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The analysis of possibilities of cooperation between renewable energy sources and energy storages

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The paper deals with the issue of energy generation in an environmentally friendly manner. Problems related to the use of selected energy sources, which cover, among others, power fluctuations and deterioration of energy quality were indicated. The methods of storing energy were described as technologies intended for cooperation with the power grid in order to alleviate the negative impact on it by RES. Types of energy storages, which, in view of their properties, demonstrate the potential for use and cooperation with photovoltaic installations and wind turbines were selected.

KEYWORDS: renewable energy sources, wind turbines, energy storages, supercapacitor, batteries, kinetic energy sources, PV

1. Introduction

Man makes constant efforts at improving the comfort of his life. This refers to the spiritual, cultural and materials spheres. Not only has technological progress over the centuries changed the method of communication, but also the model of transport, the technique of construction of places of residence, the working tools, etc. All these spheres demonstrate a constant increase in demand for energy. Initially, working was tantamount to the use of muscular strength of humans and animals. Over thousands of years, success was achieved in taming and using the energy of wind and water. Unfortunately its use was bound to inconveniences consisting in the possibility of its use only at the place of its generation, in the quantity limited by external conditions. In the age of the industrial revolution, a much more ”mobile” energy form was used for the first time, i.e. electric energy. Since that time, it has been possible to notice a constant increase in the demand for this type of energy, which is also matched by more and more efficient conventional and non–conventional methods of its generation. The ever increasing efficiency of the devices intended for generation and transmission of electric energy allowed for balancing the demand and surplus.

At present, a new important problem related to the production of electric energy appeared. It is the degradation of the natural environment. The continuous exploitation of coal deposits, dangerous methods of shale gas recovery, air pollution resulting from combustion processes or storage of radioactive waste from nuclear plants are only some of the problems which must be faced at present. On top of this, it is necessary to include changes in the landscape and destruction of local ecosystems, resulting from the use of retention reservoirs for the purposes of storing energy of large water masses. All the aforementioned risks can be minimised by a constant increase in the share of the modern energy sector based on Renewable Energy Sources (RES), cooperating with modern energy storage technologies on the market.

2. Analysis of electric energy generation in popular renewable energy sources

In accordance with the Journal of Laws, which also includes the legal act on "Energy Law", the term "Renewable Energy Source" is defined as the "source that uses the energy of wind or solar radiation, as well as the geothermal energy, the energy of waves, currents and tides, fall of rivers and the energy obtained from biomass, landfill biogas and biogas produced in the processes of discharge or treatment of wastewater or decomposition of stored plant and animal remains" [12]. Thus, renewable energy sources constitute a safe alternative for the existing broadly applied conventional energy based on coal combustion. It is estimated that the present state of technological progress allows for using the installed power which approximates 17 TW and comes from the renewable energy sources (Fig. 1) [7].

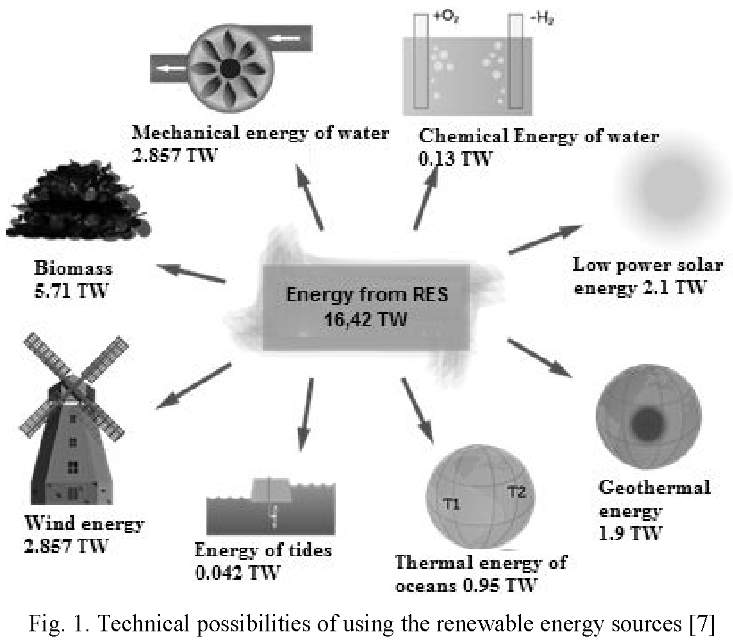


Fig. 1. Technical possibilities of using the renewable energy sources [7]

Among the aforementioned possibilities of ecological generation of energy, the greatest hopes are related to the use of energy of wind and sun in view of their availability and technological possibilities.

2.1. Wind energy sector

The wind energy sector is one of the most dynamically developing sectors of renewable energy in the world. This follows, above all, from a broad group of locations, in which such installations have good and very good conditions for generation of energy, which translates into obtaining payable investments of this type.

The convenient location of a wind turbine is characterised by several factors. Above all, of particular importance is the parameter of wind regularity both in terms of intensity and great stability in the upcoming period of time which will ensure the longest possible periods of uninterrupted operation. The structure of prevalence of a given wind speed can be presented by means of a histogram. In order to achieve the statistically representative measuring period for the wind speed, it should constitute the multiple of the annual cycle. For this reason, the wind speed histogram is interpolated by means of the analytical functions, the most frequently applicable of which is the Weibull function that has the following form [8]:

$$p(v) = \frac{k}{A} \cdot \left(\frac{v}{A}\right)^{k-1} exp[-\left(\frac{v}{A}\right)^{k}] \tag{1}$$

where: $p(v)$ – probability density, k – shape parameter, A – scale parameter, v – wind speed.

An example of the wind speed histogram, including the Weibull distribution with appropriately selected parameters ”A” and ”k” is presented in Figure 2.

The aforementioned clear periodical annual repeatability of wind refers both to its speed and direction, which is manifested in the alternately occurring periods of higher and lower windiness. The wind conditions are a consequence, to a great extent, of the geographical location and sea currents, which affect its climate. For instance, with regards to the territory of Poland, the windiness is affected by the Gulf Stream (Golfstrom) coming from the Atlantic Ocean [14].

The overall nature of wind for the given area can be determined based on the data collected by one of several organisations that make it available free–of–charge (e.g. NASA). Furthermore, it is possible to find a series of applications on the market, which allow for the analysis of windiness in the given area, using a specific wind speed. Such solutions are offered by the respective wind turbine manufacturers. Unfortunately the software of this type is more often than not based on averaged measurements and rarely takes into account the local conditions.

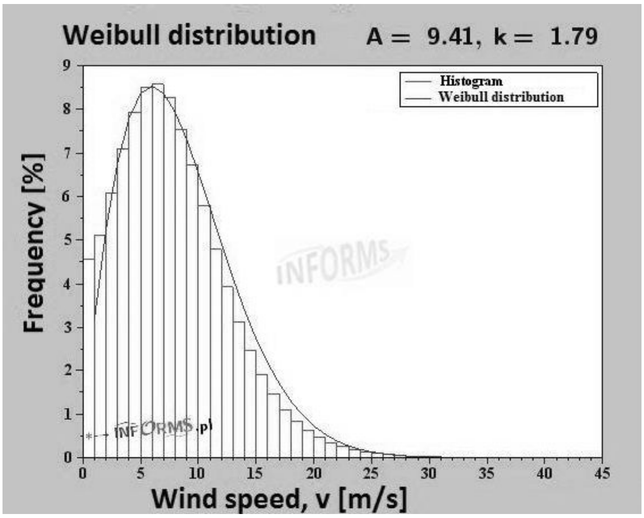


Fig. 2. Histogram of the wind speed and Weibull distribution for $A = 9.41$ and $k = 1.79$ [13]

Another element which affects the windiness is the orographic factor, that is, the terrain. This refers both to large geographic forms (valleys or mountain ranges) and smaller ones (forest areas which cause vibrations in the moving air masses). In consideration of the above, the determination of wind conditions in a specific geographical location should be preceded by performance of specialist measurements [12]. There are more and more companies which provide services which range from obtaining necessary information about a location, through selecting the measuring equipment, measuring wind at an appropriate height, analysing data regarding speed and direction of wind, to selecting the optimal wind turbine [19].

2.2. Solar energy sector

A more and more commonly used method of electric energy generation is its transformation from solar energy using a photovoltaic cell (PV). It is the construction and workmanship of the cell which determines the properties and parameters of the complete PV installation. The quantity of the electric energy generated by the photovoltaic panel is affected, above all by the value of solar radiation that reaches its surface. Conditions at a given location can be described by using the following parameters [6]:

- E [W/m^2] – solar radiation power density (the sum of the direct dispersed or deflected radiation that reaches the receiver,
- H [kWh/m^2] – sunlight (the total solar radiation energy incident to a surface unit within a specific time, day, month and year),

– h [h] – sunshine duration (number of hours during which the direct solar radiation reaches the surface of the earth at a specific time.

At the stage of design of the photovoltaic installation, it is necessary to take advantage of the information about the local level of solar radiation intensity, coming from meteorological stations, supplemented by statistical values from the last couple of years. However, the fullest data will be obtained from detailed measurements carried out in the period not shorter than one year.

The sunlight, to a great extent, depends on the position of the sun in the sky, and thus, the yield from the installation must be considered at annual time intervals. Such an analysis allows for the assumption of a relation of sunlight to geographical location (latitude) as well as the day of the year. Figure 3 presents the chart of the positions of the sun in coordinates $\alpha_s = f(\gamma_s)$, which maps the road of the sun in the sky covered during a day.

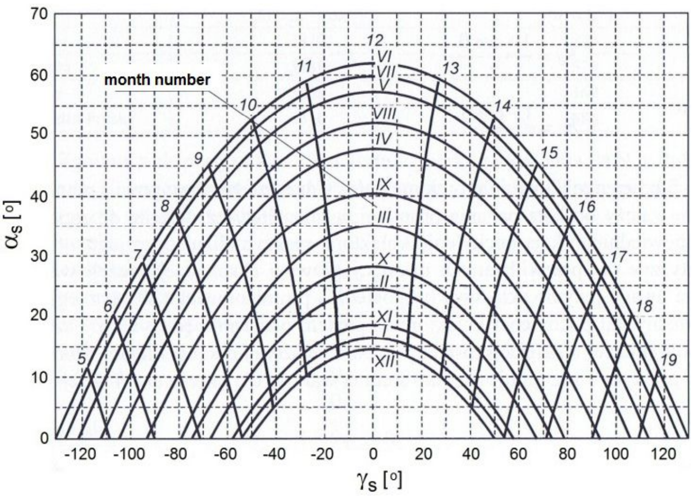
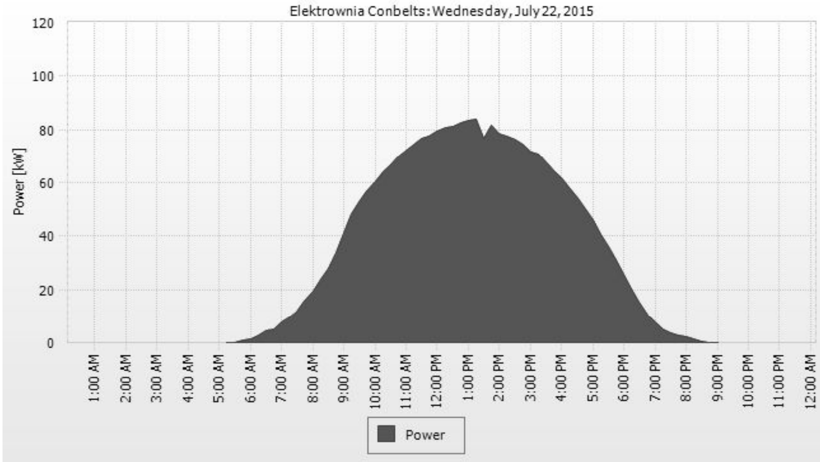


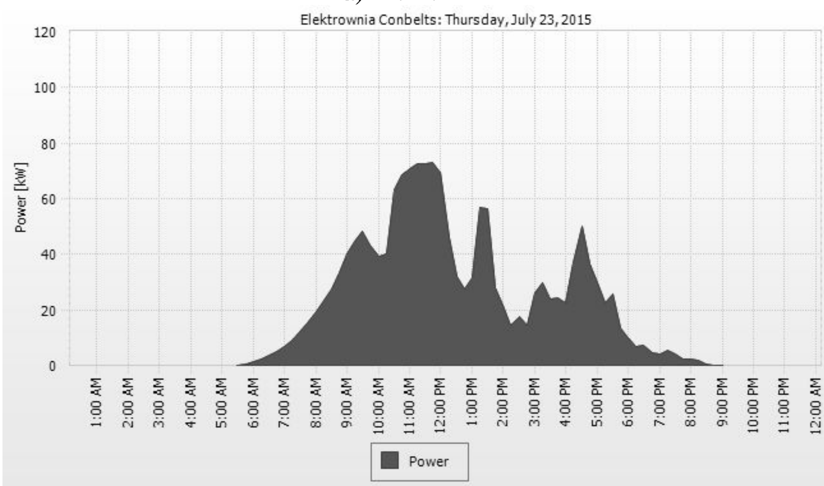
Fig. 3. Chart of the sun's position for Poznan ($\phi = 52^{o}$) [5], where: γ_s – solar azimuth – the angle that determines the deviation of the projection of the direction of direct sun rays on the earth's surface from the southern direction (to the east –negative, to the west – positive), α_s – the angle of the sun in relation to the area of the horizon

The stochastic nature of solar radiation power density per day, dependent on the weather conditions is much more complex. Such a course of two consecutive days in the same location is presented in Figure 4.

Despite the selection of the location based on satisfactory parameters of solar radiation power density and sunshine duration as well as the predictable daily nature of the generation (no generation at night–time and parabolic characteristics of generation in daytime hours), the energy yield is subject to significant variability at small intervals, resulting from the stochastic nature of the weather changes.



a) 22.07.2015



b) 23.07.2015

Fig. 4. Energy yield from the installation in Bytom during the two consecutive days in changing weather conditions [18]

3. Electric energy from RES and the power system

The analysis of factors which affect the generation of two selected sources of renewable energy, conducted in the earlier part of this publication, reveals problems related to their application on a broad scale. Both in the case of using wind and solar installations, the appropriate selection of the location of the installation, with predictable wind and sunlight parameters guarantees the appropriate generation level, but only in the averaged approach. The momentary values of power and energy still remain undetermined in view of the high dynamics of changes. In order to predict the level of generation, it is necessary to provide each installation with the network of measuring stations. The higher the number and radius of location of such stations, the bigger the database based on which it is possible to obtain a more reliable analysis of the changing weather conditions using the appropriate processing algorithms. Such a dispersed system is also related to big costs. Unfortunately, this approach allows only for prediction of the momentary generation level well in advance, which should be compliant with the up–to–date demand for electric energy. Even if the energy production level from the given RES installation is predicted several seconds in advance, the systems which allow for balancing the momentary electric energy demand and surplus are required. This follows, above all from the fact that the dynamics of conventional sources is too small in reference to the needs of implementation of fast momentary changes in the quantity of generated energy.

The best solution for the problem mentioned above seems to be the maintenance of generation from the RES installations at a permanent level. This, however, is possible only in the case of their cooperation with energy storages with very big capacities, which is not payable from the point of view of economics. Therefore, it is necessary to seek individual solutions which consist of storages of various types of energies and capacities, so as to improve the conditions of cooperation with the power system, and not to raise the unit costs of electric energy generation significantly.

4. Characteristics of the energy storing technologies

The techniques of storing energy have been known practically since the beginning of electric energy generation. Initially, the developed and the most efficient were the technologies related to the water level accumulation. Owing to this, when a dam was built on a river, an energy source and storage were obtained at the same time. The modification of this concept was the pumped–storage power plant, which only served as the energy reserve. In the year 2012, the total installed power in the world in power plants of this type exceeded 130 GW, which constitutes an increase by 30 GW in reference to the level achieved in the year 2002 [17].

The constantly increasing demand for stored energy, also in more mobile versions, resulted in the development of research on efficient energy accumulation. At present, in view of the method of accumulation of energy, storages can be divided into six categories: mechanical, pneumatic, thermal, electric, magnetic and electrochemical energy storages.

4.1. Mechanical energy storages

Mechanical energy storages include: pumped–storage power plants and kinetic energy storages among which, the technologies with flywheels are developed best.

In the case of the former ones, the principle of operation is based on pumping water to the upper reservoir (situated above) in the period of low energy demand, and in order to recover the energy, the potential for the fall of water into the lower reservoir is used. The efficiency of the pumped–storage power plants reaches 80% and although this is the most common (in terms of the installed power) method of storing energy, it is used mainly to collect energy amounting to tens and hundreds of MWh. However, it requires locations of a very specific topography, which significantly limits the area of its application.

The kinetic energy storage turns electric energy of flywheel E in accordance with the following formula:

$$E = \frac{1}{2} I\omega^2 , \quad (2)$$

where: I – moment of inertia of flywheel, ω – angular velocity.

Limitations regarding the maximum amount of energy which can be stored, are related mainly to the vulnerability of the material of which the flywheel is built to stretching. Therefore, the maximum energy density which can be stored in a storage can be determined as:

$$E_{sp} = k_s \frac{\sigma_m}{\rho} , \quad (3)$$

where: E_{sp} – maximum energy density, σ_m – maximum tensile strength of the flywheel's material, k_s – shape factor, ρ – flywheel material density.

Furthermore, depending on the material of which the rotor is made, two types of flywheels are distinguished: advanced composite (graphite or carbon fibre) flywheels or steel flywheels.

The flywheels are characterised by high power densities and high efficiencies, and in view of the lack of chemical reactions, they do not emit harmful compounds and the time of their use does not change the energy accumulation capacity. On top of this, they allow for the dynamic flow of high amounts of energy, owing to which they are fit for adjustment of the power supply frequency. A drawback of the flywheels is their high degree of self–discharge (amounting to 10%/hour) and high production cost [5].

4.2. Pneumatic energy storages

The pneumatic energy storages constitute some of the oldest forms of energy accumulation, which consists in the efficient compression of air usually in caves or mines. This method, though characterised by high capacity for energy accumulation, has a number of drawbacks of which the most important ones include: the necessity of selecting a location in the vicinity of caves and mine workings and the low efficiency amounting to 40–75%. The low efficiency of this method results from adiabatic transformations, during which it is first necessary to release large quantities of heat resulting from an increase in the temperature during the air compression, as per formula (4), and during the expansion which serves the purpose of energy recovery, it is necessary to increase the medium temperature [1].

$$T_2 = T_1 \left(\frac{P_2}{P_1} \right)^{\frac{(K-1)}{K}} \quad (4)$$

where: T – temperature, P – absolute pressure, K – polytropic index of irreversible compression, indices 1 and 2 respectively: preliminary and final compression states.

4.3. Thermal energy storages

There is a number of possibilities for storing energy in the form of difference in potentials, but in the majority of applications, it is not, later on, turned into electric energy. An exception to this rule is the recently applied thermal energy storage which cooperates with the solar thermal power plant. The principle of operation consists in the storage of heat by heating up salt in an isolated vessel. The medium collected in this way is used to heat the water vapour which supplies the classic electric energy generator [16].

4.4. Electric energy storages

This category defines the devices which allow the energy to be accumulated in the electric field and includes, above all, supercapacitors. They achieve their properties by accumulation of electric charges within a double electric layer formed at the electrode–electrolyte interface. Therefore, supercapacitors are often referred to as double–layer capacitors. It is due to the replacement of the classic capacitor plates and the solid dielectric by metal electrodes coated with a material with large area (from active carbon), separated by a thin porous isolator, that very good operating properties of the element were obtained. Above all, the supercapacitor may receive and release very high amounts of energy at a short time. The amount of this energy E can be determined by the following formula:

$$E = \frac{1}{2} C V^2, \quad (5)$$

where: V – voltage between plates, C – capacitance of the supercapacitor.

The capacitance of the supercapacitor depends on the surface of the plates, which, owing to their porous workmanship, are characterized by a much higher value than in the case of traditional capacitors. Furthermore, these systems demonstrate high power density, low environmental impact and very high efficiency (even up to 98%), high durability covering hundreds of thousands of charge–discharge cycles and broad range of operating temperatures. On the other hand, their disadvantage is the low energy resourcefulness (power density is at the level of 10 Wh/kg) and high price [7].

4.5. Magnetic energy storages

These include superconducting magnetic energy storages – SMES – where the energy is stored in the magnetic field. SMES comprise a large superconducting cell maintained at a cryogenic temperature. The stored energy may be expressed as follows:

$$E = \frac{1}{2} L I^2 , \tag{6}$$

where: L – induction coefficient, I – current.

Storages based on superconducting cells are distinguished by their relatively high efficiency and power, and have the ability to accumulate large amounts of energy. Their disadvantage is the very high cost and the relatively short energy storage time (up to several minutest) [5].

4.6. Electrochemical energy storages

Within the group of electrochemical energy storages, because of the occurring processes, it is possible to distinguish primary and secondary fuel cells and electrochemical cells.

Fuel cells generate electric energy as a result of fuel oxygenation reaction (most frequently hydrogen produced as a result of the process of electrolysis). The scheme of operation of the fuel cell supplied with hydrogen is presented in Figure 5.

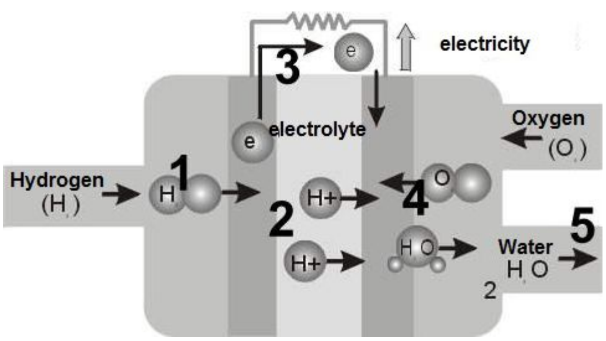


Fig. 5. Scheme of operation of the fuel cell supplied with hydrogen [15]: 1 – stage of ejection of the electrons from hydrogen, 2 – protons permeate electrolyte, 3 – electrons flow through the receiver towards the cathode, 4 – electrons reach the positive side of the electrolyte, and then combine themselves with oxygen particles, 5 – water and heat are produced

The main advantages of this technology include: quiet operation, stability of energy supply, low emission of chemical compounds detrimental to the environment, long life and relatively short time of system start–up. The disadvantages of using hydrogen as the energy storage include the low total efficiency of the process of generation and combustion of hydrogen (20–45%), the high costs of this technology and the problems with safe storage and transport of hydrogen [11].

Electrochemical cells which are casually referred to as batteries, function as an result of a chemical reaction occurring in electrolyte and at its interface with electrodes. The most frequently used types of batteries used at present are lead–acid, nickel–cadmium, lithium–ion and metal–air batteries. The principle of operation of chemical cells may be presented based on the example of the lead–acid batteries. During the discharge portion of the reaction, lead dioxide (PbO_2) is converted into lead sulphate ($PbSO_4$) at the positive plate. At the negative plate, sponge lead (Pb) is converted into lead sulphate ($PbSO_4$). This causes the sulphuric acid ($2H_2SO_4$) in the electrolyte to be consumed. This process is presented in the form of an equation in Figure 6 [10].

$Pb +$	$2H_2SO_4$	$+ PbO_2$	Discharging ⟷ Charging	$PbSO_4 +$	$2H_2O$	$+ PbSO_4$
Porous Lead	**Sulfiric Acid**	**Porous lead Dioxide**		**Lead Sulfate**	**Water**	**Lead Sulfate**
Active material of negative plate	Electrolyte	Active Material of positive plate		Active material of negative plate	Electrolyte	Active material of positive plate

Fig. 6. Electrochemical Reaction of Lead acid battery [10]

Chemical cells are characterised by a relatively high energy density at fairly limited power density (the flow of high currents significantly reduces the durability of the systems). The specification of the most important properties of various technologies of batteries is presented in Table 1.

Based on the analysis of the aforementioned types of energy storages, it is possible to define the features of an ”ideal storage”. It should demonstrate the highest possible energy density and the highest possible power density, proving its capacity to draw high amounts of energy at a short time (charging and discharging with high currents is equivalent to fast replacement of charges). Of key significance here, is also the large capacity of the storage, ideally with the infinite number of operating cycles and broad temperature range of operation.

The respective electric energy storages, because of their properties, can be assigned to selected applications. Figure 7 presents the chart that shows the areas of application of popular energy storages depending on their power and maintenance time.

Table 1. Characteristics of the respective electrochemical cell technologies [9]

Type of battery	Efficiency [%]	Cost [€/kWh]	Life [number of cycles at % discharge level]	Operating temperature [°C]	Energy density [Wh/kg]	Self–discharge [%/month]
Deep discharge lead–acid battery	72–78	50–150	1000–2000 (70%)	–5 to 40	25	2–5
Lead–acid battery	72–78	50–150	200–300 (80%)	–5 to 40	30–50	2–5
Nickel–cadmium battery	72–78	200–600	3000 (100%)	–40 to 50	45–80	5–20
Sulphur–sodium battery	89	400–500	2500 (100%)	300 to 350	100	0
Lithium–ion battery	100	700–1000	3000 (80%)	–30 to 60	90–190	1
Vanadium– redox battery	85	360–1000	10000 (75%)	0 to 40	30–50	marginal
Zinc–bromine battery	75	360–1000	3500 (100%)	0 to 40	70	marginal
Metal–air battery	50	50–200	<100	–20 to 50	450–650	marginal

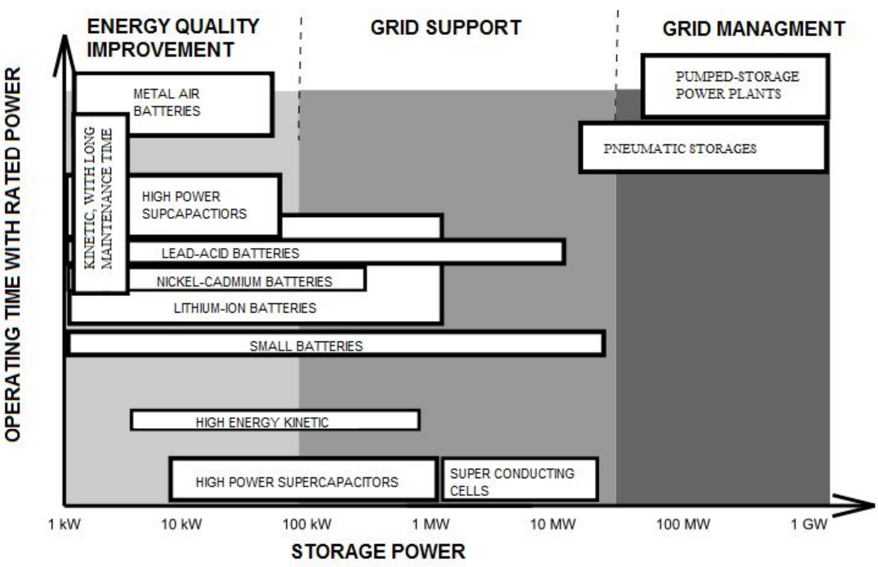


Fig. 7. Popular applications of various types of energy storages [2]

While analysing the chart from Fig. 7 it is possible to notice the possibility of meeting the requirements of the aforementioned ideal energy storage by integrating batteries, supercapacitors and flywheels into one system. The effect of such an integration is the creation of a cheap system with high amount of energy, relatively small weight and high efficiency as well as high current efficiency, stable and repeatable cycles and good properties even at low operating temperatures.

The concept of creating a hybrid energy storage is also visible in the produced optimisation software. For several years, many companies have independently developed the software that makes modelling and optimisation of the hybrid power supply possible. As well as the library of models of sources that map the real systems such as a wind turbine, a photovoltaic installation, a diesel generator, etc. also different kinds of energy storages are available. This allows the hybrid systems which generate electric energy to be modelled and analysed in the most optimal way in terms of location and costs. The most well–known software of this type includes: Hybrid Optimization of Multiple Energy Resources (HOMER), Dividing Rectangles (DIRECT), Hybrid Power System Simulation Model (HYBRID2), General Algebraic Modeling System (GAMS), Optimization of Renewable Intermittent Energies with Hydrogen for Autonomous Electrification (ORIENTE), Simulation of Photovoltaic Energy Systems (SimPhoSys), OptQuest, LINDO, WDILOG2, Determining Optimum Integration of RES (DOIRES), Geo–Spatial Planner for Energy Investment Strategies (GSPEIS) and Grid–connected Renewable Hybrid Systems Optimization (GRHYSO) [4].

5. Conclusions

Renewable energy sources constitute the future of the modern energy sector. Their application, despite many inconveniences seems to be inevitable. In the case of using wind turbines, the stability of the level of generated energy is affected by wind velocities, which causes the necessity of increasing power reserves in other sources, and also makes running of the power system difficult and causes problems in the planning of power and energy balance. In the same vein, the performance of photovoltaic sources, except the predictable lack of energy generation at night time, is, to a great extent dependent on weather conditions. Characteristics of performance and electric energy yield from these two sources complement each other and thus, it will be advantageous to use PV installations which cooperate with wind turbine units.

The improvement of cooperation of the ”wind–photovoltaic” source with the power grid will be ensured by the introduction of the system that stores energy. It must be characterised by high power and energy density, satisfactory efficiency at specific operating conditions, and above all, acceptable price from the point of view of the achieved benefits. It must be noticed that small energy storages are characterised by lower costs, which leads to investing in micro and small RES installations. Such an approach enables the easy and natural introduction of decentralisation of sources and thus, also a decrease in expenses related to transmission of energy at simultaneous increase in reliability of power supply. Furthermore, diversification of RES within a large area allows for decreasing the stochastic nature of effects of behaviours of installations, dependent on changes in weather. The ultimate selection of the size of storages as well as their number and place of installation should be determined by economic–technical analyses. This process can be sped up significantly and facilitated by using the appropriate software.

The use of supercapacitors and flywheels in the energy storage system entails one more advantage. These systems, owing to the possibility of drawing and releasing high currents very fast, allow the frequency of mains voltage to be adjusted. Even if they are greatly dispersed, they can be managed from the level of the SCADA systems, whose presence brings the power system closer to the smart–grid concept.

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