

## JOURNAL OF SECURITY AND SUSTAINABILITY ISSUES

ISSN 2029-7017 print/ISSN 2029-7025 online

2016 December Volume 6 Number 2

[http://dx.doi.org/10.9770/jssi.2016.6.2\(4\)](http://dx.doi.org/10.9770/jssi.2016.6.2(4))

### TOWARDS ENERGY SECURITY: SUSTAINABLE DEVELOPMENT OF ELECTRICAL ENERGY STORAGE

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Received 10 March 2016; accepted 22 December 2016

**Abstract.** Energy security is conditioned by numerous factors, among which solutions and patterns of energy storage play important role. Electrical energy storage (EES) is the process by which energy is stored from the power network to a form which can be used later when converted back to electrical energy. There are various ways by which electrical energy can be stored for future purposes. Nowadays, the electrical energy is mainly stored in pumped hydroelectric energy storage (PHES) that comprises about 99% of EES worldwide and the battery energy storage (BES) that uses chemical energy with both methods yielding characteristic advantages and disadvantages. Electrical energy is mainly stored when there is low demand and when there is high generation of power at low costs. The energy is then used when there is high demand of power and the generation cost is high or when there are no other means of generating electrical energy. Electrical energy storage has many uses such as in the electrical devices, motor vehicles and stationery energy resources and is gaining special attention with the widespread usage of renewable energy sources (RES).

In this paper, we are focusing on the sustainable development of the electrical energy storage. We are drawing a comparison of the advantages and disadvantages of pumped hydroelectric storage and batteries that use chemical energy and assess their implementation based on various scenarios of the future development. We conclude that although HPS is still the more economical option, new advances in BES might alter the energy market and change the rules of the game by fostering the sustainable development through the more effective storage and transportation of electric energy.

**Keywords:** energy security, sustainable development, electric energy storage, pumped storage plants, battery storage, renewable energy

**Reference** to this paper should be made as follows: Strielkowski, W.; Lisin, E.; Tvaronavičienė, M. 2016. Towards energy security: sustainable development of electrical energy storage, *Journal of Security and Sustainability Issues* 6(2): 235–244.

DOI: [http://dx.doi.org/10.9770/jssi.2016.6.2\(4\)](http://dx.doi.org/10.9770/jssi.2016.6.2(4))

**JEL Classifications:** M20, Q21, Q41

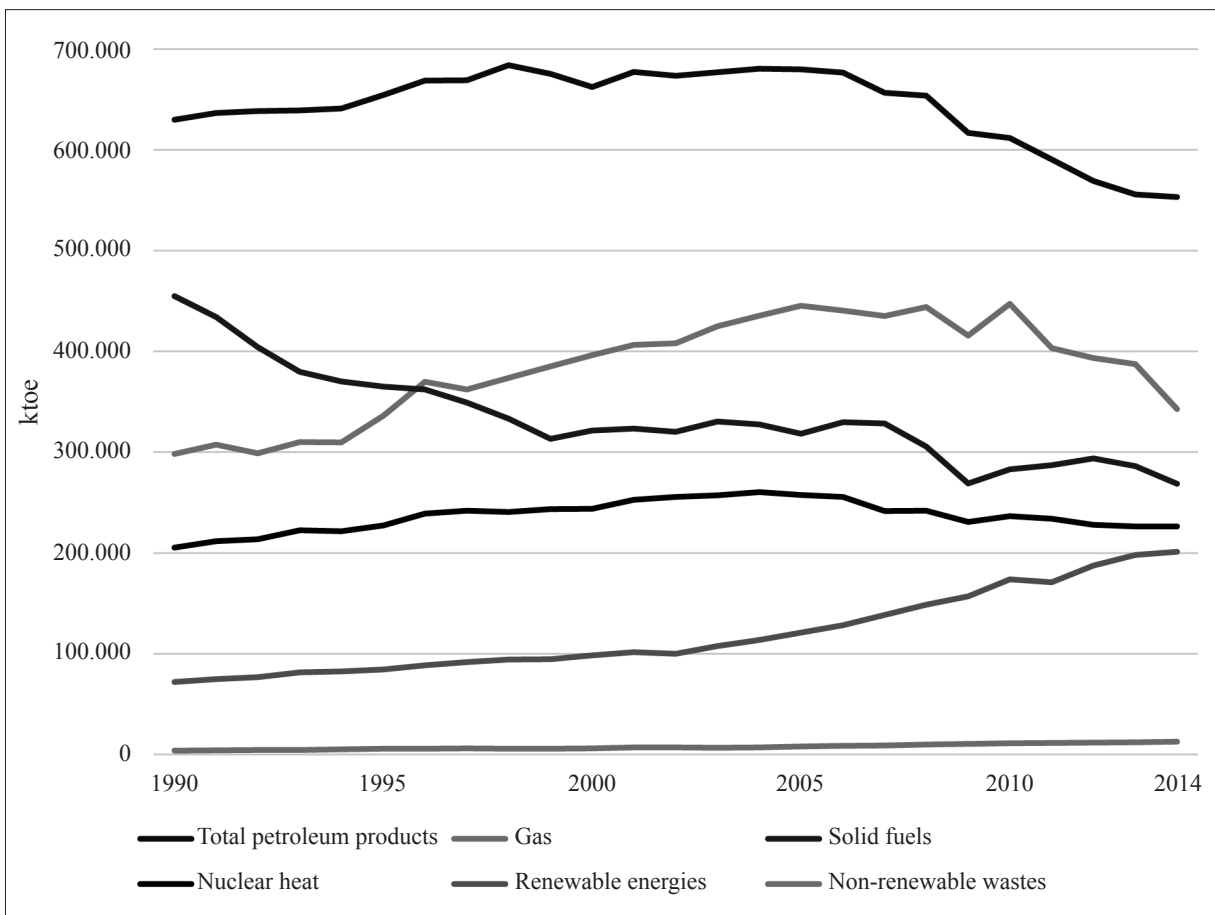
## 1. Introduction

The access to reliable, clean and affordable energy has been the foundation of the world flourishing prosperity and economic growth from the beginning of industrial revolution. For the future to be sustainable, energy for use must be derived from renewable energy sources (sustainable fuels). Sustainable energy sources are more economical and compatible with the surroundings as they tend to pollute less than other conventional energy

sources. In contrast, unsustainable sources cannot be replenished, pollute and have a finite supply. Chart 1 that follows, provides an account of energy consumption in the EU-28 countries. Statistics provided and behavioural patterns of both, business companies and households, witness, that although the portfolio of energy sources is changing towards the sustainable sources of energy, the overall generation and consumption is increasing (Strielkowski 2016; Tvaronavičienė 2016; Rezk et al. 2016; Šimelytė et al. 2016).

Examples of sustainable sources of energy include solar energy, wind energy, hydro energy and tidal energy. Energy produced from these sources has to be converted into electricity for domestic and industrial uses (Armaroli and Balzani, 2011).

However, the electricity produced from these sources cannot be stored for long and therefore it requires efficient energy storage devices. An energy storage system plays three main roles. Firstly, it reduces the cost of electricity by storing electricity produced at off-peak times as the price is always lower. Secondly, there is the need to enhance the reliability of power supply (Gogus, 2009). Energy storage systems support consumers when power network failures occur due to unavoidable circumstances. For industrial and domestic grid applications electricity must be available 24 hours a day, even minute to minute fluctuations cause great disruptions with costs estimated to be so huge, billions of dollars annually.



**Chart 1:** Gross energy consumption in the EU-28 (1990-2014), in ktoe

Source: Eurostat (2016)

Therefore, for large scale production of energy to be achieved there is a need to develop efficient energy storage devices. And finally, the third role of energy storage systems is to maintain and improve power quality; frequency and voltage (Gogus, 2009). There are different types of energy storage systems which include Pump hydro energy storage systems and chemical energy storage.

Hydro pumped power storage plants involves the use of two reservoirs one at a higher level and another at a lower level. When there is an immediate demand for power, the head gates are opened. Water is allowed to flow from the higher-level reservoir through the pipes powering the turbine into the lower level reservoir. It's the movement of the turbines that turns the generator which generates electricity. Electricity is generated by the generator throughout the use of powerful magnets and coils of wire. It is the quick spinning of the coils inside the magnets, which produces electricity. The water that exits from the pipe flows into the lower level reservoir instead of re-entering the river and flow downstream. When the demand for electricity is low, let say at night the water in the lower level reservoir is pumped back into the higher-level reservoir to be used again. The significant difference between hydro pumped storage system and hydroelectric power system is that in hydro pumped the water is continuously reused while hydroelectric system the water that generates electricity continues to flow downstream after use (Mansoor, 2000).

Batteries and electrochemical capacitors are the main sources of electrical energy storage today that uses chemical energy to store energy. They both utilize electrochemistry to store the electricity produced from the solar, wind or hydro for future use. The significant difference between them is that electrochemical capacitors store energy directly as charge while batteries store energy in chemical reactants capable of generating charge. Although electrochemical capacitors have higher power densities than batteries the energy storage densities are currently lower for batteries and are insufficient in many applications. In order to increase the energy density in batteries, new materials are required (Gogus, 2009).

Electrical energy storage started in the twentieth century when the power stations were being closed overnight and people required power supply at night (Zakeri and Syri, 2015). Therefore, the power stations used to store power in the lead-acid accumulators for supply at night. Thence, the utility companies realized that flexibility of energy supply was important and they came up with the first central station for energy storage which was pumped hydroelectric storage in the year 1929. By the year 2005, there were more than two hundred pumped hydroelectric storage stations in the whole world which produced approximately one hundred Giga watts (Xie et al., 2014). Due to the ever-rising requirement of electricity in the industries, homes and other environmental requirements, the practical application of the electrical energy supply has risen. Majority of the governments around the world have also started various electrical storage programs to ensure that the countries do not face any power outages in the future.

## **2. Literature review: hydro pumped storage and battery storage**

Nowadays, battery energy storage accounts for just 1% of world's EES with Pumped Hydroelectric Energy Storage (PHES) making up the remaining 99% (Newbery, 2016). Pumped Storage Plants (PSP) first introduced in the 1960s represent the overwhelmingly established bulk EES technology with an operation output capacity reaching about 164 GW in 2016 (Barbour et al., 2016). This capacity has been growing for past 8 years at an average of 2.7% per annum (EIA, 2016).

Most of the energy produced during generation is lost through various inefficiencies encountered in energy conversion and distribution processes. Energy is lost from its point of generation, transmission, distribution and even in storage. When steam turbines are used to generate electricity, 65% of all prime energy is lost as heat. Also, electricity generation installations do not always deliver their theoretical capacity as expected because of the variations in the demand and the need to shut down to carry out routine maintenance of the equipment. The resistance of the cables in which current flows through between the generating plant and the user's premises leads to further losses due to the joule heating ( $I^2R$  losses). When there is need to store the energy for future use and to cater for the fluctuations in demand, it is expected to experience some inefficiency because of the heat losses (Kreith and Goswami, 2007).

For pumped hydroelectric storage system, the roundtrip efficiency loss is around 20% to 30%. This means that about 70% of the electrical energy used to pump water into the higher reservoir can be gained back in the process. The following reasons are the main causes of efficiency losses; the rolling resistance, the turbulence in the

penstock and in the tailrace, leakages of the reservoir, and flow fluctuations due to summer/winter seasons. The overall average lifetime efficiency of a battery results in 68%. For a new battery, the efficiency is about 85% (a round trip charge) but with time their efficiencies tend to decrease up to 50%. The battery also requires some inverters to convert direct current into alternating electricity to be used by common domestic appliances. The efficiency of the battery is also affected by the efficiency of the type of inverter used (Kreith and Goswami, 2007).

For pumped storage plants it has the tendency to store huge capacity of energy since it only requires two reservoirs of water and which are at different sea levels. Because these reservoirs hold very large volumes of water it is considered to be a large scale storage system. The amount of energy generated depends on the mass of pumped water and the difference in height between the two reservoirs (Mansoor, 2000). Batteries have relatively low energy capacity storage as compared to that of the hydro pump storage system. Battery capacity is determined by the amount of active material contained in the battery e.g. in lead batteries it is determined by the number of plates in the battery. Battery capacity shows the maximum capacity of energy that can be withdrawn from the battery under certain conditions. A battery rated energy storage is given by the following formula:

$$E_{rated} = C_{rated} * V_{nominal} \quad (1)$$

where:

$V_{nominal}$  - is the nominal battery voltage

$C_{rated}$  - is the battery rated ampere-hour capacity.

The actual usable energy of a battery is given by the product of  $E_{rated}$  and allowable depth of discharge (around 50%) (Gogus, 2009). However, the exact energy storage capabilities of the battery can change significantly from the nominal rated capacity as the capacity of the battery depends on the age, the charging and discharging patterns and past history of the battery. This explains why a new battery usually stores high capacity of energy and decreases with time as the battery ages.

The lifetime of batteries is short as compared to that of hydro pumped storage systems. Batteries have a short life span because of the occurrence of the unwanted chemical or physical changes or the loss of active materials from which they are made of. The changes are always irreversible and thus affect the overall performance of the battery. Under different conditions, the active materials in batteries may break down or else combine in many different ways which might result in the reduction in the quantity of these materials and consequent reduction in cell capacity. Heat also affects the life of the batteries as small increases in temperature have major influences on battery performance accelerating both the desired and undesired chemical reactions. Pump hydro storage system has a long-life span e.g. the first pumped storage hydro plant was constructed in Switzerland; it started operations on 1909 and is still operating at the present (Mansoor, 2000). There are some conditions which when maintained, pumped hydro storage plant can exist for a very long time. First is by ensuring that the two water reservoirs do not dry up and by making sure there is a difference in the height of the two reservoirs.

There is a huge potential in batteries to be dangerous if they are not carefully designed or when abused. The most recent case is the explosion of Samsung Galaxy note 7 batteries which were as a result of an error in design. When a battery is charging lithium ions moves from cathode to anode and vice versa when it is being used. An electrolyte conducts the current by assisting ions to move more easily between the two sides. Although ions need to move, the cathode and anode themselves should never touch since they would redirect energy to the electrolytes. To avoid this from happening, battery manufacturers insert separators between them (Bellu, 2009). And this is the reason why Samsung Galaxy note 7 exploded, the separators were flawed. In addition to that, lead is one of the most toxic metals we have in our midst. It can enter our bodies by either inhalation of lead dust or ingestion after touching our mouths with lead-contaminated hands. Children are the most affected by ingestion of button batteries since every 3 hours a child must visit an emergency department to be treated. In many of the household items, we must find button batteries such as toys, watches, and remote controls (Armaroli and Balzani, 2011). When swallowed by children they stuck in the upper esophagus and react spontaneously with saliva. This makes the battery to discharge a current that hydrolyses water hence generating hydroxide and serious damage occurs within a very short time which can even lead to death.

When it leaks onto the ground, lead and acid particles pollute the soil and become airborne when dry. Pregnant mothers are the most vulnerable to lead exposure since their tissues are developing. High levels of lead do affect child's growth, cause brain damage, induce behavioural problems and harm kidneys. Lead in adult's causes memory loss, affect the reproductive system, high blood pressure and lowers the ability to concentrate (Bellu, 2009). In contrast pump, hydro storage plant does add any waste to the surroundings like the case of batteries. The landscape is not greatly affected as pump hydro storage systems are made from already existing lakes in mountains. Its main disadvantage is the need to have huge tracts of land which have to be cleared in case there is vegetation cover. Also, the water that is tapped to be used in the process is not allowed to flow downstream which is a major blow to the communities living downstream.

Hydro pump storage construction is very expensive and the time taken to complete the project is long. Huge amounts of capital and labour are needed to construct the dam to prevent the water from flowing. In addition, installation of the turbines and pumps is expensive. The cost of batteries is relatively low as compared to that of hydro pump storage. The cost of a battery depends on the storage capacity of the battery. The higher the capacity of a battery the higher the purchasing cost. The maintenance cost associated with batteries is still high because battery tends to decrease the capacity of stored energy with time. This means that there is a need to replace the active materials of the battery after much use (Bellu, 2009). Battery energy storage represents one of the most crucial features in the fundamental development of today's electricity markets. Although still modest today, it is envisaged to play a key role in storing electricity from various renewable energy sources and is essential for the electrification of transport in the years to come.

For some time now, the transformative prospect of power storage has been just around the corner, and presently, storage aggregates a small drop in a vast sea (Gallagher, 2009). Affordable storage of electric energy is often viewed as the lacking connection between alternate renewable energy and daily dependability. It can be argued that electrical energy storage (EES) technologies represent a key element of a renewable energy system (Kyriakopoulos and Arabatzis, 2016).

Although water storage currently dominates the world's conventional (EES), rapid ongoing decreases in the cost of batteries raises hopes that batteries based on storing energy using chemical components and reactions will offer a new and attractive storage option. Newbery and Strbac (2016) summarize estimates for 2020 battery energy storage costs which range from €253-€345/kWh for the battery pack as opposed to the today's costs of about €1117.

Energy stored in batteries from renewable energy source such as wind turbines during off peak periods could be discharged during peak periods as opposed to running non-renewable sources such as natural gas turbines which are more expensive. The value obtained from storing cheap or free energy obtained from renewable sources during off-peak or low-demand periods which could be sold during peak hours (which are mostly in the afternoon) can be calculated by simply taking the market price difference between the time periods.

### **3. Sustainability aspects in electrical energy storage**

When it comes to analysing the sustainability aspects of both types of electrical energy storage, it becomes obvious that the pumped hydroelectric storage is the most widely used for of electrical storage. In large scale power production it typically consists of the three main compartments. It has two reservoirs which are placed at different elevations and a pump to pump that is used to pump water to the higher points. Electricity is stored in the form of hydraulic potential and it can be changed back to electric power when needed. It also contains a turbine that is turned by water and to generate hydroelectric power. The amount of stored electricity is proportional to the amount of water stored in the reservoir. Some high dams store hydroelectric power in underground mine shafts while others which have good technology uses open sea as storage (Rehman et al., 2015).

Since 2008, the rate of development of PHES has increased to harness the growing energy demand in the 1990s and 2000s and anticipation of increased wind generation. The most recent PHES projects in Europe have been

commissioned in Austria and Spain (2013-2014). Comparing to other regions of the world, Europe has the most PHES capacity with about 80% of it developed in 1960-1990. Most of the facilities can be found in the mountainous regions of Austria, France, Germany, Italy, Spain, and Switzerland. The development of PHES was coordinated with significant increases in nuclear capacity, although some countries that do not have nuclear power (e.g. Austria) also installed considerable PHES capacities (Barbour et al., 2016).

The existing batteries draw from the chemical energy, have short lifetimes and prove inviable under the current electricity prices (Staffell and Rustomji, 2016), while the hydro power EES use the free storage medium (water) and can operate for more than 100 years. Nevertheless, their potential of gravitational energy is remarkable weak compared to chemical energy and their high capital costs and their distance from demand centres sometimes make them less favourable options than BES.

The hydro pumped storage has various advantages over the batteries which use chemicals because it can store large volume of energy and over a long period. The hydro pumped storage also has higher efficiency than the batteries. They are more durable than the batteries and it is also cheaper to maintain a hydro pumped storage than the batteries which use chemicals. It also costs less to convert one unit of energy in the hydro pumped storage. Because there is low evaporation of water stored in the reservoirs, therefore the hydro power can be stored for months and years. The pumped hydro storage has a rating of approximately one thousand mega Watts. There are various pumped hydro storages with a rating of 5GW per year. The hydro power storage has the highest rating among all the electric energy storages. Statistics shows that there are more than two hundred hydro pump storages in the world. The first facility was set up in Italy and Switzerland in the 1890s but the first large scale facility was set up in the United States in 1929 (Rehman et al., 2015). The facility was constructed in Hartford and it is referred to as Rocky River pumped hydro storage. The largest pump hydro storage facilities are in Europe, Japan and USA and they generate approximately three percent of the world generation capacity.

Some of the drawbacks of the pump hydro storage are the lack of sites where the two reservoirs can be built as well as the scarcity of large dams. It is also very costly to construct a pump hydro storage. The cost of constructing a pump hydro storage it typically hundreds or thousands millions of dollars and this is out of reach for most developing countries watts (Xie et al., 2014). It also takes a very long time to construct a pump hydro storage which has a large storage capacity. Another drawback is the long lead time which is approximately ten years. There are also very many environmental issues which must be considered before constructing a hydro pump storage. This is because the environment is usually destroyed when constructing hydro pump storage and those constructing must ensure that they do not interfere with the life of aquatic animals or endangering their lives. The process of constructing hydro pump storage also involves the destruction of trees and other forms of vegetation so that the reservoirs can be constructed and this is destruction of the environment. The facility must ensure that they fulfil all the environmental requirements before they are allowed to construct the pump hydro storage.

The batteries on the other hand use chemical reactions to store electricity and then convert it back to electrical energy. There are various types of batteries such as lead acid, alkaline batteries and lithium ion batteries among others. There are batteries which are used once and there are others which are recharged and used several times (Dimov et al., 2003). The batteries vary in shapes and sizes and the voltage stored also varies depending on the size and the type of battery. Most of the electronics and equipment which use batteries are portable such as wrist watches, smartphones, and motor vehicles among others. There are other huge batteries which are used as stand by power banks for houses and computer data centres.

Batteries contain various numbers of voltaic cells and they convert the chemical energy chemical energy to electrical energy. The batteries have negatively charged ions called anions and positively charged ions which are referred to as cations. During the charging process the reduced at the cathode and the anions are reduced at the anode. The electrodes do not come into contact and during the discharging process the cations are added at the cathode while the electron re added at the node (Ferreira et al., 2013). The primary batteries are those which are used once and they are discarded once the power is exhausted. These types of batteries have a chemical reaction which is not reversible which means that they cannot be recharged once the power has been depleted.

When the reactants in the battery are depleted, the primary batteries stop producing power.

The secondary batteries on the other hand are those which can be recharged once the power is depleted. This means that the batteries have chemical reactions which are reversible. The chemical reactions are reversed by applying electric current to the battery and this sets the chemical reactants in the original state and then the batteries are used for several times (Thackeray et al., 2012). However, the secondary batteries cannot be used forever because they suffer from loss of electrolyte and internal corrosion. The performance of the batteries depends on the several factors such as the internal chemistry, current drain, the temperature and the stated at which the battery is stored. The batteries do not perform well in low temperatures and in extreme high temperatures. The batteries usually explode when they are subjected to high temperatures and the secondary batteries also explode once they are overcharged (Ferreira et al., 2013).

#### 4. Electrical storage and the electrification of transport

Another frontier battery storage technology includes the use of battery electric vehicles (BEVs) or simply electric vehicles (EVs) to provide grid services. EVs could provide frequency regulation and offer fast response competitive with spinning reserves. Some vehicle technologies could provide peak-shifting services useful for integrating intermittent generation sources (Pierpoint, 2016). It can be shown that EVs can provide indirect storage by interrupting their charging and hence reducing demand to match reduced supply from other sources, as can other demand side responses.

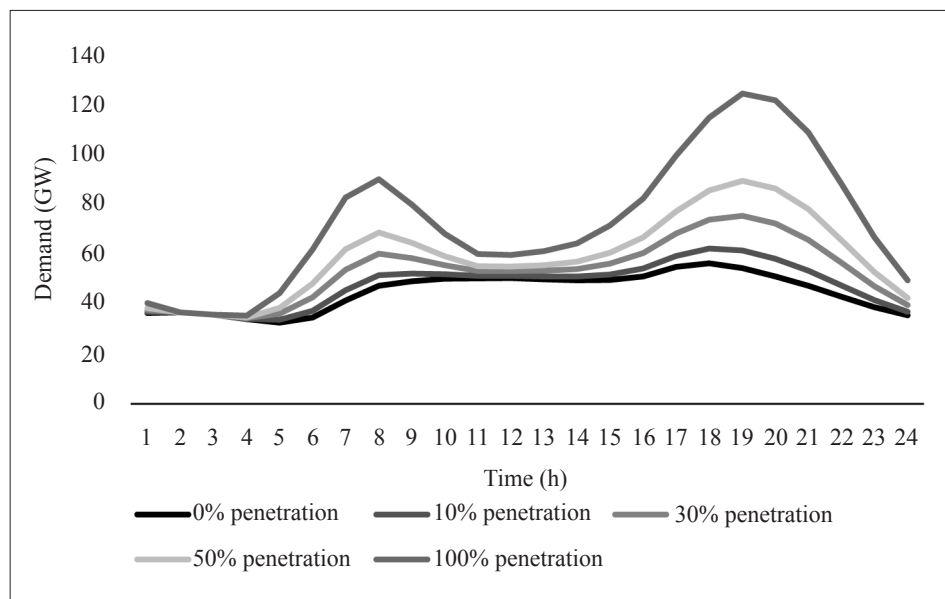


Chart 2: UK winter demand profile under different scenarios of EV and EHP penetration

Source: Strbac et al. (2016)

According to the U.S. Department of Energy (2016), sales of light EVs constituted about 1.2 million in 2015 (growing at an average 83% p.a. over the past four years). If the average battery size is estimated to be 24 kWh, this amounts to just under 30 GWh. Newbery (2016) estimates that the 2012 global car fleet included 773 million, growing since 2000 at 2.9% p.a., which if this continued would give a car fleet of 1.12 billion by 2025. If by then the share of EVs had grown to 10%, there would be 112 million EVs, which with 24 kWh/EV with 2.7 TWh, more than the world current PSP storage (only a part of that storage would be indirectly accessible).

Recent technological developments in the automotive and heating systems sectors have techno-economically enabled this transition with the production and efficient operation of EV. This is demonstrated at Chart 2 above that presents an expected typical winter day demand profile in the UK, under different scenarios regarding the

penetration of EV and EHP (as a percentage of the total number of light/medium-sized vehicles and domestic or commercial buildings respectively).

Nevertheless, due to the natural energy intensity of transportation vehicles and heating loads, the environmental and energy security potential of this transition is accompanied by the introduction of a considerable amount of new demand in power systems. Going further, due to the temporal patterns of vehicles' and heating systems' use by the consumers the new demand peaks disproportionately higher than the increase in the total electrical energy consumption.

## **Conclusions and discussions**

The pump hydro storages have a longer life than the batteries. The rechargeable batteries can operate for several cycles until the battery stops operating efficiently and the non-rechargeable batteries operate only once. The batteries discharge at faster rate when compared to the evaporation rate of the hydro pump storage which can store the energy for many years. The pump hydro storage can also work at any temperatures provided the water is not in frozen state. The hydro pump storage also does not explode easily as the batteries. The batteries made from Zamboni pile have a long lifetime but they give their power in nanoamp range (Zakeri and Syri, 2015). For instance, the Oxford Electric Bell has been operational using the original pair of cells made from Zamboni piles since it was constructed in the year 1840 up to date.

The other downside of the batteries is that they lose approximately eight to twenty percent of the power stored per year when they are not in operation. They self-discharge occurs due to the chemical reactions which occur within the cell even when they are not being used. The self-discharge rate decreases as at low temperatures but the batteries also do not function properly at the low temperatures (Ferreira et al., 2013). The hydro pump on the other hand can store hydro energy for very many years because the rate of water evaporation is very low.

The primary and secondary batteries have various advantages over the pump hydro storage. Most of the batteries are portable while the pump hydro storage cannot be moved from one place to the other (Dimov et al., 2003). The batteries are also cheaper than the hydro pump storage. The batteries are also manufactured in various industries and the process takes a short time while the pump hydro storages takes very many years and it takes a lot of resources to construct these facilities. The pump hydro storage also requires a vast area for construction while the batteries are constructed in industries. The batteries do not require to be connected to a source of electricity all the time and this makes it possible for them to be used in areas where there is no electric connection (Thackeray et al., 2012). Unlike the pump hydro storage which requires a lot of resources for replacement, the batteries can be replaced easily.

The main disadvantages of using the rechargeable or the non-rechargeable is that they can only be used for a limited time. The batteries and the pump hydro storages can lead to environmental degradation. The batteries contain harmful chemicals which are hazardous to the environment if they are disposed of wrongly. The batteries can also explode and lead to fires or chemical pollution. The hydro pump storage on the other hand leads to environmental pollution because trees and aquatic animals are destroyed when constructing the facilities. However, the electrical energy storages are essential because they provide people with electrical energy when there is high demand of electricity or during times when there is low supply of electrical power.

## ***Acknowledgements***

*This paper was supported by the Ministry of Education and Science of the Russian Federation, research project No. 26.1795.2014/K.*



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