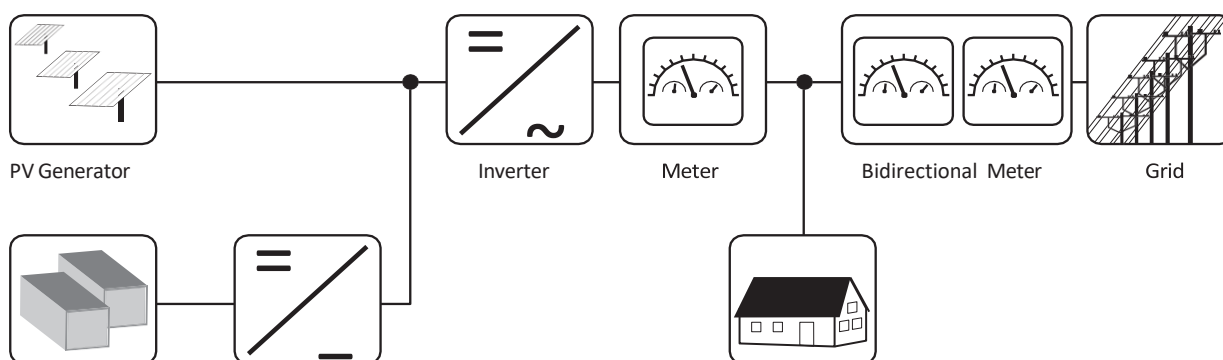
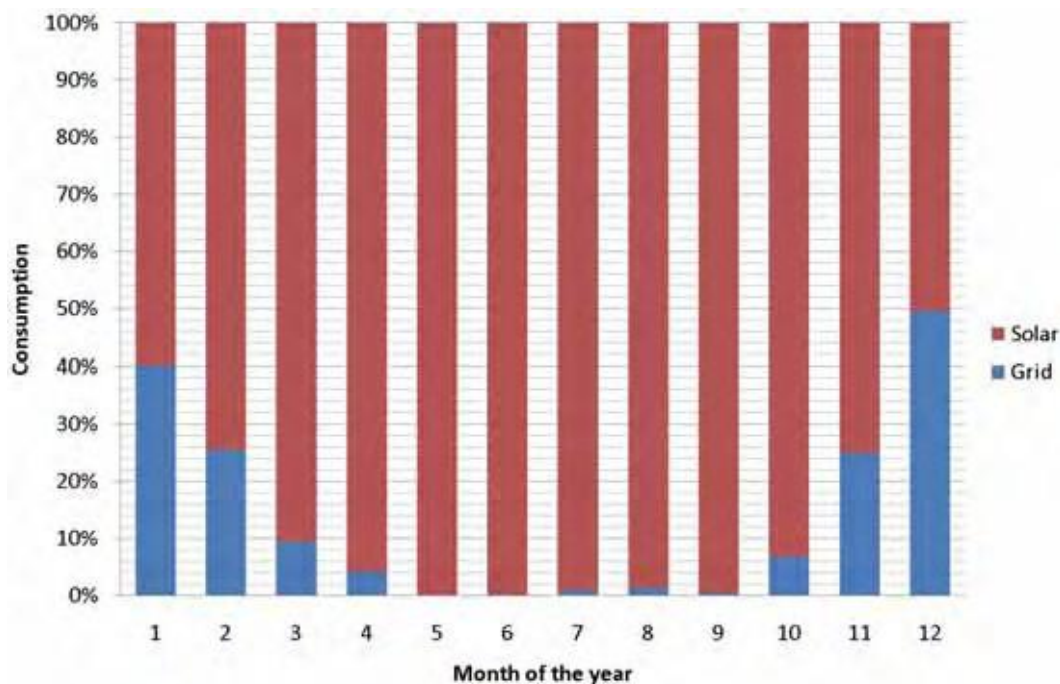


Figure 3-7 | PV system designed for energy self-consumption (Fraunhofer ISE)



**Figure 3-8 | Consumption of a typical household with a storage system: energy consumed from the grid and from the PV system (Fraunhofer ISE)**

Therefore self-consumption of power will become an important option for private households with PV facilities, especially as the price of electricity increases.

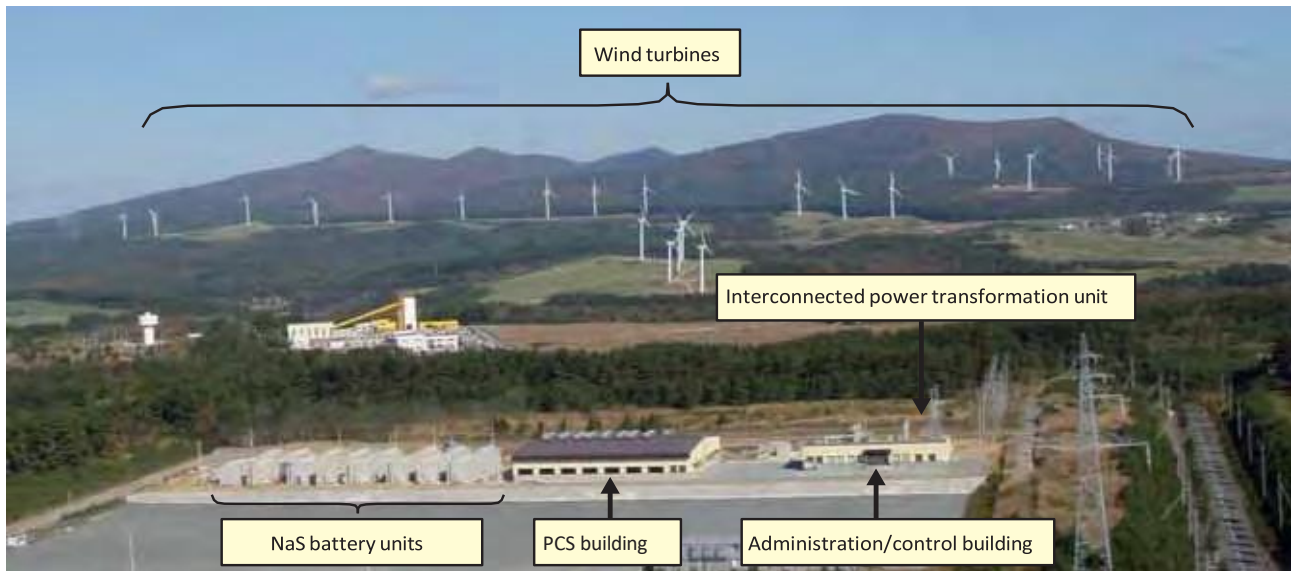
Figure 3-7 shows an example of system design. To measure the amount of energy consumed or fed into the grid two meters are needed. One meter measures the energy generated by the PV system. The other meter works bidirectionally and measures the energy obtained from or supplied to the grid. The generated energy that is not immediately consumed is stored in the battery.

In order to examine how much electricity can be self-supplied from PV, the results from a simulation for a typical household in Madrid may be of interest [sch11]. The total consumption of the household over one year is about 3 400 kWh. The aim is to use as much energy internally as possible, with a 10.7 kW PV generator and a 6 kWh lithium ion storage system. Figure 3-8 shows the electricity consumption of the household over a year. Regardless of the time of energy production, the storage provides the energy generated by the PV generator to electrical appliances. Supply and demand can be adjusted to each other. The integrated storage system is designed to cover 100 % of the demand with the energy generated by the PV system during the summer. During the rest of the year a little additional energy has to be purchased from the grid.

To provide a consumer-friendly system at low cost, maintenance cost in particular needs to be low and the most important factor for stationary batteries is still the price per kWh. Currently for this application lead acid batteries are the most common technology because of the low investment costs. Lithium ion batteries are generally better in efficiency and in the number of cycles, but they have much higher investment costs. NaNiCl batteries are also an option for this application, but they need daily cycling to avoid additional heating.

### Smoothing out for wind (and PV) energy (MWh class)

The Japan Wind Development Co. Ltd. has constructed a wind power generation facility equipped with a battery in Aomori, Japan (Futamata wind power plant, shown in Figures 3-9 and 3-10). This facility consists of 51 MW of wind turbines (1 500 kW x 34 units) and 34 MW of NaS batteries (2 000 kW x 17 units). By using the NaS battery



**Figure 3-9 | General view of the Futamata wind power plant (Japan Wind Development Co.)**

the total power output of this facility is smoothed and peak output is controlled to be no greater than 40 MW. Operation started in June 2008.

Figure 3-11 shows an example of output from this facility. The electric power sales plan is predetermined one day before. In order to achieve this plan, the NaS battery system controls charging or discharging in accordance with the output of wind power generation. This facility meets the technical requirements of the local utility company to connect to the grid.



**Figure 3-10 | NaS battery units – 34 MW (Japan Wind Development Co.)**

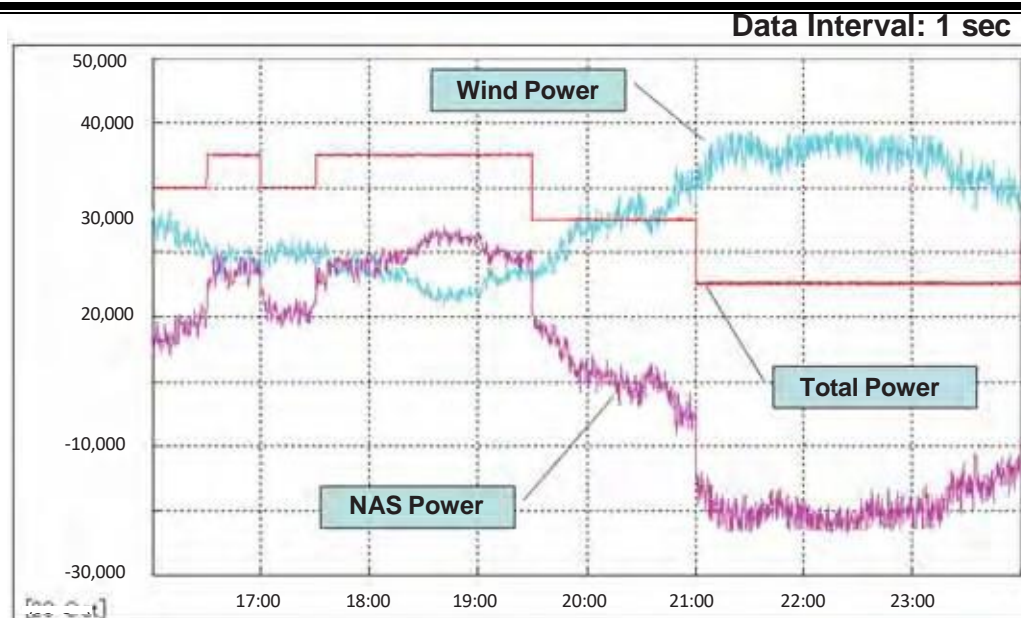


Figure 3-11 | Example operational results of constant output control over 8 hours (NGK)

### 3.3.2 Smart Grid

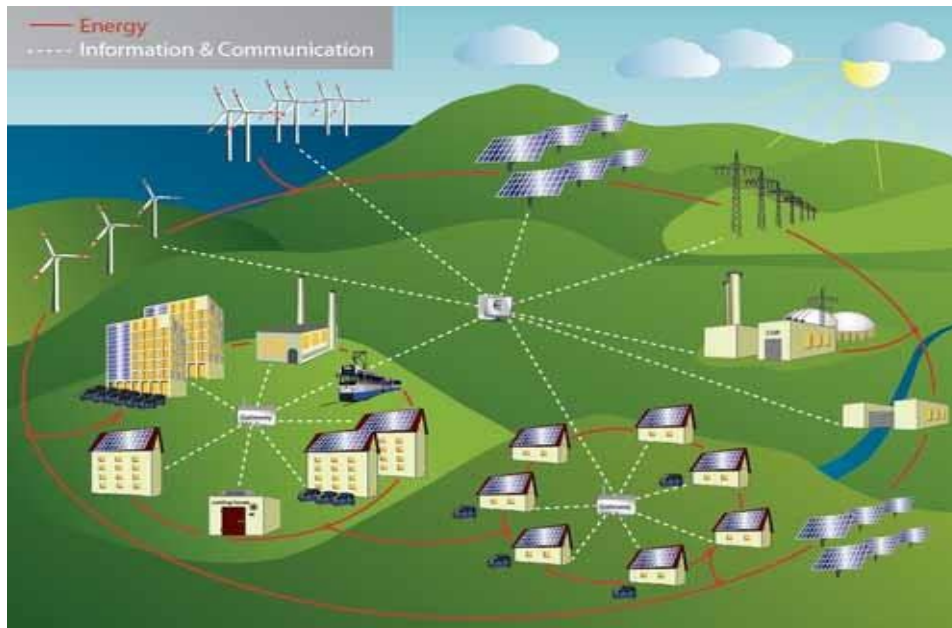
Today's grids are generally based on large central power plants connected to high-voltage transmission systems that supply power to medium and low-voltage distribution systems. The power flow is in one direction only: from the power stations, via the transmission and distribution grid, to the final consumers. Dispatching of power and network control is typically conducted by centralized facilities and there is little or no consumer participation.

For the future distribution system, grids will become more active and will have to accommodate bi-directional power flows and an increasing transmission of information. Some of the electricity generated by large conventional plants will be displaced by the integration of renewable energy sources. An increasing number of PV, biomass and on-shore wind generators will feed into the medium and low-voltage grid. Conventional electricity

systems must be transformed in the framework of a market model in which generation is dispatched according to market forces and the grid control centre undertakes an overall supervisory role (active power balancing and ancillary services such as voltage control).

The Smart Grid concept (Figure 3-12) is proposed as one of the measures to solve problems in such a system. The Smart Grid is expected to control the demand side as well as the generation side, so that the overall power system can be more efficiently and rationally operated. The Smart Grid includes many technologies such as IT and communications, control technologies and EES. Examples of EES-relevant applications in the Smart Grid are given below.

Penetration of renewable energy requires more frequency control capability in the power system. EES can be used to enhance the capability through the control of charging and discharging



**Figure 3-12 | The Smart Grid (Fraunhofer ISE)**

from network operators, so that the imbalance between power consumption and generation is lessened.

In some cases, EES can reduce investment in power system infrastructure such as transformers, transmission lines and distribution lines through load levelling in certain areas at times of peak demand. EES for this purpose may also be used to enhance frequency control capability.

A further option is so-called demand-side management, involving smart grids and residential users. With intelligent consumption management and economic incentives consumers can be encouraged to shift their energy buying towards periods when surplus power is available. Users may accomplish this shift by changing when they need electricity, by buying and storing electricity for later use when they do not need it, or both.

Electrochemical storage types used in smart grids are basically lead acid and NaS batteries, and in some cases also Li-ion batteries. For this application redox flow batteries also have potential because of their independent ratio of power and energy, leading to cost-efficient storage solutions.

### 3.3.3 Smart Microgrid

A smart factory, smart building, smart hospital, smart store or another intermediate-level grid with EES may be treated as a “Smart Microgrid”<sup>8</sup>. For flexibility in resisting outages caused by disasters it is very important to deploy Smart Microgrids, that is, distributed smart power sources, as an element in constructing smart grids.

EES is an essential component of a Smart Micro- grid, which should be scalable, autonomous and

<sup>8</sup> Note that the term “microgrid” has been the subject of various specific definitions, none of which is assumed here.

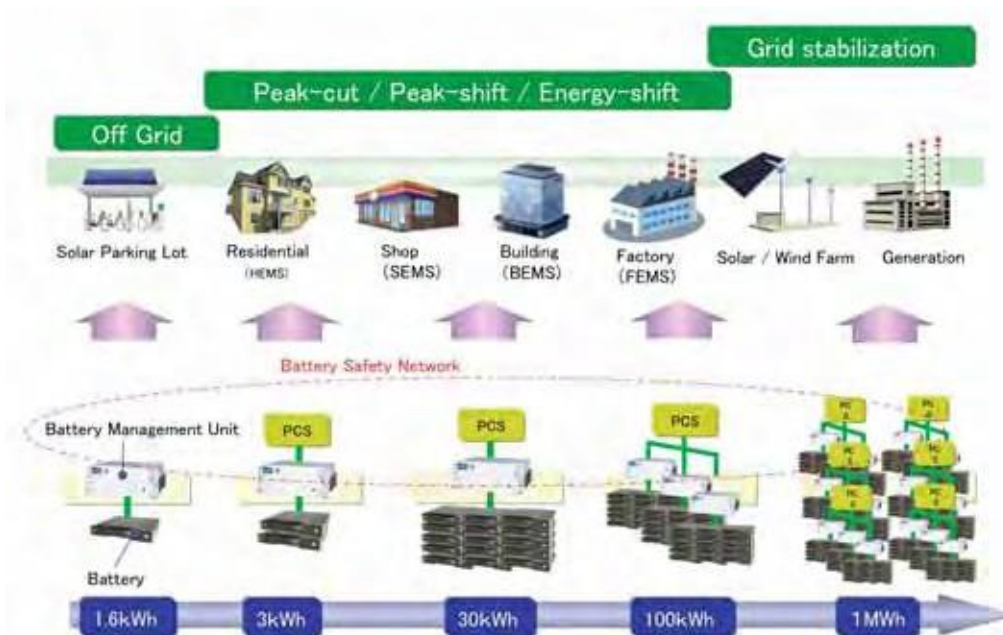


figure 3-13 | Scalable architecture for EES applications in a Smart Microgrid

ready to cooperate with other grids. The architecture for the Smart Microgrid should have a single controller and should be scalable with respect to EES, i.e. it should adjust smoothly to the expansion and shrinkage of EES (battery) capacities according to the application in for example a factory, a building, a hospital or a store. The microgrid and EES should in general be connected to the network; even if a particular Smart Microgrid is not connected to a grid, for example in the case of an isolated island, it should still have similar possibilities of intelligent adjustment, because an isolated Smart Microgrid can also expand or shrink. Figure 3-13 shows a schematic of a scalable architecture.

In Annex B two examples are given, a factory and a store, which have fairly different sizes of batteries, but with controllers in common. Microgrids controlled in this way have the features of connecting and adjusting to the main grid intelligently, showing and using the input and output status of batteries, and controlling power smoothly in an emergency (including isolating the microgrid from the main grid if needed). These are the characteristics needed in Smart Microgrids, regardless of EES scale or applications.

### 3.3.3 Smart House

The concept of the Smart House is proposed in order to use energy more efficiently, economically and reliably in residential areas. EES technologies are expected to play an important role.

The consumer cost of electricity consists of a demand charge (kW) and an energy charge (kWh). Load levelling by EES can suppress the peak demand; however, charge/discharge loss will simultaneously increase the amount of electricity consumed. Consumers may be able to reduce electricity costs by optimizing EES operation.

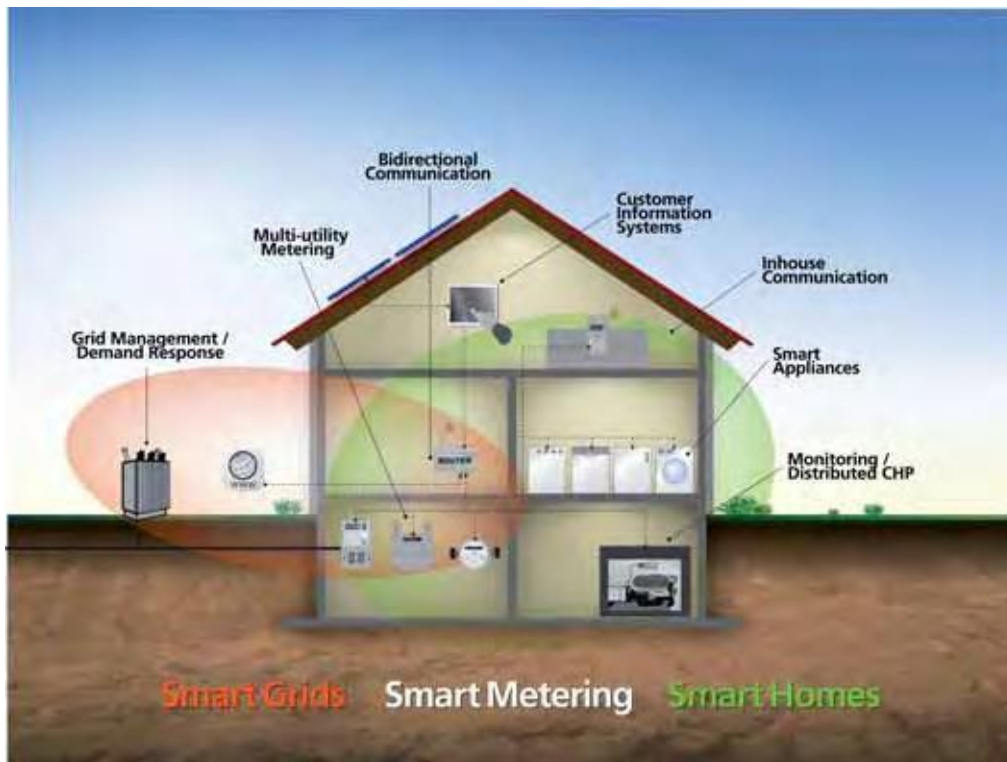


Figure 3-14 | The Smart House (Fraunhofer ISE)

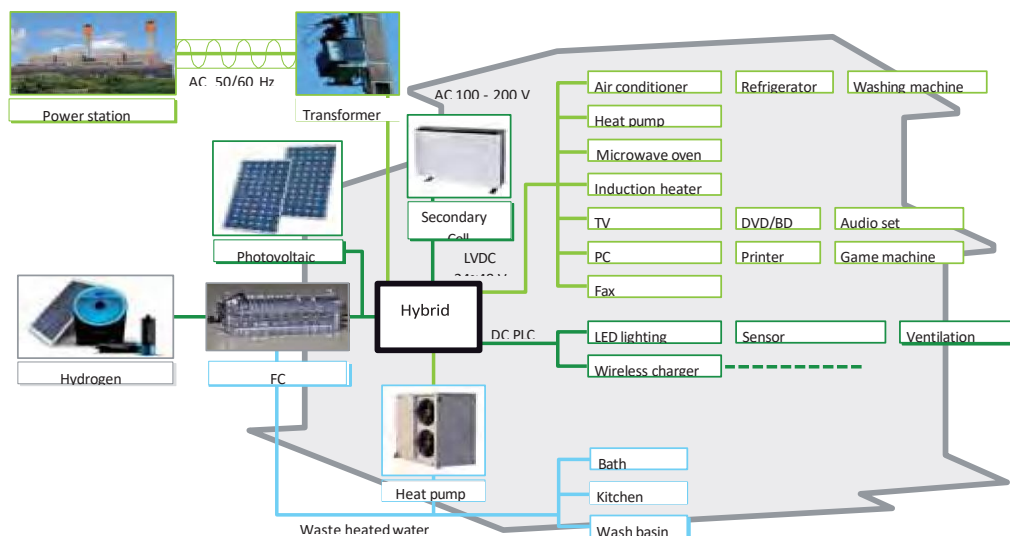


figure 3-15 | Future home energy network in a smart house (IEC White Paper 2010)

2) Some consumers prefer to use their own renewable energy sources. EES can reduce the mismatch between their power demand and their own power generation.

3) In specific situations such as interruption of power supply, most on-site renewable generators have problems in isolated operation because of the uncontrollable generation output. EES may be a solution.

Figure 3-14 schematically represents the smart house, and Figure 3-15 maps a possible energy architecture for it. In smart houses mainly lead acid systems are used currently, but in the future Li-ion or NaNiCl batteries in particular may be installed because of their high cycle lifetime and their ability to deliver high peak power.

### 3.3.4 Electric vehicles

Electric vehicles (EVs) were first developed in the 19th century but, since vehicles with conventional combustion engines are much cheaper and have other advantages such as an adequate driving range of around 500 km, electric vehicles have not been introduced in large quantities to the market. The main obstacle for building electricity-driven vehicles has been the storage of energy in batteries. Due to their low capacity it has not been possible to achieve driving ranges that would be accepted by the consumer. The emerging development of battery technology in recent years presents new possibilities, with batteries displaying increased energy densities.

In the transitional period of the next few years, mainly hybrid cars will come onto the market. They combine an internal combustion engine with an electric motor, so that one system is able to compensate for the disadvantages of the other. An example is the low efficiency in partial-load states of an internal combustion engine, which can be compensated for by the electric motor. Electric drive-trains are particularly well suited to road vehicles due to their precise response behaviour, their high efficiency and the relatively simple handling of the energy storage. In spite of the advantages of electric motors, the combination of an electric drive-train with an internal combustion engine is reasonable. That is because electricity storage for driving ranges of up to 500 km, which are achieved by conventional drive-trains (and petrol tanks), are not feasible today.

**Hybrid classes and vehicle batteries** Generally the different hybrid vehicles are classified by their integrated functions, as shown in Figure 3-16. The power demand on the battery increases with additional integrated functions. The more functions are integrated in the vehicle, the higher the potential of fuel savings and therefore the reduction of carbon dioxide emissions. While vehicles up to the full hybrid level have already entered the market, plug-in hybrids and pure electric vehicles are not yet established in larger quantities. Regarding energy storage for vehicles, today lead acid batteries are commonly used in micro-hybrids. In combination with a double-layer capacitor there might also be options for their use in mild or full hybrids, but since technically better solutions are available and economically feasible they will not play any role in the future. NiMH batteries are mainly used in hybrid vehicles because their system is well-engineered and, compared to Li-ion batteries, they are actually more favourable especially due to safety issues. Good cycle stability in low states of charge which often appear in hybrid cars is characteristic for these batteries. All Toyota hybrid vehicles use a

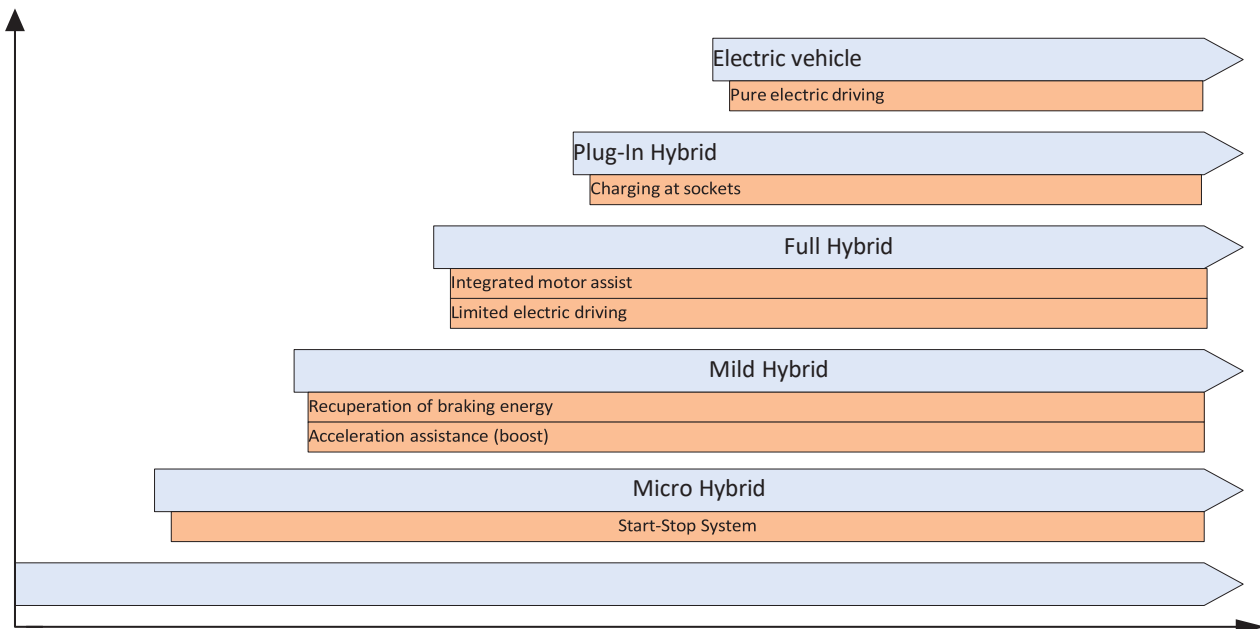


Figure 3-16 | Hybrid classes sorted by electrical power and functional range, against stage of development (Fraunhofer ISE)

Table 3-1 | Differences between hybrid and electric vehicles' power trains [smo09]

Specifications	Micro Hybrid	Mild Hybrid	Full Hybrid	Plug-In Hybrid	Electric vehicle
Power motor	2 – 8 kW	10 – 20 kW	20 – 100 kW	20 – 100 kW	< 100 kW
Capacity Batteries	< 1 kWh	< 2 kWh	< 5 kWh	5 – 15 kWh	15 – 40 kWh
DC voltage	12 V	36 – 150 V	150 – 200 V	150 – 200 V	150 – 400 V
Potential in saving fuel	- 8 %	- 15 %	- 20 %	- 20 %	--
Range for electrical driving	--	< 3 km	20 – 60 km	< 100 km	100 – 250 km

EES type

Lead Acid, NiMH, Li-Ion

NiMH, Li-Ion NiMH, Li-Ion Li-Ion Li-Ion, NaNiCl

NiMH battery with 1.3 kWh and 40 kW. Toyota has sold in total about 3 million hybrid vehicles with this battery; this means the total storage volume sold is about 4 GWh and 120 GW.

A major problem of this technology is the limited potential for further technical or economic improvements. With lithium ion batteries becoming technically more favorable and having significant potential for cost reduction there does not seem to be a medium-term future for NiMH batteries.

Lithium batteries are ideally suited for automotive use, for both electric vehicles and hybrid electric vehicles.

For the hybrid vehicles a good choice might be the lithium-titanate battery because of its high cycle stability and power density. With rising battery capacities for more advanced hybrid types, the relatively low energy density of the lithium-titanate batteries has a bigger effect on the total car weight that results in a higher energy demand. Therefore lithium-iron-phosphate and especially lithium-NMC batteries with high energy densities are preferred for plug-in-hybrids and pure electric cars – for the latter the driving range is the most important criterion.

An alternative battery technology for pure electric cars is the high-temperature sodium-nickel-chloride battery (also called ZEBRA battery). It has a huge self-discharge rate of about 10 % per day in stand-by status from having to keep the battery

at a high temperature. Therefore these NaNiCl batteries are preferred for fleet vehicles such as buses, where they are in permanent operation and no additional battery heating is usually necessary.