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The Role of Electrical Energy Storage Technologies in Electrical Use

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Abstract— *Electrical Energy Storage, EES, is one of the key technologies in the areas covered by the IEC. EES techniques have shown unique capabilities in coping with some critical characteristics of electricity, for example hourly variations in demand and price. In the near future EES will become indispensable in emerging IEC-relevant markets in the use of more renewable energy, to achieve CO2 reduction and for Smart Grids. Historically, EES has played three main roles. First, EES reduces electricity costs by storing electricity obtainedatoff-peaktimeswhenitspriceislower,foruseatpeak times instead of electricity bought then at higher prices. Secondly,inordertoimprovethereliabilityofthepowersupply, EES systems support users when power network failures occur due to natural disasters, for example. Their third role is to maintain and improve power quality, frequency andvoltage.*
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I. INTRODUCTION

Twocharacteristicsofelectricityleadtoissuesinits use, and by the same token generate the market needs for EES. First, electricity is consumed at the same time as it is generated. The proper amount of electricity must always be providedtomeetthevaryingdemand.Animbalancebetween supply and demand will damage the stability and quality (voltage and frequency) of the power supply even when it does not lead to totally unsatisfied demand. The second characteristic is that the places where electricity is generated are usually located far from the locations where it is consumed 1. Generators and consumers are connected through power grids and form a power system. In function of thelocationsandthequantities ofpowersupplyanddemand, much power flow may happen to be concentrated into a specific transmission line and this may cause congestion. Since power lines are always needed, if a failure on a line occurs(becauseofcongestionor anyotherreason)thesupply of electricity will be interrupted; also because lines are alwaysneeded,supplyingelectricitytomobileapplicationsis difficult. The following sections outline the issues caused by these characteristics and the consequent roles ofEES.

II. ELECTRICITYANDTHEROLEOFESS

A. High Generation Cost during Peak DemanPeriods

Power demand varies from time to time (see Figure 1),andthepriceofelectricitychangesaccordingly.Thepricefor electricity at peak demand periods is higher and at off-peak periods lower. This is caused by differences in the cost of generation in each period. During peak periods when electricity consumption is higher than average, power suppliers must complement the base-load power plants (such as coal-fi red and nuclear) with less cost-effective butmoreflexible forms of generation, such as oil and gas fired generators. During the off-peak period when less electricity is consumed, costly types of generation can be stopped. This is a chance for owners of EES systems to benefit financially. From the utilities' viewpoint there is a huge potential to reduce total generation costs by eliminating the costlier methods,throughstorageofelectricitygeneratedbylow-cost powerplantsduringthenightbeingreinsertedintothepower grid during peak periods.

WithhighPVandwindpenetrationinsomeregions,cost- free surplus energy is sometimes available. This surplus can be stored in EES and used to reduce generation costs. Conversely, from the consumers' point of view, EES can lower electricity costs since it can store electricity bought at lowoffpeakpricesandtheycanuseitduringpeakperiodsin the place of expensive power. Consumers who charge batteriesduringoff-peakhoursmayalsoselltheelectricityto utilities or to other consumers during peakhours.

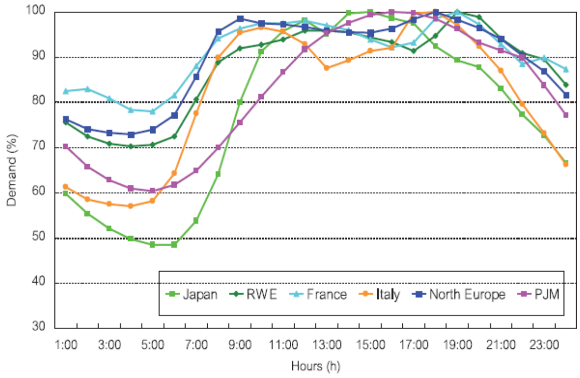

Fig.1. ComparisonofDailyLoadCurve *(IEEJ–TheInstituteofEnergy Economics, Japan,2005)*

B. . Need for Communication and FlexibleSupply

A fundamental characteristic of electricity leads to the utilities' second issue, maintaining a continuous and flexible power supply for consumers. If the proper amount of electricity cannot be provided at the time when consumers need it, the power quality will deteriorate and at worst this may lead to a service interruption. To meet changing power consumption appropriate amounts of electricity should be generatedcontinuously,relyingonanaccurateforecastofthe variations in demand. Power generators therefore need two essential functions in addition to the basic generating function. First, generating plants are required to be equipped with a “kilowatt function”, to generatesufficientpower (kW) when necessary. Secondly, some generating facilities must possess a frequency control function, fi ne-tuning theoutputso as to follow minute-by-minute and second-by second fluctuations in demand, using the extra power from the “kilowatt function” if necessary. Renewable energy facilities suchassolarandwinddonotpossessbothakWfunctionand a frequency control function unless they are suitably modified. Such a modification may be a negative power margin (i.e. decreasing power) or a phase shift inverter2.

EES is expected to be able to compensate for such difficulties with a kW function and a frequency control function. Pumped hydro has been widely used to provide a large amount of power when generated electricity is in short supply.Stationarybatterieshavealsobeenutilizedtosupportrenewableenergyoutputwiththeirquickresponsecapability.

C. Long distance between Generation andConsumption

Consumers'locationsareoftenfarfrompower generating facilities, and this sometimes leads to higher chances of an interruption in the power supply. Network failures due to natural disasters (e.g. lightning, hurricanes) and artificial causes (e.g. overload, operational accidents) stop electricity supply and potentially influence wide areas. EES will help users when power network failures occur by continuing to supply power to consumers. One of the representative industries utilizing EES is semiconductor and LCD manufacturing, where a voltage sag lasting for even a few milliseconds impacts the quality of the products. A UPS system, built on EES and located at a customer's site, can keep supplying electricity to critical loads even when voltage sag occurs due to, for example, a direct lightning strike on distribution lines. A portable battery may also serve as an emergencyresourcetoprovidepowertoelectricalappliances.

D. Congestion in PowerGrids

This issue is a consequence of the previous problem, a long distance between generation and consumption. The powerflowintransmissiongridsisdeterminedbythesupply and demand of electricity.In the process of balancing supply and demand power congestion can occur. Utility companies try to predict future congestion and avoid overloads, for example by dispatching generators' outputs or ultimately by building new transmission routes. EES established at appropriate sites such as substations at the ends of heavily- loaded lines can mitigate congestion, by storing electricity while transmission lines maintain enough capacity and by using it when lines are not available due to congestion. This approach also helps utilities to postpone or suspend the reinforcement of powernetworks.

E. Transmission ByCable

Electricity always needs cables for transmission, and supplying electricity to mobile applications and to isolated areas presents difficulties. EES systems such as batteries can solve this problem with their mobile and charge/discharge capabilities. In remote places without a power grid connection recharging an electric vehicle may present a challenge, but EES can help realize an environmentally friendly transport system without using conventional combustion engines.

III. EMERGING NEED FORESS

TherearetwomajoremergingmarketneedsforEES as a key technology: to utilize more renewable energy and less fossil fuel, and the future SmartGrid.

A. More Renewable Energy, Less FossilFuel

In on-grid areas, the increased ratio of renewable generation may cause several issues in the power grid (see Fig. 2). First, in power grid operation, the fluctuation in the output of renewable generation makes system frequency control difficult, and if the frequency deviation becomes too wide system operation can deteriorate. Conventionally, frequency control is mostly managed by the output change capability of thermal generators. When used for this purpose thermal generators are not operated at full capacity, but with some positive and negative output margin (i.e. increases and decreases in output) which is used to adjust frequency, and this implies inefficient operation. With greater penetration of renewable generation this output margin needs to be increased, which decreases the efficiency of thermal generation even more. Renewable generation units themselves in most cases only supply a negative margin 3. If EES can mitigate the output fluctuation, the margins of thermal generators can be reduced and they can be operated at a higher efficiency.

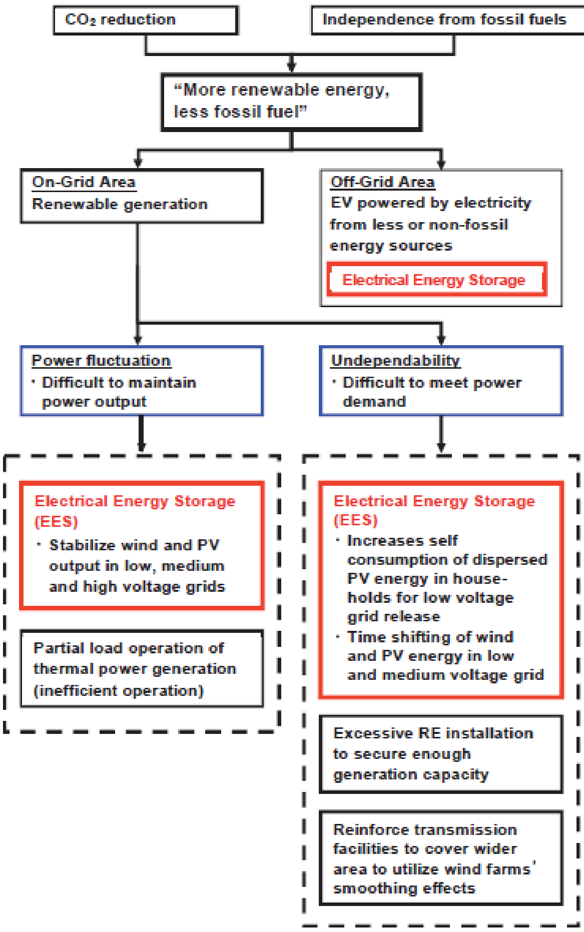

Fig. 2. Problems in renewable energy installation and possible solutions

(TEPCO)

Secondly,renewableenergyoutputisundependablesince it is affected by weather conditions. Some measures are available to copewiththis.

One is to increase the amount of renewable generation installed, i.e. provide overcapacity, so that even with undependability enough power can be secured. Another is tospread the installations of renewable generators over a wide area, to take advantage of weather conditions changing from place to place and of smoothing effects expected from the complementarity of wind and solar generators. These measures are possible only with large numbers of installations and extension of transmission networks. Considering the cost of extra renewable generation and the difficulty of constructing new transmission facilities, EES is a promising alternative measure.

In off-grid areas where a considerable amount of energy isconsumed,particularlyinthetransportsector,fossilenergy should be replaced with less or non-fossil energy in such products as plug-in hybrid electric vehicles (PHEVs) or electric vehicles (EVs) (see Fig. 2). More precisely, fossil fuels should be replaced by low-carbon electricity produced mainly by renewable generation. The most promising solution is to replace petrol or diesel-driven cars by electric oneswithbatteries.Inspiteofremainingissues(shortdriving distance and long charging time) EES is the key technology for electricvehicles.

B. Smart GridIssues

EES is expected to play an essential role in the future SmartGrid.SomerelevantapplicationsofEESaredescribed below. First, EES installed in customer-side substations can control power flow and mitigate congestion, or maintain voltage in the appropriate range. Secondly, EES can support the electrification of existing equipment so as to integrate it into the Smart Grid. Electric vehicles (EVs) are a good example since they have been deployed in several regions, and some argue for the potential of EVs as a mobile, distributed energy resource to provide a load-shifting function in a smart grid. EVs are expected to be not only a new load for electricity but also a possible storage medium that could supply power to utilities when the electricity price ishigh.AthirdroleexpectedforEESisastheenergystorage medium for Energy Management Systems (EMS) in homes andbuildings.WithaHomeEnergyManagementSystem,forexample,residentialcustomerswillbecomeactivelyinvolved in modifying their energy spending patterns by monitoring their actual consumption in real time. EMSs in general will need EES, for example to store electricity from local generation when it is not needed and discharge it when necessary, thus allowing the EMS to function optimally with less power needed from thegrid.

IV. CLASSIFICATION OF EESSYSTEMS

A widely-used approach for classifying EES systems is the determination according to the form of energy used. In Fig. 3.EES systems are classified into mechanical, electrochemical, chemical, electrical and thermal energy storage systems. Hydrogen and synthetic natural gas (SNG) are secondary energy carriers and can be used to store electrical energy via electrolysis of water to produce hydrogen and, in an additional step, methane if required. In fuel cells electricity is generated by oxidizing hydrogen or methane. This combined electrolysis-fuel cell process is an electrochemicalEES.However,bothgasesaremulti-purpose energy carriers. For example, electricity can be generated in a gas or steam turbine. Consequently, they are classified as chemical energy storage systems. In Fig.3 thermal energy storage systems are included as well, although in mostcaseselectricity is not the direct input to such storage systems. But with the help of thermal energy storage the energy from renewableenergysourcescanbebufferedandthuselectricity can be produced on demand. Examples are hot molten salts in concentrated solar power plants and the storage of heat in compressed air plants using an adiabatic process to gain efficiency.

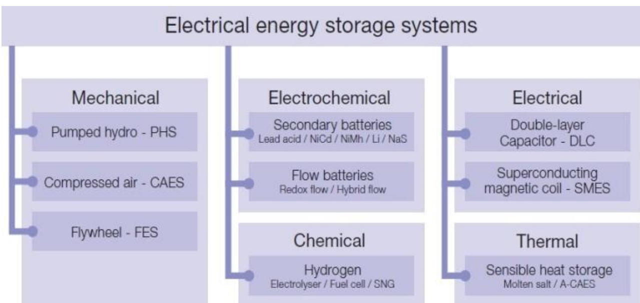

Fig.3. Classification of electrical energy storage systems according to energy form *(Fraunhofer ISE)*

V. ROLE OF ELECTRICAL ENERGYSTORAGE TECHNOLOGY

Generally, the roles for on-grid EES systems can be described by the number of uses (cycles) and the duration of theoperation,asshowninFigure1-3. For themaintenanceofvoltage quality (e.g. compensation of reactive power), EES with high cycle stability and short duration at high power output is required; for time shifting on the other hand longer storage duration and fewer cycles are needed. The following sections describe the roles indetail.

A. The Roles from the viewpoint of autility

1) Timeshifting

Utilities constantly need to prepare supply capacity and transmission/distribution lines to cope with annually increasing peak demand, and consequently develop generation stations that produce electricity from primary energy. For some utilities generation cost can be reduced by storingelectricityatoff-peaktimes, forexampleatnight,and discharging it at peak times. If the gap in demand between peak and off-peak is large, the benefit of storing electricity becomes even larger. Using storage to decrease the gap betweendaytimeandnight-timemayallowgenerationoutputtobecomeflatter,whichleadstoanimprovementinoperating efficiency and cost reduction in fuel. For these reasons many utilities have constructed pumped hydro, and have recently begun installing large-scale batteries atsubstations.

2) Power quality

A basic service that must be provided by power utilitiesistokeepsupplypowervoltageandfrequencywithintolerance,whichtheycandobyadjustingsupplytochanging demand. Frequency is controlled by adjusting the output of power generators; EES can provide frequency control functions. Voltage is generally controlled by taps of transformers, and reactive power with phase modifiers. EES located at the end of a heavily loaded line may improve voltage drops by discharging electricity and reduce voltage rises by chargingelectricity.

3) Making more efficientuseof thenetwork

In a power network, congestion may occur when transmission/distributionlinescannotbereinforcedintimeto meet increasing power demand. In this case,large-scalebatteriesinstalledatappropriatesubstationsmaymitigatethe congestion and thus help utilities to postpone or suspend the reinforcement of thenetwork.

4) Isolatedgrids

Where a utility company supplies electricity within asmall,isolatedpowernetwork,forexampleonanisland,the power output from small-capacity generators such as diesel and renewable energy must match the power demand. By installing EES the utility can supply stable power to consumers.

5) Emergency power supply for protection and control equipment

Areliablepowersupplyforprotectionandcontrolis
very important in power utilities. Many batteries are used as an emergency power supply in case of outage.

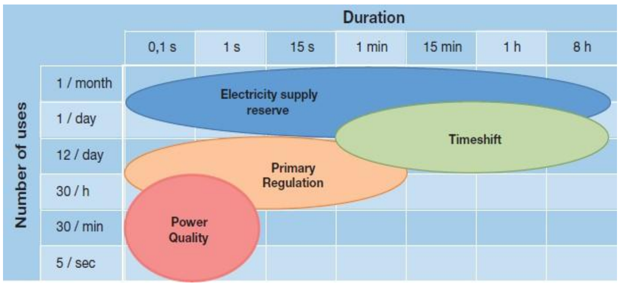

Fig. 4.Different uses of electrical energy storage in grids, depending on the frequency and duration of use[eus06]

B. The Roles from the Viewpoint of theCustomers

1) Time shifting/costsavings

Power utilities may set time-varying electricity prices, alowerpriceatnightandahigheroneduringtheday, to give consumers an incentive to flatten electricity load. Consumers may then reduce their electricity costs by using EES to reduce peak power needed from the grid during the day and to buy the needed electricity at off-peaktimes.

2) Emergency powersupply

Consumers may possess appliances needing continuity of supply, such as fi re sprinklers and security equipment. EES is sometimes installed as a substitute for emergency generators to operate during an outage. Semiconductor and liquid crystal manufacturers are greatly affected by even a momentary outage (e.g. due to lightning) in maintaining the quality of their products. In these cases, EES technology such as large-scale batteries, double-layer capacitors and SMES can be installed to avoid the effects of a momentary outage by instantly switching the load off the networktotheEESsupply.Aportablebatterymayalsoservein an emergency to provide power to electricalappliances.

3) Electric vehicles and mobileappliances

Electric vehicles (EVs) are being promoted for CO2 reduction. High-performance batteries such as nickel cadmium, nickel metal hydride and lithium ion batteries are mounted on EVs and used as power sources. EV batteriesare also expected to be used to power in-house appliances in combinationwithsolarpowerandfuelcells;atthesametime, studies are being carried out to see whether they canusefullybeconnectedtopowernetworks.Thesepossibilitiesareoftenabbreviated as “V2H” (vehicle to home) and “V2G” (vehicle togrid).

C. The Roles from the viewpoint of generators of renewable energy

1) Timeshifting

Renewableenergysuchassolarandwindpowervis subject to weather, and any surplus power may be thrown away when not needed on the demand side. Therefore, valuable energy can be effectively used by storing surplus electricity in EES and using it when necessary; it can also be sold when the price ishigh.

2) Effective connection togrid

The output of solar and wind power generation varies greatly depending on the weather and wind speeds, which can make connecting them to the grid difficult. EES used for time shift can absorb this fluctuation more cost-effectively than other, single-purpose mitigation measures (e.g. a phase shifter).

D. Standards forESS

For mature EES systems such as PHS, LA, NiCd, NiMH and Li-ion various IEC standards exist. The standards cover technical features, testing and system integration. For the other technologies there are only a few standards, covering specialtopics.Uptonownogeneral,technologyindependent standard for EES integration into a utility or a stand-alone grid has been developed. A standard is planned for rechargeable batteries of anychemistry.

Standardization topics for EESinclude:

- terminology
- basic characteristics of EES components and systems, especially definitions and measuring methods for comparison and technicalevaluation
  – capacity, power, discharge time, lifetime, standard EES unitsizes
- communication betweencomponents
  – protocols,security
- interconnectionrequirements
  – power quality, voltage tolerances, frequency, synchronization, metering
- safety: electrical, mechanical,etc.
- testing
- guidesforimplementation.

E. Technical Comparison of EESTechnologies

The previous sections have shown that a wide range of different technologies exists to store electrical energy. Different applications with different requirements demand different features from EES. Hence a comprehensive comparison and assessment of all storage technologies is rather ambitious, but in Fig. 5. a general overview of EES is given.Inthisdouble-logarithmicchartheratedpower(W)is plotted against the energy content (Wh) of EES systems. The nominal discharge time at rated power can also be seen, covering a range from seconds to months. Fig. 5.comprisesnotonlytheapplicationareasoftoday’sEESsystemsbutalso the predicted range in future applications. Not all EES systems are commercially available in the ranges shown at present,butallareexpectedtobecomeimportant.Mostofthe technologies could be implemented with even larger power output and energy capacity, as all systems have a modular design, or could at least be doubled (apart from PHS and some restrictions for underground storage of H2, SNGandCAES). If a larger power range or higher energy capacity is not realized, it will be mainly for economic reasons (cost per kW and cost per kWh, respectively).

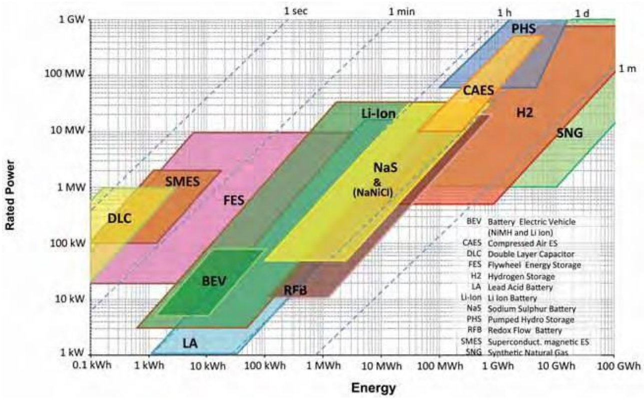

Fig. 5. Comparison of rated power, energy content and discharge time of different EES technologies *(Fraunhofer ISE)*

On the basis of Fig. 5. EES technologies can be categorized as being suitable for applications with:

- **Shortdischargetime**(secondstominutes):double- layer capacitors (DLC), superconducting magnetic energy storage (SMES) and flywheels (FES). The energy-to-power ratio is less than 1 (e.g. a capacity of less than 1 kWh for a system with a power of 1 kW).
- **Medium discharge time** (minutes to hours): flywheel energy storage (FES) and – for larger capacities – electrochemical EES, which is the dominant technology: lead-acid (LA), Lithium ion (Li-ion) and sodium sulphur (NaS) batteries. The technical features of the different electrochemical techniques are relatively similar. They have advantages in the kW – MW and kWh - MWhrange when compared to other technologies. Typical discharge times are up to several hours, with an energy-to-power ratio of between 1 and 10 (e.g. between 1 kWh and 10 kWh for a 1 kW system). Batteries can be tailored to the needs of an application: tradeoffs may be made for high energy or high power density, fast charging behavior or long life, etc.
- **Long discharge time** (days to months): hydrogen (H2)andsyntheticnaturalgas(SNG).FortheseEES systems the energy-to-power ratio is considerably greater than10.

VI. PRESENT STATUS OFAPPLICATION

The cases that are described here have already been implemented by electric utilities and consumers. These are respectivelytimeshiftandinvestmentdeferralfortheformer, and emergency supply and power quality for thelatter.

A. 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 whennecessary.
3) Postpone investment needed by mitigating network congestion through peak shift.
4) Provide stable power for off-grid systems (isolated networks).
5) Provide emergency powersupply.

B. Utility use (conventional power generation, grid operation &service)

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 can do so by varying the rotational speed of the motor.

C. Utility's emergency power supply

Important facilities, such as power stations, substations andtelecommunicationstations,needpowersourcesfortheir 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 applicationaremostlyDCsourcesandsupportedbybatteries. Historically lead acid batteries have been used for this purpose.

D. Utility's off-grid systems (isolatedgrids)

Inthecasewhereautilitycompanysupplieselectricityin 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 commonlyused.

E. *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 electricityandstoringitinEES.Theresultisloadlevelingby time-shifting.

2) Secure a reliable and higher-quality power supply for important factories and commercialfacilities.

VII. CONCLUSION

Intheelectricitymarket,globalandcontinuinggoals are CO2 reduction and more efficient and reliable electricity supply and use. Many studies have shown that EES is indispensable for the introduction of large amounts of renewable energy. Therefore, the necessary volume and timingofEESisstronglydependentonthepaceofrenewable energy development. The Smart Grid integrates facilities on both the utility (grid) side and the customer side by using advancedinformationtechnologies;thebenefitsfromthiscan only be achieved if storage is available. EES is therefore considered to be a key component of the Smart Grid, among other things as a basic requirement for coping withelectricaloutages caused by disasters. In addition, the Smart Grid is likely to use, and possibly to require, dispersed storage (e.g. batteries installed for local purposes). This in turn implies overall control of many dispersed small storage installations together in the grid. The implication is that autonomous operation, easy extension and coordination with grids are important characteristics of future EES.

Microgrids will be a key to the “smart” energy use of communities, factories, buildings etc. Smallscale EES is absolutely imperative for microgrids to achieve fair and economic consumption of electrical energy. In order to optimize cost efficiency, microgrids also require that their EES should be connected to the grid (as does the grid – see above) and be able to adjust smoothly to increases and decreases in the amount of electrical energy. consumed. Dispersed facilities, whether generation or storage (for example the EES in a smart house or an electric vehicle), are normallyownedbyendusers,whohaveinprincipletheright to decide how to use the facilities. This implies a differentiated policy and regulatory regime, with conditions applying to centralized facilities distinguished from those applying to dispersedones.

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