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An overview of cost-effective energy storage technologies

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ABSTRACT

After the industrial revolution and world technological growth, humanity and society seek to use energy resources more efficiently. The global economy currently relies on electricity for the economic and development of world nations. Electrical energy is used mostly in cities and commercial industries. This study focuses on changing the energy production and consumption patterns in Kabul as it is faced with many challenges and problems in providing needed electrical energy within its power network. For solving these problems and challenges, national policymakers are searching for practical and economical methods to provide electric energy for capital region in a sustainable manner. One suggestion is the storage of electrical energy, which can act when the network is under pressure and to avoid power outages. Electric Energy storage(EES)can be used as a secondary source to those regions which are not connected to the national power network. This research aims to find the most appropriate and practical solutions for the storage of extra and additional electrical energy at Kabul city.

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1. Introduction

Energy storage can be achieved after energy is transformed from one form to another form of storable energy and back when needed. Despite the remarkable growth worldwide, electricity generated from renewable sources is not delivered at a constant or easily adjustable-rate to provide an immediate response to demand. The growth of decentralized renewable energy production leads to greater network load stability problems and requires energy storage. Nevertheless, in the next 20–30 years, all sustainable energy systems will have to be based on the rational use of traditional resources and greater use of renewable energy.

Advantages from decentralized electrical production from renewable energy sources include a more secure supply for consumers with fewer environmental hazards. However, the unpredictable nature of these sources requires that network provisioning and usage regulations be established for optimal system operation. Renewable resources fluctuate independently from demand, yet are abundant as conversion systems are becoming more affordable. Their significant contribution to sustainable energy use will require considerable further development of storage methods.

Historically, EES has played three main roles. First, EES reduces electricity costs by storing electricity obtained at off-peak times when its price is lower and deploying at peak times instead of using electricity bought at higher rates. Second, to improve the reliability of the power supply, EES systems support users when power network failures occur. Finally, EES helps to maintain and improve power quality, frequency and voltage. Main objective of this study is outlined as following:

- Finding the appropriate applicable electricity storage technologies for Kabul.
- Finding the appropriate economic electricity storage technologies for Kabul.

2. Storage technologies

2.1. Pumped Hydro Storage

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Pumped hydro storage (PHS) makes use of two vertically separated water reservoirs. It uses low-cost electricity to pump water from the lower to the higher elevated reservoir using either a pump and turbine or a reversible pump-turbine [1]. During periods of high demand, it acts as a conventional hydropower plant, releasing water to drive turbines and thereby generating electricity. The main advantage of this technology is that it is readily available. It uses the power of water, a highly concentrated renewable energy source, and this technology currently the most used for high-power applications. Pumped storage sub-transmission stations will be essential for the storage of electrical energy. PHS has a conversion efficiency, from the point of view of a power network, of about 65–80%, depending on equipment characteristics.

The first PHS plants were used in Italy and Switzerland in the 1890s. By 1933 reversible pump-turbines with motor-generators were available. Typical discharge times range from several hours to a few days. Advantages are a very long lifetime and practically unlimited cycle stability of the installation. Main drawbacks are the dependence on topographical conditions and large land use. The main applications are for energy management via a time shift, namely no spinning reserve and supply reserve.

2.2. Compressed air energy storage

Compressed air (compressed gas) energy storage (CAES) has been used since the 19th century for different industrial applications including mobile ones using air as a storage medium. Electricity compresses air and stores it in either an underground structure or an above-ground system of vessels or pipes. When needed the compressed air is mixed with natural gas and burned in a modified gas turbine. Typical underground storage options are caverns, aquifers, or abandoned mines. If the heat released during compression is dissipated by cooling and not stored, the air must be reheated prior to expansion in the turbine; this process is called diabatic CAES and results in low round-trip efficiencies of less than 50%. Diabatic technology is well-proven; the plants have a high reliability and are capable of starting without extraneous power [2]. The advantage of CAES is its immense capacity; disadvantages are low round-trip efficiency and geographic limitations.

2.3. Flywheel energy storage

Flywheel energy storage (FES) rotational energy is stored in an accelerated rotor, a massive rotating cylinder. The main components of a flywheel are the rotating body/cylinder (comprised of a rim attached to a shaft) in a compartment, the bearings, and the transmission device (motor/generator mounted onto the stator). The energy is maintained in the flywheel by keeping the rotating body at a constant speed. An increase in the speed results in a higher amount of energy stored [3]. To accelerate the flywheel, electricity is supplied by a transmission device. If the flywheel's rotational speed is reduced, electricity may be extracted from the system by the same transmission device.

Available since about 1970, flywheels of the first generation use a large steel rotating body on mechanical bearings [4]. Advanced FES systems have rotors made of high-strength carbon filaments, suspended by magnetic bearings, and spinning at speeds from 20,000 to over 50,000 rpm in a vacuum enclosure. The main features of flywheels are excellent cycle stability, a long life, little maintenance, high power density, and the use of environmentally inert material. However, flywheels have a high level of self-discharge due to air resistance and bearing losses and suffer from low current efficiency.

2.4. Hydrogen (H2)

A typical hydrogen storage system consists of an electrolyzer, a hydrogen storage tank, and a fuel cell. An electrolyzer is an electrochemical converter which splits water with the help of electricity into hydrogen and oxygen [5]. It is an endothermal process, so heat is required during the reaction. Hydrogen is stored under pressure in gas bottles or tanks, and this can be done practically for an unlimited time. To generate electricity, both gases flow into the fuel cell, where an electrochemical reaction occurs that hydrogen and oxygen react and produce water, heat is released, and electricity is generated. Oxygen is not stored but vented to the atmosphere on electrolysis, and oxygen from the air is taken for the power generation [6]. Gas motors, gas turbines, and combined cycles of gas and steam turbines are under discussion for power generation.

Hydrogen systems with fuel cells (less than 1 MW) and gas motors (under 10 MW) can be adopted for combined heat and power generation in decentralized installations. Gas and steam turbines with up to several hundred MW could be used as peaking power plants. The overall AC-AC efficiency is around 40%.

Hydrogen can be stored either as a gas under high pressure, a liquid at very low temperature, adsorbed on metal hydrides, or chemically bonded in complex hydrides. For stationary applications, gaseous storage under high pressure is the most popular choice. Smaller amounts of hydrogen can be stored in aboveground tanks or bottles under pressures up to 900 bar. For larger amounts of hydrogen, underground piping systems, or even salt caverns with several 100,000 m^3 volumes under pressures up to 2000 bar can be used.

2.5. Double-layer capacitors

Electrochemical double-layer capacitors (DLC), also known as supercapacitors, have been around for 60 years. They fill the gap between classical capacitors used in electronics and general batteries because of their nearly unlimited cycle stability, extremely high power capability, and their many orders of magnitude higher energy storage capability when compared to traditional capacitors. This technology still has a large development potential for compact designs that could lead to much higher capacitance and energy density than conventional capacitors.

Two main features are the extremely high capacitance values (of the order of many thousand farads) and the possibility of high-speed charges and discharges due to extraordinarily low inner resistance not available with conventional batteries. Other advantages include durability, high reliability, no maintenance, long lifetime, and operation over a wide temperature range and in diverse environments (hot, cold and moist) [7].

The lifetime operation reaches one million cycles (or ten years of operation) without any degradation except for the solvent used in the capacitors, which deteriorates in 5 or 6 years irrespective of the number of cycles. DLCs are environmentally friendly and easily recycled or neutralized. The efficiency is typically around 90%, and discharge times are in the range of seconds to hour. They can reach a specific power density about ten times higher than that of conventional batteries (only very-high-power lithium batteries can reach nearly the same specific power density). However, their specific energy density is about ten times lower. Because of their properties, DLCs are well-suited for applications with a large number of short charge/discharge cycles where their high-performance characteristics can be used. DLCs are not suitable for storage over more extended periods because of their high self-discharge rate, their low energy density, and high investment costs.

2.6. Superconducting magnetic field energy storage

Superconducting magnetic energy storage (SMES) systems work according to electrodynamics. The energy is stored in a magnetic field created by the flow of direct current in a superconducting coil kept below its superconducting critical temperature. Though when superconductivity was discovered over 100 years ago, a temperature of about 4 °K was needed. Today, materials are available which can function at around 100 °K. Now a coil made of superconducting material works with power conditioning equipment and a cryogenically cooled refrigeration system. The main advantage of SMES is the very quick response time as the requested power is available almost instantaneously. The system is characterized by its high overall round-trip efficiency (85-90%) and the very high-power output which can be provided for a short period of time. While there are no moving parts in the main portion of SMES, the overall reliability depends crucially on the refrigeration system.

In principle the energy can be stored indefinitely as long as the cooling system is operational, but longer storage times are limited by the energy demand of the refrigeration system. Large SMES systems with more than 10 MW power are mainly used in particle detectors for high-energy physics experiments and nuclear fusion. To date, a few, rather small SMES products are commercially available for power quality control in manufacturing plants such as microchip fabrication facilities.

2.7. Sodium sulfur (NaS) battery

Sodium sulfur batteries consist of liquid (molten) sulfur at the positive electrode and liquid (molten) sodium at the negative electrode; the active materials are separated by a solid beta alumina ceramic electrolyte. The NaS battery temperature is kept between 300 °C and 350 °C to keep the electrodes molten. NaS batteries reach typical life cycles of around 4,500 cycles and have a discharge time of 6.0 hours to 7.2 hours. They are efficient (AC-based round-trip efficiency is about 75%) and have a fast response. These attributes enable NaS batteries to be economically used in combined power quality and time shift applications with high energy density.

The NaS battery technology has worked at around 200 sites in Japan, Germany, France, USA and UAE. The main drawback is that a heat source is required to maintain operating temperatures, which uses the battery's own stored energy and reduces the battery performance.

2.8. Nickel-cadmium (Ni-Cd) battery

In commercial production since the 1910s, nickel-cadmium (Ni-Cd) has seen periodic advances in electrode technology and packaging. Ni-Cd batteries remain relevant by providing simple implementation, long life, and reliable service without complex management systems. Ni-Cd batteries are the only batteries capable of performing well even at low temperatures in the range from -20 °C to -40 °C. Large battery systems using vented Ni-Cd batteries operate on a scale similar to lead acid batteries [8]. Because of the toxicity of cadmium, these batteries are presently used only for stationary applications in Europe and have been prohibited for customer use since 2006.

3. Concentrating solar power energy storage (CSP Storage)

Concentrated Solar Power (CSP) is ideally suited to storing solar thermally. There are several ways CSP technologies receive the heated fluid to store thermal energy from the sun; once ready to store, a huge metal tank stores the hot liquid, whether as molten salts (at about 565°C) for power tower CSP or in a heat transfer fluid (at about 400°C) for parabolic-trough CSP [9].

3.1. Tower CSP

In tower CSP, a molten salt mix, like sodium nitrate and potassium nitrate, is heated by reflecting sunlight with mirrors onto a receiver atop a central tower that is encircled by a solar field of flat mirrors (heliostats). This molten salt is cycled up the tower "cold" at 260°C and is then heated by the focused sunlight aimed at the receiver. Once heated, this now 565°C molten salt flows down the tower where it can either be used right away in the power block to generate electricity or be stored thermally in the hot tank for later use.

3.2. Parabolic through CSP

In a parabolic trough CSP plant, the heat transfer fluid (HTF) is an oil heated in pipes throughout the solar field by reflecting focused sunlight on a narrow pipe that runs the length of its reflecting trough shaped mirrors (heliostats) [10]. This hot oil then transfers solar heat along bigger pipes to the power block where it can either be used or held in a holding tank to store thermal energy until it is needed.

In both CSP technologies, when the thermal energy in the molten salt or the HTF is ready to be used, it is sent to a heat exchanger. Heat is extracted and used to boil water to run a steam turbine in a power block. Like the older thermal plants, CSP generates electricity by rotating giant machinery [11]. With its heat extracted, the now "cooler" molten salt is stored in a second tank ready to be sent up the tower to be heated again by the sunlight reflected onto the receiver.

3.3. Longevity

Molten salts lose only about 1 degree of heat a day, so it is possible to store the maximum amount of thermal energy for months. It is more profitable to use the stored energy daily and get paid for the daily and nightly deliveries of electricity. One can also size thermal solar energy storage capacity relative to the solar field that harvests the sunlight so that it can be stored for months. Molten salt thermal energy storage can be heated and cooled daily for at least 30 years. If the tanks need corrosion repair, the molten salt would be cooled off over a few months and emptied.

We studied different storage technologies to recommend the most appropriate, applicable, and economic electricity storage technologies for Kabul city based on available international information. First, using the information about the national electricity network, the needed energy amount of Kabul city and peak energy usage hours are found to calculate the energy shortfall. These results are compared to the performance of power systems in other countries. Finally, recommendations for solutions to Kabul's electricity problems are made.

4. Result and discussion

Lithium-ion battery: Lithium-ion (Li-ion) batteries have become the most important portable and mobile storage technology (e.g. laptop, cellphone, electric bicycle, and electric car) since around 2000. High cell voltage levels of up to 3.7 Volts mean that the number of cells in series with the associated connections and electronics can be reduced to obtain the target voltage. For example, one lithium-ion cell can replace three NiCd or NiMH cells, which have a cell voltage of only 1.2 Volts.

Another advantage of Li-ion batteries is their high gravimetric energy density and the prospect of large cost reductions through mass production. Although Li-ion batteries have a share of over 50 % in the small portable devices market, there are some challenges for developing larger-scale Li-ion batteries. The main obstacle is the high cost (more than USD 600/kWh) due to special packaging and internal overcharge protection circuits. Li-ion batteries generally have very high efficiency, typically 95-98%. Nearly any discharge time from seconds to weeks can be realized, which makes them a very flexible and universal storage technology. Standard cells with 5000 full cycles can be obtained on the market at short notice. However, higher cycle rates are possible after further development depending on the materials used for the electrodes. Since Li-ion batteries are currently still expensive, they can only compete with lead-acid batteries in those applications which require short discharge times (e.g., as primary control backup).

Safety is a serious issue in Li-ion battery technology: most of the metal oxide electrodes are thermally unstable. They can decompose at elevated temperatures, releasing oxygen, which can lead to a thermal runaway [12]. To minimize this risk, Li-ion batteries are equipped with a monitoring unit to avoid overcharging and over-discharging.

Usually, a voltage-balance circuit is installed to monitor the voltage level of each cell and prevent voltage deviations among them. Li-ion battery technology is still developing, and there is considerable potential for further progress. Research is focused on the development of cathode materials.

Table 1: Installation cost of electricity storage technology (2016).

Storage Technology	Cost($/kWh)
Pumped Hydro	21-100
Lithium ion	1050-1260
Lead acid	263-473
NaS	386-735

Table 2: Installation cost of electricity storage technology (2030).

Storage Technology	Calendar life (Years)	Cycle life (Equivalent Full-Cycles)	Depth of Discharge (%)	Energy density (Wh/L)
Pumped Hydro	30-100	12000-100000	80-100	0-2
Compressed Air	20-50	10000-100000	35-50	2-6
Flywheel	30-60	151259-302518	75-90	2-200
Lithium ion	15-31	9549-38194	84-100	200-620
Lead acid	4-21	538-5375	50-60	50-100
NaS	14-36	1500-15000	100	140-300

Table 3: Characteristics of electricity storage technology in 2016.

Storage Technology	Calendar life (Years)	Cycle life (Equivalent Full-Cycles)	Depth of Discharge (%)	Energy density (Wh/L)
Pumped Hydro	30-100	12000-100000	80-90	0-2
Compressed Air	20-50	10000-100000	35-50	2-6
Flywheel	15-25	100000-200000	75-90	2-200
Lithium ion	10-20	5000-20000	84-95	200-620
Lead acid	3-15	250-2500	50-60	50-100
NaS	10-25	1000-10000	100	140-300

5. Conclusion

Electrical energy as an inclusive, clean, and transmittable energy is a good option over other energies, and it plays an important role in the development and modernization of the world. Electricity demand is ever increasing as more nations are growing and developing. As the capital of Afghanistan, Kabul faces challenges in meeting local demand for electrical energy, and the government seeks solutions to find economical at the same time sustainable methods to provide electricity. This study identifies options to make a selection for an appropriate solution to store extra electrical energy for the energy grid through peak times. We recommend that the best energies to store energy are pumped hydro storage and Li-ion batteries for Kabul.

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