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Impacts of large-scale battery energy storage systems on Russian wholesale electricity and capacity market

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Abstract

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As a flexible power source, energy storage finds its application in different aspects of electricity market. The forecasts and technologies improving allow implementing more energy storage solutions all over the world. In this thesis the impact of battery energy storage systems on the Russian wholesale electricity and capacity market in the conditions of current market model is estimated. An arbitrage mechanism impact to equilibrium price of electricity is considered. Different options of using batteries are calculated in order to estimate economic profitability. Among these are participation in capacity market, price and characteristics for li-ion batteries forecast, and growth of difference between on- and off-peak prices. Meanwhile the net present value is calculated for every variant.

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ABBREVIATIONS

BESS	Battery Energy Storage Systems
BM	Balancing market
BOP	Balance of plant
CAES	Compressed air energy storage
CCS	Competitive Capacity Selection
CDA	Capacity Delivery Agreements
CFS	Centre of Financial Settlements
DAM	Day-Ahead market
EES	Electrical Energy Storage
FAS	Federal Antimonopoly Service
FBES	Flow battery energy storage
FGC UES	Federal Grid Company United Energy System
FES	Flywheel energy storage
HPP	Hydro power plant
HV	High Voltage
IDGCs	International distribution grid companies
LCO	Lithium Cobalt Oxide
Li-ion	Lithium-Ion
LFP	Lithium iron phosphate

LTA	Long Term Agreements
LV	Low voltage
MV	Medium voltage
NPP	Nuclear power plant
NPV	Net present value
PCS	Power conversion system
PHS	Pumped hydro station
R&D	Research and development
RES	Renewable energy source
SMES	Superconducting magnetic energy storages
SCR	Secondary control reserve
SoC	State of charge
TCR	Tertiary control reserve
T & D	Transmission and Distribution
TPP	Thermal power plant
UPS	United Power System
WACC	Weighted average capital cost
WECM	Wholesale electricity and capacity market
XHV	Extra High Voltage

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1. INTRODUCTION

The installed capacity of Russia’s power plants is by 42% higher than peak power consumption by enterprises and the population of the country. Difference is about 65 GW. Most of this capacity was built due to lack of network capacity or congestion in transmission grid. Export reserves average 20% of installed capacity. (Semashko, 2013)

Inability to store electricity, caused due to too expensive storage prices, leads to the need for reserves of generating capacity, network capacity as well as fuel reserves in power plants. The amount of capacity reserves in power plant is normalized (in accordance with the Russian state standard), and the cost of maintaining reserves is included in the consumers’ electricity bill and distributed among all end users.

Energy storage will became a significant component in the development of energy systems. A perfect model design of a smart electricity grid is not possible without participation of energy storages. There is a constant balance between production and consumption in electrical grid. If production does not match demand, a frequency in the grid changes leading to equipment failure and power outages. When comparing electricity prices during the night and during peak hours the difference in market price can be up to 80 % (Nordpoolspot, 2017). This makes energy storages an interesting option as electricity can be produced during the night and used during the peak hours. Energy storages would also remove peak demand from daily loads, thus, help to avoid using occasional expensive electricity generation with, for example, a gas turbine.

There are number of possible energy storage applications that can be applied in modern network.

- Ensuring power quality of substations;
- Ancillary services;
- Grid support applications;
- Renewables integration applications;
- End user applications;

Main goals of energy storages implementation in a grid are: more flexible interaction of different electricity market components, security of supply, possibility to implement more renewable energy sources (RES), and sustainability.

The integration of such energy storage facilities into mutually integrated systems (with the possibility of regulating the volumes of mutual transfer of energy, frequency and load in electric networks) will become the main task of maintaining a stable operation of energy networks in future. In general, market for energy storage systems is already estimated at $ 100 billion annually, and according to expert's forecasts, by 2040 its volume will increase up to $ 250 billion. Total capacity of energy storage will reach 25 GW by 2030 (Nykvist and Nilsson, 2015).

Since the end of January 2016, there are already exist two operating storage systems in South Korea (with a capacity of 9 MWh and 6 MWh). In the Netherlands, a 20 MWh energy storage facility has been already integrated into the national grid. In 2016 – 2017, it is planned to connect six energy storage systems with a total capacity of 90 MW in Germany. Then in Great Britain in autumn 2016, a tender was held for $ 86 million to build eight energy storage facilities based on lithium-ion (li-ion) batteries, which would be combined into a single system with a total capacity of 211 MW in future. (The Global Energy Storage Opportunity, 2017)

The reasons for the emergence of a new approach in electricity market are linked with (Berdnikov, 2012):

- Continuous increasing of electricity price in Russia;
- Necessity of increasing energy and environment efficiency of electric power industry;
- Growth of consumers requirements for reliability and quality of power supply;
- Changing of operation's conditions of electricity and capacity market.

Application of energy storage in Russia is not widely spread yet due to economic inefficiency referred to cost of storages. However, there is a certain price spread in the electricity market prices between peak and off-peak prices that can potentially allow implementation of storages. There are some research centers in Russia such as Skolkovo, Research and Development (R&D) center at FGD UES and the Energy Efficiency Center of Inter RAOUES that study electrochemical batteries and supercapacitors. There is large manufacturer of Li-ion's solutions factory "Liotech". Joint efforts of the FGC UES and ENERZ contribute to two projects of stationary batteries that serve for redundancy of power supply for consumers' own needs in especially important objects (Novikov, 2012). There is also one operating pumped hydro plants owned by RusHydro. The rest are under planning or construction.

In the Master's thesis description of current situation as well as future forecasts in the storage market is presented. Overview includes technologies, applications, effects to the grid, and challenges of storages. There is description of Russian wholesale electricity and capacity market (WECM).

The objective in this thesis is investigation of impacts of large-scale battery energy storage systems (BESS) on WECM. For this, the assessment of economic effect from arbitrage application is used.

Research question relates to how the implementation of power storage will influence on the equilibrium electricity market price. As storage, electrochemical li- ion technology is applied with its characteristics. In addition, a sensitivity analysis is done in order to estimate possible development of battery technologies use in Russian electricity and capacity market.

Scientific novelty of this dissertation is the effect of the energy storage devices on the equilibrium price in the process of applying the arbitration mechanism. The relevance for the Russian market is that there are no publications dealing with the participation of storage batteries on the wholesale market. The linear model was used in the work as a key relationship between demand and price.

The field of application of the results is the wholesale electricity and capacity market, as well as the development of intelligent active-adaptive networks.

2. LITERATURE REVIEW

This section performs an overview of energy storages, their technology, cost, applications, challenges, effects, and future prospects.

2.1. Technologies

The following provides the description of energy storage technologies, which are classified by the type of stored energy (Figure 1).

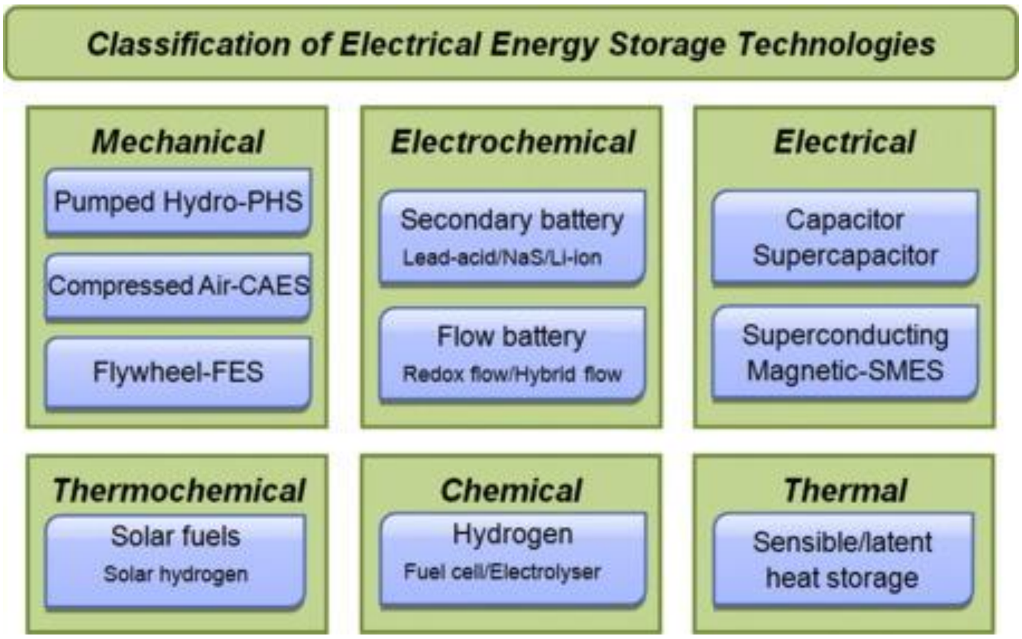

Figure 1. Classification based on the form that energy stored in the system (Luo et al., 2015)

2.1.1. Mechanical energy storage

Mechanical energy storage systems typically operate by converting electricity into various forms of energy. It is differed in 3 main technologies: pumped hydro storage (PHS), compressed air energy storage (CAES), and flywheel energy storage (FES).

1) PHS

For PHS work two water reservoirs separated vertically are needed. First, the water is pumped to the higher reservoir during off-peak electricity demand hours. After that, the water can be released back into the lower reservoir. In the cycle, water pushes a turbine during discharging and a pump when it is charged. Turbine drives generator that deliver electricity to transformer. All processes are schematically illustrated in the figure 2.

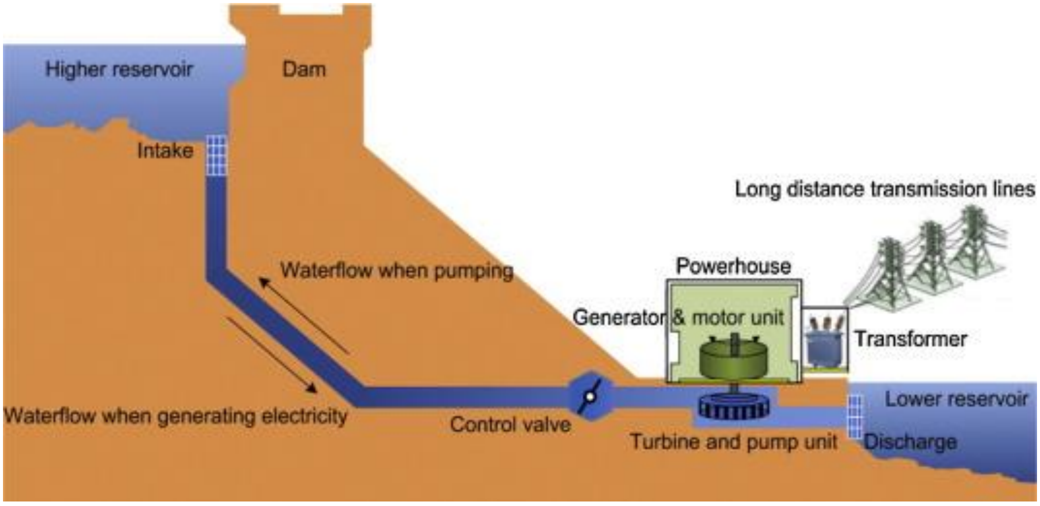

Figure 2. PHS plant layout (Luo et al., 2015)

2) CAES

Air is compressed when the energy demand is low and stored in a large reservoir which could be either naturally occurring or man-made. When the energy is required, the air is released from the reservoir and drives a gas turbine generator. Figure 3 shows schematic diagram of CAES system.

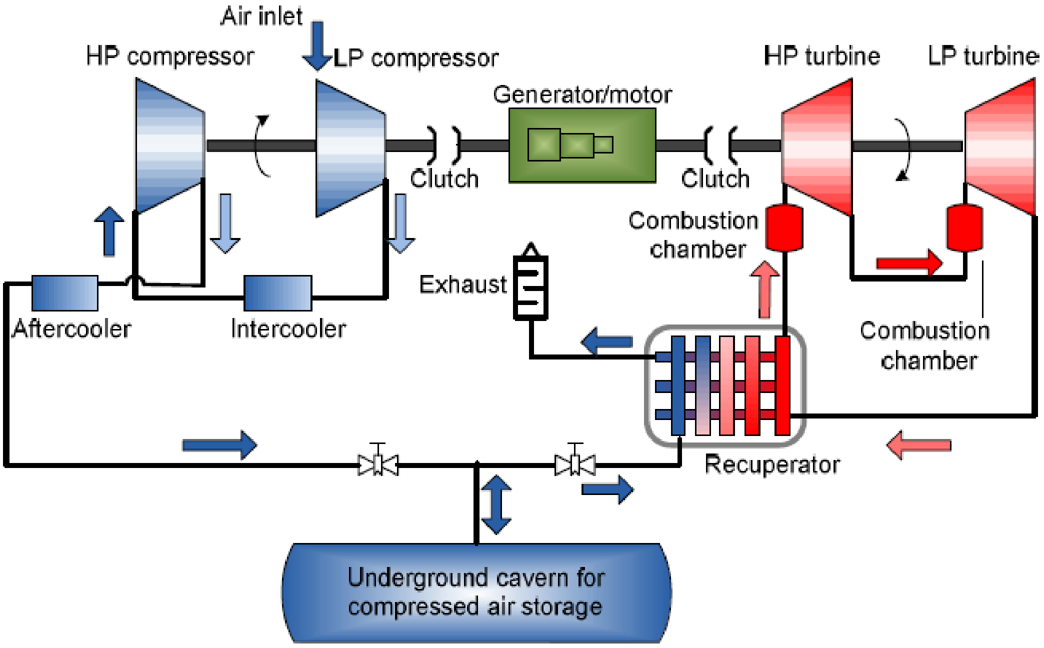

Figure 3. Schematic diagram of CAES system (Luo et al., 2014)

3) FES

FES uses electric energy input that is stored in kinetic form. Flywheel structure with its components is shown in figure 4. When the stored energy is required, flywheel is decelerated to convert kinetic energy to electricity through the application of an integrated motor/generator. Flywheels are typically operated in vacuum to reduce the effect of drag force (Lefebvre and Tezel, 2017).

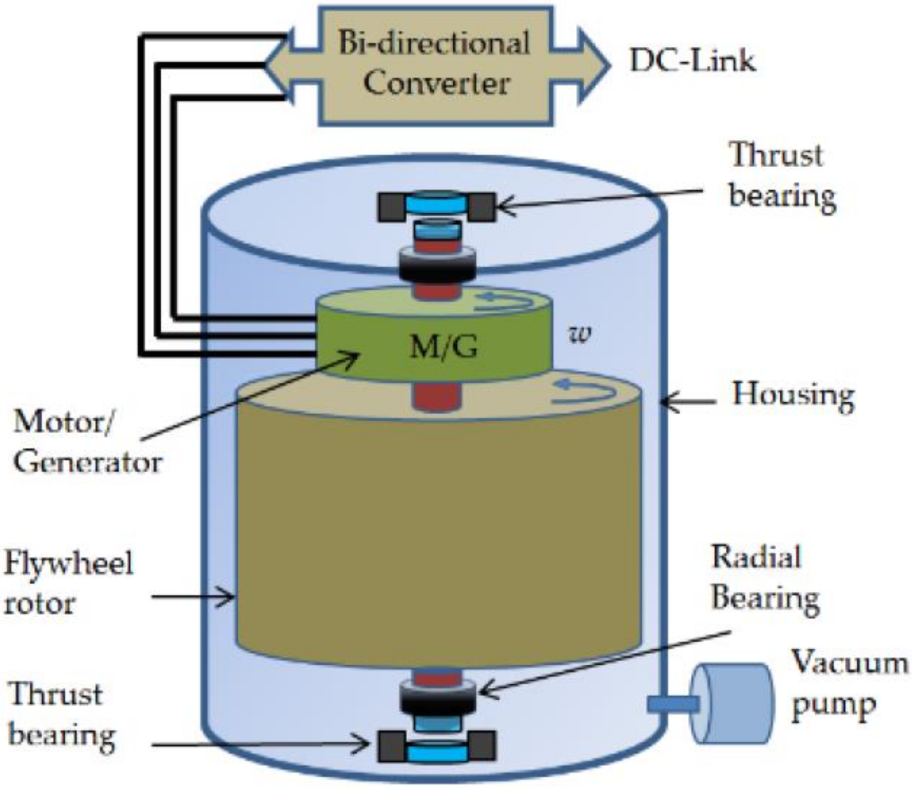

Figure 4. Structure and components of flywheel (Amiryar and Pullen, 2017)

2.1.2. Electrochemical energy storage

1) Secondary battery

Chemical energy contained in the active material is converted into electrical energy. A BESS (Figure 5) consists of a number of cells that can be connected in series or parallel, where first connection type change voltage with constant capacity, and second change capacity, but with constant voltage. Each cell contains two electrodes (anode and cathode) with electrolyte between them (Luo et al., 2015).

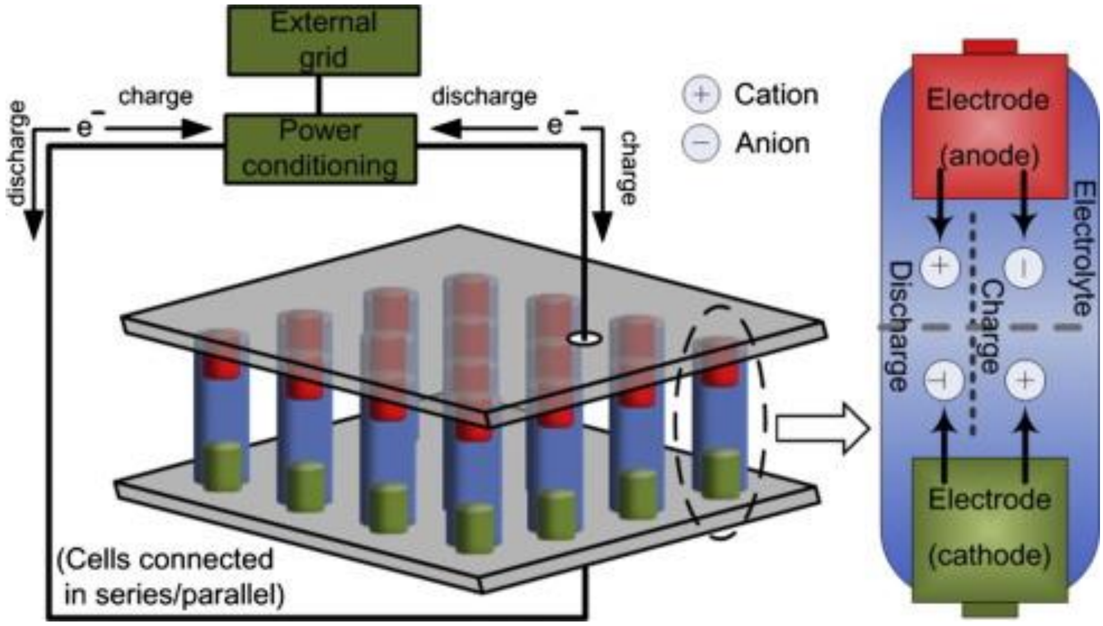

Figure 5. Schematic diagram of a battery energy storage system operation

2) Flow battery energy storage (FBES)

A FBES stores energy in two soluble redox couples contained in external liquid electrolyte tanks. The electrolytes is pumped from the tanks to the cell stack which consists of two electrolyte flow cells separated by ion selective membranes (Figure 6). The operation of FBES is based on reduction-oxidation reactions of the electrolyte solutions. During the charging phase, one electrolyte is oxidized at the anode and another electrolyte is reduced at the cathode, thereby the electrical energy is converted to the electrolyte chemical energy. During discharging the above process is reversed (Qi and Koenig, 2017).

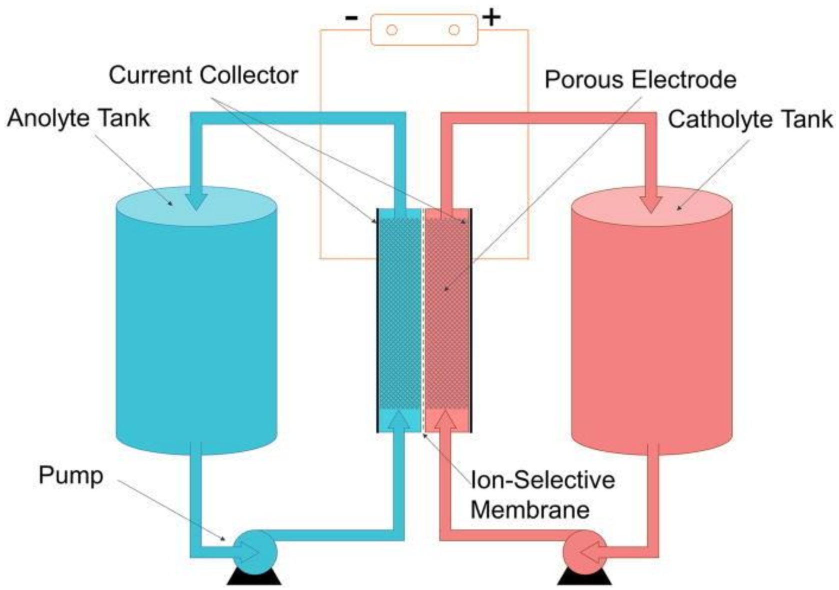

Figure 6. Schematic illustration of a redox flow battery (Qi and Koenig, 2017)

2.1.3. *Electrical energy storage*

1) Supercapacitor

Supercapacitors accumulate energy by electrostatic means, polarizing the electrolyte solution (Figure 7). There is no chemical reaction energy in the supercapacitor, during the accumulation of energy in the supercapacitor despite the fact that the supercapacitor is an electrochemical device. Supercapacitors can be charged and discharged thousands of times due to the high reversibility of the mechanism of energy storage. The supercapacitor is an electrochemical capacitor that has the ability to accumulate an extremely large amount of energy in relation to its size and in comparison with a conventional capacitor.

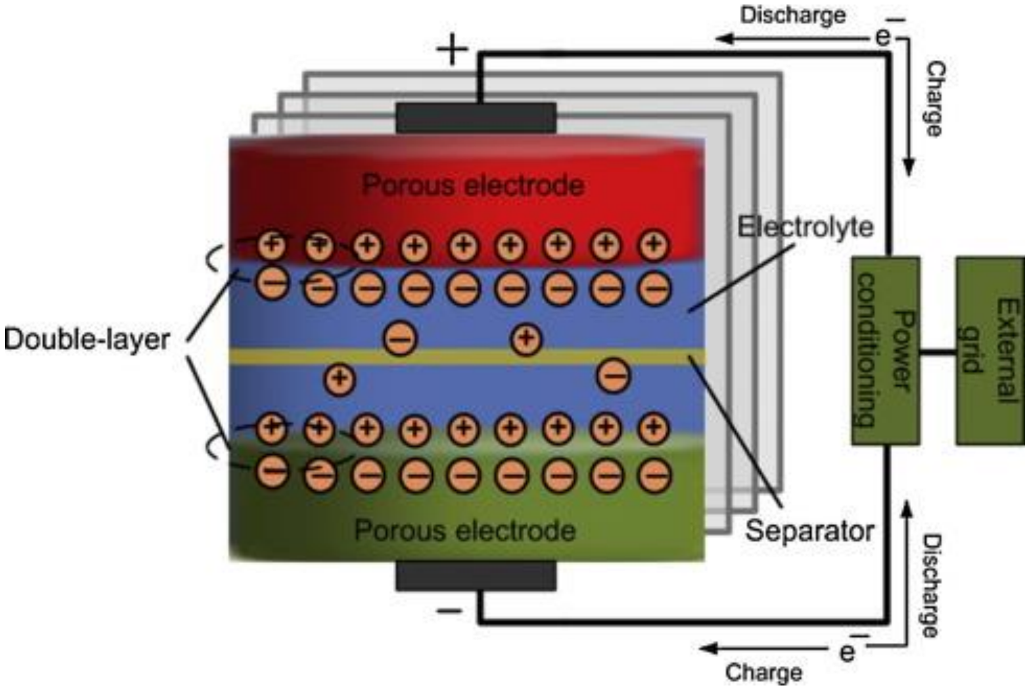

Figure 7. Schematic diagram of a supercapacitor system (Luo et al., 2015)

2) Superconducting magnetic energy storage (SMES)

There are 3 main components of SMES (Figure 8): a superconducting coil, a power conditioning subsystem, and refrigeration and vacuum subsystem. The SMES system stores electrical energy in the magnetic field produced by the Direct Current (DC) in the superconducting coil which has been cryogenically cooled to a temperature that below its superconducting critical temperature. Generally, when current passes through a coil, the electrical energy will be dissipated as heat due to the resistance of the wire. However, if the coil is made from a superconducting material, such as mercury or vanadium, under its superconducting state (normally at a very low temperature), zero resistance occurs and the electrical energy can be stored with almost no losses.

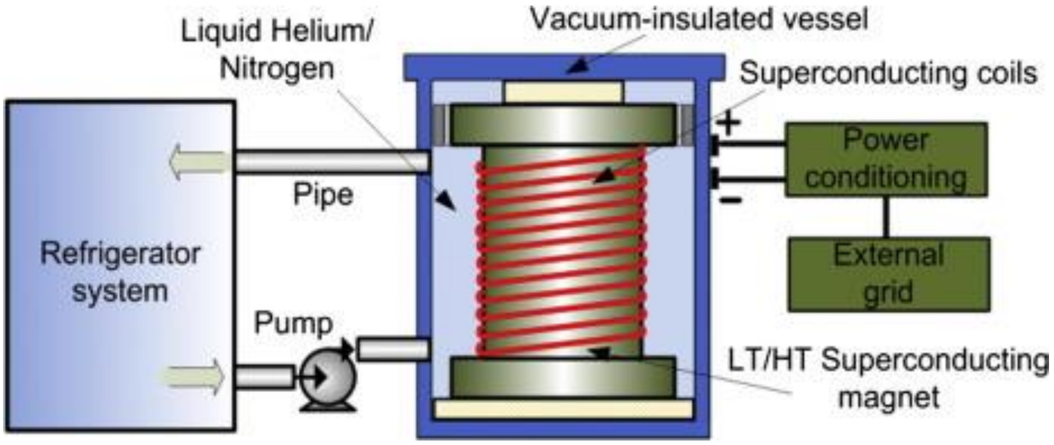

Figure 8. Schematic diagram of SMES system (Luo et al., 2015)

2.1.4. Thermal energy storage

1) Heat storage

There are three main types of thermal energy storage systems: sensible heat, latent heat, and thermo-chemical. The basic principle of all thermal energy storage systems is to store the excess energy in a system for use at a later time (Dincer, 2002).The 3 steps of heat storage cycle presented in figure 9: charging, storing, and discharging.

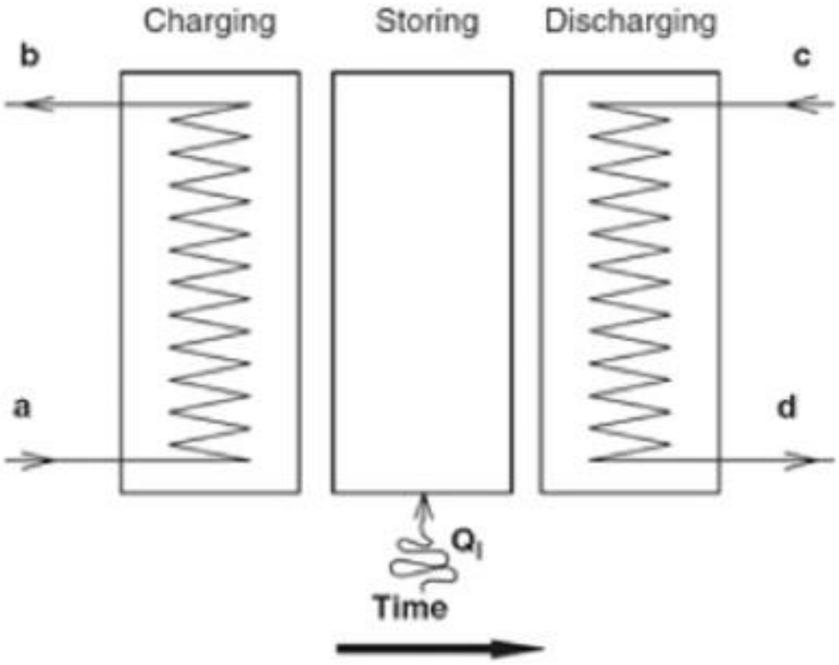

Figure 9. Basic principle of thermal energy storage system (Dincer, 2002)

- Sensible heat storage systems (Lefebvre, 2017)

The thermal energy is stored as an internal energy induced by temperature changes in the material. The energy, which is available as heat, is stored as a result of its isolation from its surroundings that can occur due to physical barriers present.

- Latent heat storage systems (Hyman, 2011)

Heat is absorbed or released due to changing the phase of a material at a constant temperature. For example, the transformation from gaseous, liquid, and solid states.

- Thermo-chemical energy storage (Abedin, 2011)

It includes thermo-chemical reactions and sorption processes, both of which obtain energy through a thermal supply. In thermo-chemical reactions, energy is stored through a reversible reaction and then recovered when the reaction is reversed.

2.2. Applications

Different sources that consider applications of energy storages suggest mostly the same classification. The applications differ by place in a grid where they are used: in generation, in transmission, in distribution, or at customer level (Table 1).

Table 1. Energy Storage segmentation (eera-set.eu, 2016)

Generation		**Transmission**	**Distribution**	**Customers Services**
Conventional	**Renewable**			
Black Start	Distribution Generation Flexibility	Participation to the primary frequency control	Capacity support	End – user peak shaving
Arbitrage	Capacity Firming	Participation to the secondary frequency control	Dynamic, local voltage control	Time - of- use energy cost management
Support to Conventional Generation	Limitation of Upstream Perturbation	Participation to the tertiary frequency control	Contingency grid support	Particular requirements in power quality
	Curtailment Minimization	Improvement of the frequency stability of weak grids	Intentional islanding	Continuity of energy supply
		Investment deferral	Reactive power compensation	Limitation of upstream disturbances
		Participation to angular stability	Distribution power quality	Compensation of the reactive power
			Limitation of upstream perturbations	

This work focuses on energy storages within centralized system with conventional generation only, where currently is lack of any RES that are connected to a grid. Thus it omits renewable-based power generation participation. Centralized system means parallel work of all united power systems (UPS) in the synchronous zone. Conventional generation includes thermal power plants (TPP), nuclear power plants (NPP) and hydro power plants (HPP).

Black start implies that energy storage is one of the solutions to reduce the downtime in the grid, as it can be used to energized distribution and transmission actives in power plants in order to bring power systems online after a serious failure in the grid. Many power plants require electricity in order to operate but plants with black start could pay for starting up power plants without the need of electricity. The figure 10 depicts the operation of energy storage power output and how the transmission line energizing process is connected to the grid via connecting the generator line to the grid with a nominal voltage to avoid transient process and unsuccessful starting of the generator (Táczi, 2016).

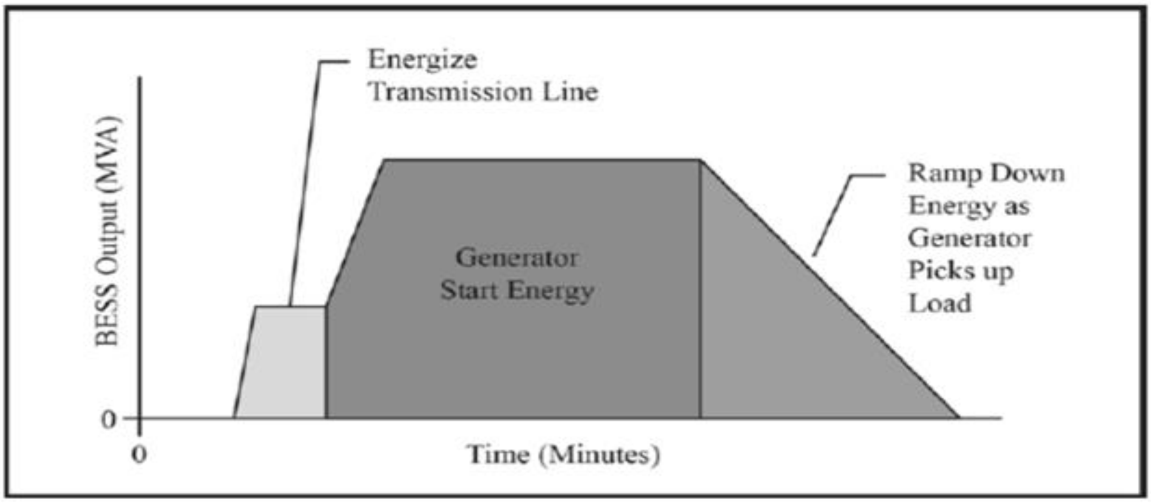

Figure 10. Black start service by energy service (Táczi, 2016)

Main function of storage supporting the conventional generation is an optimization of operation of existing power plant assets. It includes generator bridging that firm generator’s load while one is stopping and another is starting up. While generator is ramping, battery gives enough time to generator to handle changing of load.

Arbitraging electricity prices is one of the most common application for storage. Brijs (2016) defines arbitrage as a making profit by participant by means of buying commodity at relatively low price and selling this commodity when price is rather high. This definition includes initial investments, does not require to purchase and sale at the same time, and allows using different commodities (Brijs et al., 2016).

An arbitrage is carried due to difference of on-peak and off-peak hours prices within the framework of day-ahead market (DAM). Off-peak prices are typical when demand is low and sources of electricity with cheaper marginal price are used. During on-peak hours, the demand is the highest, thus, more expensive sources of electricity generation are needed. Using of arbitrage at grid level allow to shift peaks and adjust power price. Main principle of how energy storage works is presented in the Figure 11.

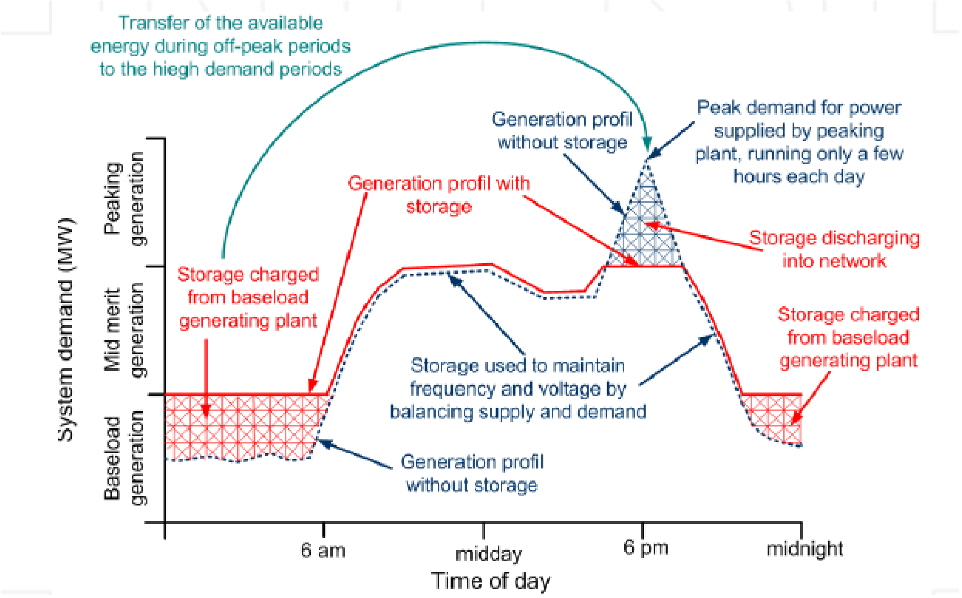

Figure 11. Fundamental idea of the energy storage (Hussein Ibrahim and Adrian Ilinca, 2013)

Each type of application requires definite characteristic and properties that are presented in the appendix 1. Moreover, different energy storage technologies are suitable for certain field of application because of their characteristics. Figure 12 presents the application range of different storage technology according to energy stored and power output.

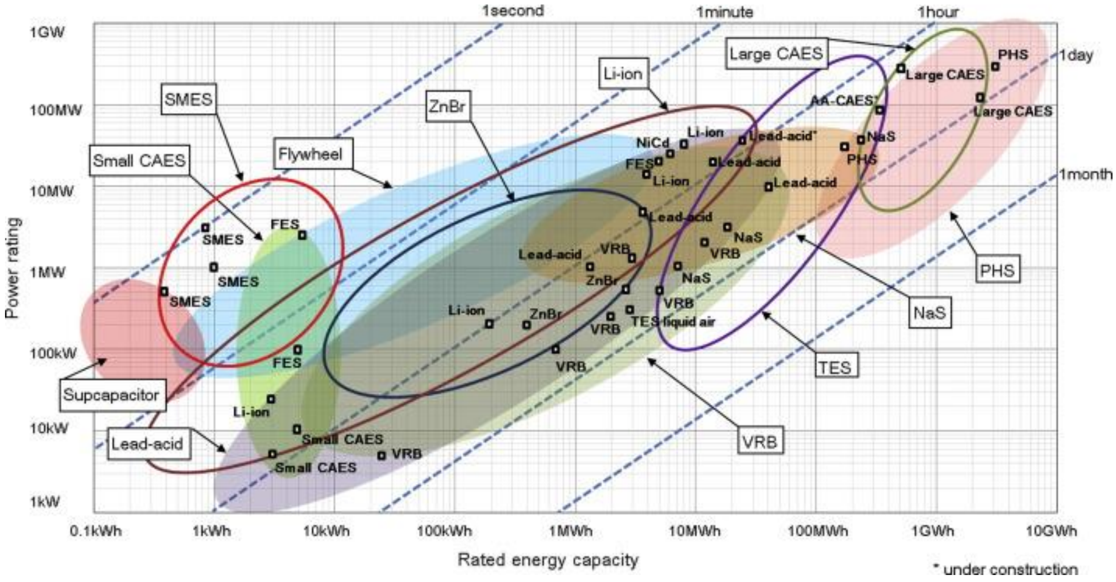

Figure 12. Fields of application of the different storage techniques according to stored energy and power output (Luo et al., 2015).

Link between storage application and technology can be seen in figure 13. From the figure it can be concluded that one technology is not suitable for all applications. For example, in load levelling the pumped hydro is the best solution. However for frequency fluctuations or peak shaving it makes no sense to use pumped hydro due to its size and response time. Thus, choice of the storage technology is very sophisticated and an approach varies because of place, goal etc. The various significant applications are discussed below.

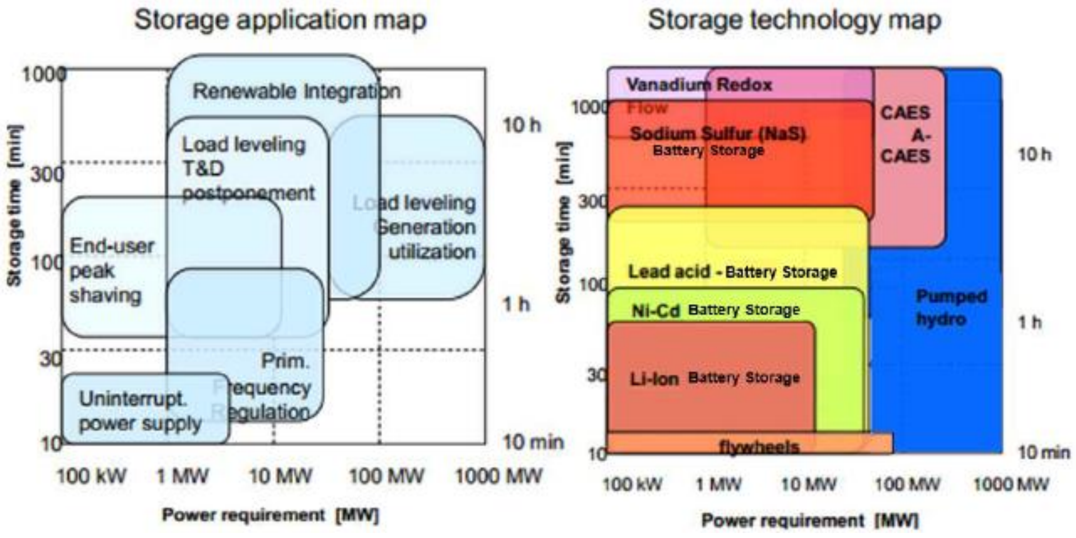

Figure 13. Mapping of energy storage attributes and suitability to various services (Carnegie et al., 2013)

Application of grid-scale storages in electric power engineering contribute to the next effects (Kononenko, 2014):

- Reducing loss of electricity;
- Extend the life-cycle of generating equipment by balancing the load curve and reducing the number of start-stop cycles;
- Increase of reliability and stability of power system operation;
- Reducing the load on electric networks;
- Incentive to develop alternative energy;
- Mitigating consumption peaks;
- Ensuring quality and reliability of electricity supply.

Also, the economic effect is achieved due to:

- Demand response, in case of end user active participation;

- Arbitrage effect due to differences in tariffs for the purchase of electricity during hours of minimum loads and its sale at peak hours.

In addition, so called spinning reserve capacity and electric power is provided in case of emergency outages in the network or power plants. Thus there is no need to maintain an expensive reserve of capacity at power stations or within network reserve. An additional economic effect is achieved due to:

- Ancillary services for frequency regulation;
- Maintenance of voltage levels in the installation sites;
- Creating of local smart grids.

This work concentrates on possibility of energy storage use in Russian wholesale electricity market now and in future in conditions of current model. Another main issue is dedicated to a tendency of price and demand changing during on and off-peak hours.

Choice of application for energy storage is strongly related to the place in the grid where it will be connected. Electricity grid can be divided into 4 levels: high- and extra- high voltage (HV and XHV), medium voltage (MV) and low voltage (LV).Table 2 shows that secondary control reserve (SCR), tertiary control reserve (TCR) and energy trading can be provided by BESS successfully and sustainably in all grid levels (Müller et al., 2017).

Table 2. Evaluation of technical grid level readiness (more stars equal higher readiness) for providing a certain application with BESS under constrains of BESS sizing and cost (Müller et al., 2017)

Grid level	XHV	HV	MV	LV
GRID	*	*	**	***
SELF	*	*	*	***
Peak-shaving	*	*	**	***
Uninterrupted power supply	*	*	**	***
PCR	***	***	***	**
SCR	***	***	***	***
TCR	***	***	***	***
Islands	*	*	***	***
Trading	***	***	***	***
Black-Start	***	***	**	*

Earlier, battery energy storages were related to small-scale technologies due to their properties and price. However, such situation was overcome thanks to growing market of smart phones, electric vehicles, and other devices requiring longer life. Nevertheless, scale of batteries still depends on their application. Small and large-scale application of energy storage is distinguish by place of usage. Thus, small scale technologies such as batteries relate to residential and industrial customers. While power suppliers predominantly use pumped hydro and compressed air energy storage (CAES) that are parts of large scale system (Berrada et al., 2017).

As a rule, large scale usage has higher number of charge and discharge cycles, so a lifespan is shorter than for small scale application. A benefit of Li-ion batteries is an ability of storing energy over a longer amount of full cycles which has a significant value at grid level (Oldenmenger, 2013).

This work considers usage of batteries at large-scale level. It relates to storages services that influence the whole centralized grid sector.

2.3. Overview of current situation

Nowadays there are a lot of possible storage solutions in the market. Many factors create difference in their performance. Such factors are technology, manufacture, an application and etc. Discharge duration differs considerably from milliseconds to hours. Energy storages are significant component in development energy system. It has started to increase in value with the increasing amount of RES in power grids. Modeling of smart grids cannot be fully performed without participation of storages. Further development of intermittent energy sources is restricted by percentage of energy storages in network (Hussein Ibrahim and Adrian Ilinca, 2013).

Most mature mechanical energy storage technology is a PHS. Table 3 presents main characteristics of PHS. Pumped hydro storage has the highest installed capacity and the number of installations continues to grow worldwide (Figure 14). The technology is proven, and has showed its feasibility. Unfortunately, for its operation and deployment the necessary conditions are needed. This factor is height difference between the two reservoirs. Another challenge is densely populated areas, where due to communities PHS cannot be installed. Russian experience shows that due to high investment costs and long construction period PHS has not been built (Lengaes.rushydro.ru, 2017).

Table 3. Pumped Hydro characteristics Summary (ecofys.com, 2014)

Technology	Maturity	Cost ($/kW)	Cost ($/kWh)	Efficiency	Cycle Limited	Response Time
Pumped Hydro	Mature	1500-2700	138-338	80-82	No	Second to minutes

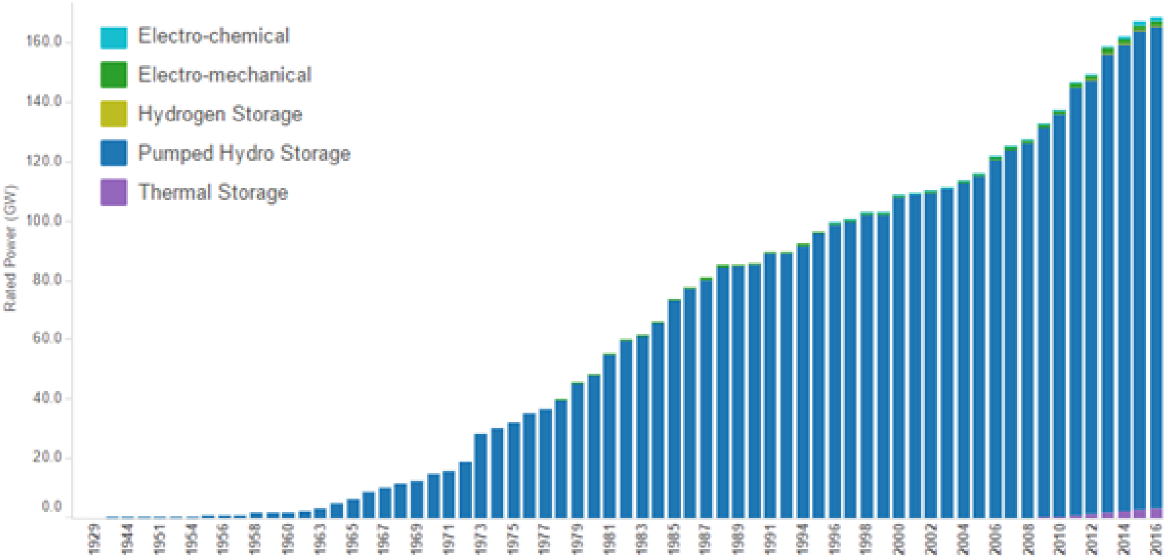

Figure 14. Global project storage installations over time (Energystorageexchange.org, 2017)

In addition to PHS there are two energy storage technologies (Figure 15). Electrochemical has the highest number of currently under development projects. A leader of electro-chemical storages is li-ion battery.

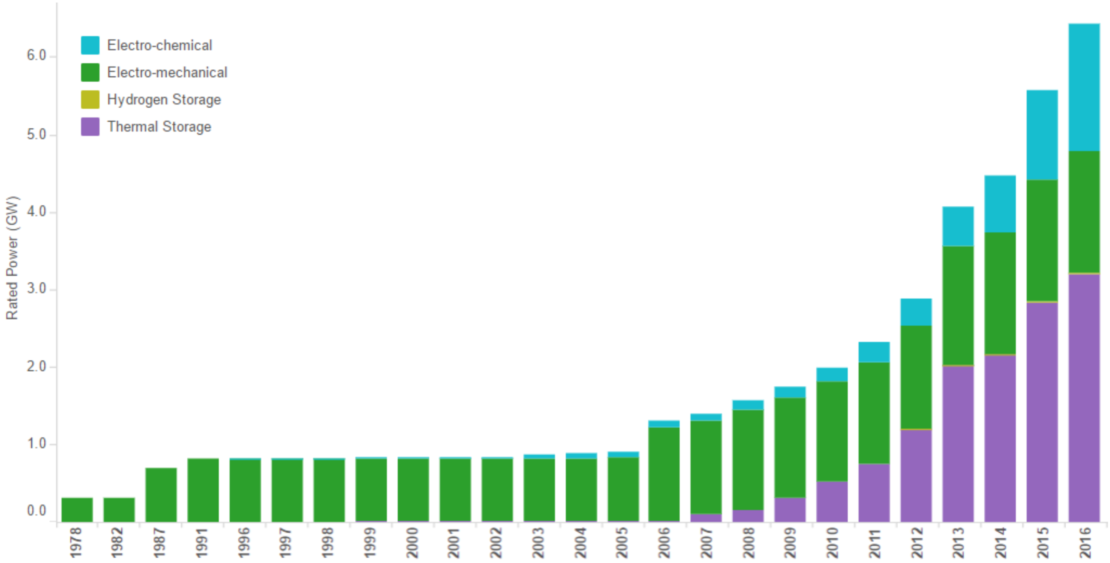

Figure 15. Global Project storage installation without PHS (Energystorageexchange.org, 2017)

When comparing the number of on-going projects, the electro-chemical storage has been more popular compared to other applications. Table 4 presents all operational projects with their total rated power. Number of projects show that hydrogen storage and liquid air energy storage are still far from commercialisation.

Table 4. Technology Types (Energystorageexchange.org, 2017)

Technology Type	Operating storage systems	Rated Power (MW)
Electro-chemical	985	3100
Pumped Hydro Storage	352	183800
Thermal Storage	206	3622
Electro-mechanical	70	2616
Hydrogen Storage	13	18
Liquid air energy storage	2	5

Main advantages of electric batteries are: fuel flexibility, environmental benefits (depending on type), possibility to install either inside a building or next to facilities fast response to load changes, system stability increase, low standby losses and high efficiency. However, the disadvantages include: low energy densities, small power capacities, high maintenance costs (in large scale facilities), short life cycle and most batteries contain toxic materials (Rautiainen, 2016), (Chen, 2009).

The third storage type is a thermal energy storage system. Thermal storages are like batteries, only instead of storing electricity, they store heat or cold in a tank. They could easily be used to benefit from the waste heat generated in the industry. Unfortunately, they are still suffering from high investment costs, large space requirements and low efficiencies, that makes many thermal storages unprofitable (IRENA, 2013).

Some technologies have prospects for development in future that correlate with R&D and mass production, while some have already reached their potential and have not so much opportunity for declining prices in the future. Figure 16 presents technical maturity of Electrical Energy Storage (EES) systems.

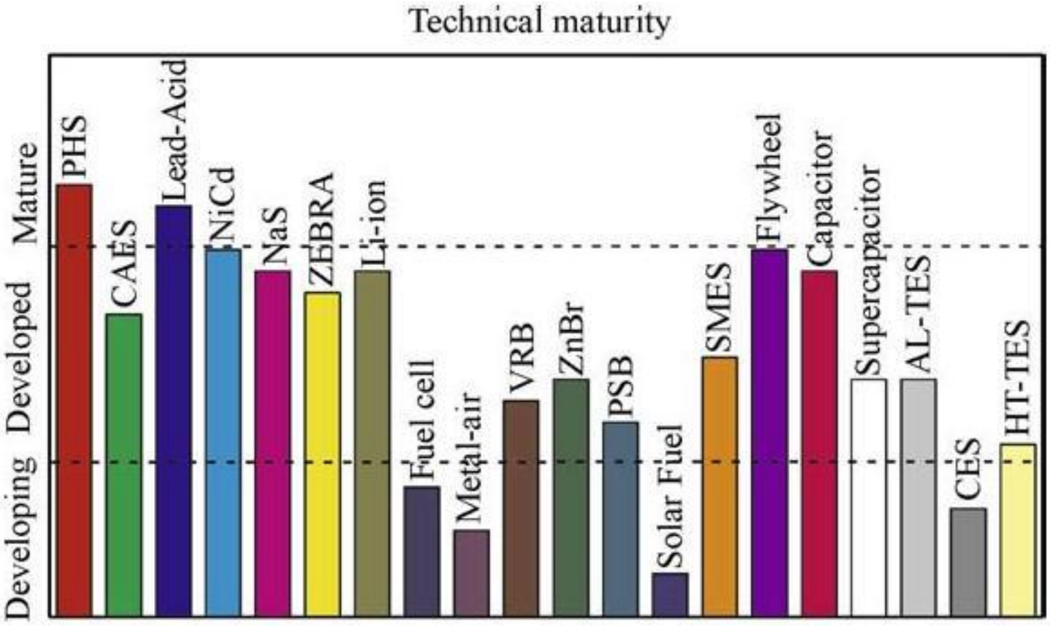

Figure 16. Technical maturity of EES system (Chen et al., 2009)

Most of the electro-chemical projects are battery energy storage systems. They are directly rechargeable batteries. Their growth is primarily caused by plummeting prices and improved properties. In addition, the increasing amount of RES installations, particularly wind power, in the electricity network and development of the concept of smart grids contribute to the new age of battery usage (IRENA, 2013).

Li-ion batteries have the largest share among new storage projects and installations. The batteries, known to the public mainly as cell phone batteries, are used in smaller scale applications. Batteries have experienced an intense price decrease during last years and according to the forecasts (Nykvist and Nilsson, 2015) this trend will continue in the future. As a counterpart to the Li-ion battery, the lead-acid battery technologies can be applied for much larger scale energy storage in stationary applications and they are already commercially available (Rautiainen, 2016).

The main characteristics of flow batteries are high storage capability, long duration, fast response time and low efficiencies. The flow batteries have a possibility to change charge and discharge modes in 1 millisecond. The energy required to circulate the electrolyte and losses caused by the chemical reactions lead to low efficiency. One of the advantages is that the system does not have any self-discharge since electrolytes are stored separately and cannot interact with each other. It allows the flow battery to remain competitive and contribute to the future power systems (Divya, 2009).

Figure 17 shows current and projected prices for different battery types. In this projection, it can be clearly seen how li-ion batteries will dominate the future market and how the flow batteries can stay relevant due to the high storage capacity. The main advantage of sodium based battery options is that they can be stored with zero charge compared to li-ion batteries that require a minimum of 20 % charge during storage. However, sodium battery is lacking in other properties compared to the different options and are not expected to be in common usage in the future (IRENA, 2015).

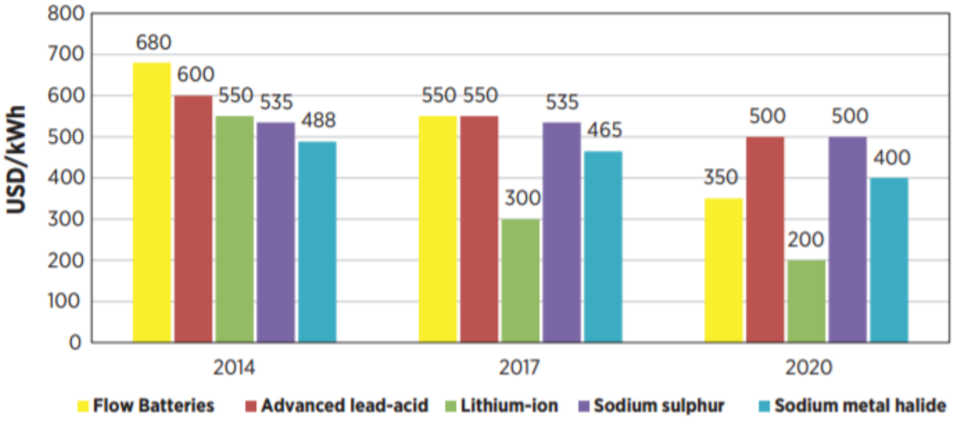

Figure 17. Lowest current and projected battery cell price for utility-scale application (IRENA, 2015)

There are different possible solutions within Li-ion batteries. They vary as in technology and application field as in price (Figure 18). Each technology has specific pros and cons. For instance, Lithium Cobalt Oxide (LCO) battery has advantages in specific energy and relatively low cost, on the other hand it has such disadvantages as limited lifespan and dangerous chemistry. As known, batteries serve for different aspects of human life, so an application field varies from low power application to back-up of a grid. While Lithium Nickel Cobalt Aluminium batteries find their application in electric vehicles (Tesla), power tools, etc., but such type as lithium iron phosphate (LFP or LiFePO4) is more suitable for renewable energy storage, stationary batteries or high power application. The price of various type of technology is different due to cathode material cost, inherent characteristics, level of development in the field and etc.

Specific energy and power density has important difference. Energy is the amount of charge in a battery, which is usually expressed as Watt hours (Wh). On the other hand, power is an instantaneous measure of how much energy flows through the circuit and is usually expressed as Watts (W). The main difficulty regarding power value is that it does not tell reader for how long the battery can be used. Specific energy or energy density indicates the nominal battery’s energy per unit of mass (Wh/kg). Thus, if a system has a high energy density then it is able to store a lot of energy in a small amount of volume. Power density illustrates the maximum power per unit of volume (W/l), which shows how rapidly energy can be delivered for a given volume. Charge and discharge rates of a battery are governed by C-rates. The capacity of a battery is commonly rated at 1C, meaning that a fully charged battery rated at 1Ah should provide 1A for one hour. It must be mentioned that power density shows the power at 1C per unit of volume and that batteries do not usually operate at that speed (Layton, 2008).

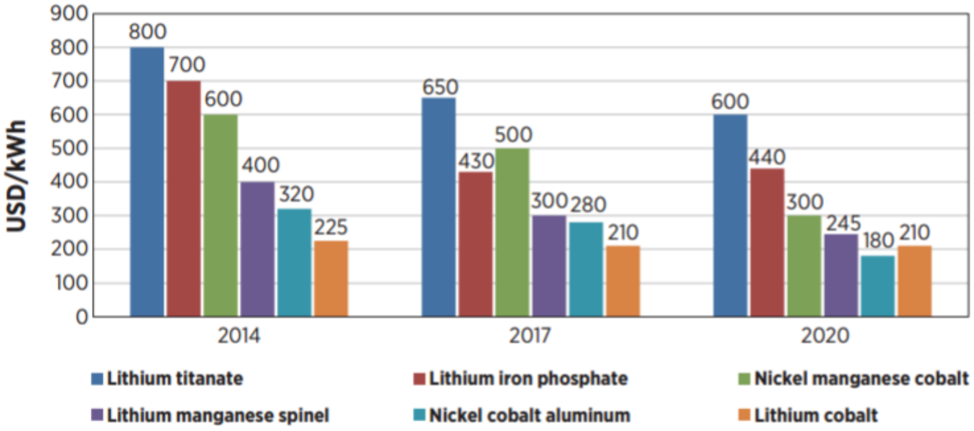

Figure 18. Lowest cell price of li-ion chemistries for utility-scale applications (IRENA, 2015)

2.4. Challenges

The conventional power system has large amounts of generating sources whose generation could be easily varied to match the load demand. Also most of these systems operate in an interconnected manner and the power from generators in other areas can be used to balance the load demand. In such a situation it is very difficult to justify the economic gains obtained in using storage technologies.

Deployment of storages has three main barriers that have to be overcome. First factor is a cost competitiveness analysis of energy storage technology that includes also manufacturing and grid integration. To obtain best solution it is required to consider life-cycle cost as well as performance for energy storage technology, namely round-trip efficiency, energy density, cycle life. Some features are presented in the appendix 2. However, prices for different technologies have already changed since the year of the publication. Second challenge is a technical one. It includes factors for ensuring user's confidence such as safety validation, reliability and performance of the storages. Third is a non-discriminatory regulatory and market environment. Value propositions for grid storage require a level playing field market between the different service providers (storage, demand response, generation, grid reinforcement, etc.). (Latour, 2015)

To political barrier is related a situation that energy storage is not schematically compensated and this is one of the main barriers as some of the stakeholders associated in the electricity market are part of the regulated market such as transmission system operator and distribution system operator while the others are part of the deregulated market. This division in bodies has reduced the acceptability of energy storage in meeting the supply and demand response.

Location is another barrier associated with the promotion of energy storage. Basically it related to PHS. It is one of the key factors that customers consider before installing an energy storage system in support to the grid connection, for balancing supply and demand at all time. A closer location of the storage system to the existing grid would strengthen the grid and also increase the revenues. Otherwise owner should ensure connection to the grid. However suitable location should satisfy needs and requirements of all stakeholders.

3. PROFILE OF RUSSIAN WHOLESALE ELECTRICITY MARKET

According Federal Law No.35-FZ of March 23, 2003 "On the Electric Power Industry" - “The wholesale electricity and capacity market (WECM), is the field of circulation of special commodities - electricity and capacity - within the United Power System of Russia within the boundaries of the common economic space of the Russian Federation.” (The State Duma, 2003)

Participants of the wholesale market are suppliers (generating companies) and buyers (energy sales organizations, large consumers of electricity, and guaranteeing suppliers) of electric energy and capacity. Also among other market subjects there are dispatching department, network organizations, and regulator of rules (The State Duma, 2003).

The design scheme of the energy system includes a set of load and consumption nodes connected by lines simulating power lines. Different price of electricity is established for each nodes of the system based on generators offers and suppliers bids. In May 2017, there are 9164 nodes in design model operated by system operator (so-ups.ru, 2017).

The activity of all entities, price forming, terms of interaction with counterparties are under the government’s control. The list of technological infrastructure is following:

- Federal Grid Company United Energy System (OJSC FGC UES) is the operator and manager of Russia’s unified electricity transmission grid system, including high voltage transmission lines, and it holds the status of a natural monopoly controlled by ROSSETI. FGC UES was created for grid maintenance and reinforcement, provision of the unity for technological control and government policy realization in power industry;
- PJSC ROSSETI is the operator of energy grids in Russia (controlled by the government, namely Federal Agency for State Property Management of the Russian Federation);
- OJSC “System operator of the unified power system” (SO UPS) is a specialized organization, solely performing centralized operational dispatch management of the Unified Energy System of Russia;

- NP “Market Council” – non-commercial organization that set the rules for all the participants of Russia’s energy market and controls their relationships;
- OJSC "Trading System Administrator" is the organizer of electricity trading on the wholesale market. It is 100% subsidiary of NP Market Council.
- CJSC "Centre of Financial Settlements"(CFS) – ensure a financial part of wholesale market between its participants. CFS is a subsidiary of Trading System Administrator and NP Market Council;
- Interregional distribution grid companies (IDGCs) – is an organization that realize transmission between regions.

Russian wholesale market is separated into UPS. According to GOST 21027-75 – “UPS is an aggregation of several power systems, united by a common operating mode, which has a general dispatching control as the highest level of control in relation to the dispatching offices of its power systems” (State Committee of Standards of the Council of Ministers of the USSR, 1975). Seven UPS are allotted within the electricity market of Russia. Each of which corresponds to the operating area of one of the United Dispatch Controls and one of the Trunk Power Grids.

UPS Center, which is a part of Europe price zone, is investigated in this dissertation. Total capacity of UPS Center is 52878, 57 MW (according to 01.01.2017) (So-ups.ru, 2017). TPP produce about 55-65 % of the generation in this zone. Moreover during the peak hours they increase their generation. NPP provide approximately 30-40% of generated power and form base load. They should work with constant generation to ensure the best capacity factor. Third source for electricity generation is hydro power. The share of hydro is pretty small (1-5 %) with increasing output during peak hours (Atsenergo.ru, 2017).

There are three sectors of physical electricity trading:

- Long-term bilateral agreements (regulated contracts);
- Day-a-head market. Day-ahead competitive auction of power for delivery the next day;
- Balancing market (BM). SO UPS provide operation each 3 hours before the delivery. There are final adjustments that are made to ensure the appropriate frequency level in the grid and security of supply.

Most part of electricity trading is carried out in DAM. For each hour, the equilibrium price for electricity is determined on the basis of price bids of suppliers and price bids of electricity buyers within relevant price zone, taking into account the need to ensure the flow of electricity.

There are 2 different pricing zones (1 and 2 in figure 19), non-pricing zones (3 and 4 in figure 19) and isolated zone (5 in figure 19) where competition is impossible. Retail market tariffs are regulated only within non-pricing zone, where the government sets limits for maximum and minimum price.

Figure 19. Zones of Russian electricity market (Energo-consultant.ru, 2016)

Wholesale market consists of two price zones. First price zone includes European part of Russia and Ural. Second price zone includes Siberia. In non-price zone electricity is sold at regulated tariffs that are observed by Federal Antimonopoly Service (FAS) (FAS, 2017). There are Arkhangelskaya oblast, Kaliningradskaya oblast, Komi Republic, Far East regions and other isolated regions, where a competition between suppliers is impossible. Thus, electricity is also sold at regulated tariffs in this regions.

According to Russian federal law (The State Duma, 2003), it is prohibited to combine activities of electricity transmission and dispatching administration that are natural monopolies, along with generation, purchase and sale of electricity which recognized as competitive, within the boundaries of one pricing zone.

There is a support mechanism for generating facilities based on renewable energy sources technologies. Thus, government encourages generating companies by establishing the premium added to equilibrium price on wholesale market. Moreover, the law establishes the minimum obligatory volume of RES-based electricity for purchasers on wholesale market. Such support should lead to higher deployment of RES in the future. (np-sr.ru, 2017)

Centralized generation is inherent within wholesale market. Mainly, TPP provides regulation of frequency by decreasing or increasing their power output. Power generators should be able to perform two important functions in addition to the basic generation function (iec, 2011). These are ability to generate kilowatt of power when necessary and frequency control. Therefore, power plant has to be equipped with different capacity facilities to participate in other markets. For second function plant is responsible for following minute-by-minute and second-by-second fluctuations in demand.

3.1. Capacity markets

Capacity market in Russia was created for ensuring in the short, medium, and long term of such a volume of generating capacity, which is sufficient to cover the entire electricity consumption in the electric power system at any time with the appropriate parameters of reliability and quality (Malyshev, 2013). Among the main mechanisms of selling capacity on the wholesale market are (np-sr.ru, 2017):

- Competitive Capacity Selection (CCS) for the competition of old generators;
- Capacity Delivery Agreements (CDA) for new TPP. It ensures the compensation of capital expenditures and pre-determined operating costs for 10 years;
- Long-Term Agreements (LTA) for new HPP and NPP;
- Must-run generators.

Capacity market should consider differences in electricity consumption that varied during the day as well as in dependence on season of the year. Thus, generators must be able to cover all peaks during the year. However peaks are rare and plant's equipment stay without work. That reflects in plant money losses as well as customers bill. Another problem is that a majority of conventional power plants operates at a loss during the summer times because there is no need in heating that composes significant value.

Furthermore, as a rule, power plants have a big share of inefficient equipment which is basically participating in capacity market. Also, for contingency regulation during peak hours, sources with the higher marginal price are operated. Currently, demand's covering realizes according consequent load of generating equipment in order of price bid's rising. That means that covering of consumption peaks carried out by the most expensive and at the same time less effective generation.

4. USING BESS IN LARGE-SCALE MARKET AND ITS IMPACT

Different reports, raising the topics of energy arbitrage, omit the fact that storages influence the equilibrium price (Corey, Iannucci and Eyer, 2004), (Mohd et al., 2008). The idea is that while charging in off-peak hours storages get low price, thereby, acting as an additional demand and increasing market price. Then, it replaces sources with inefficient and expensive marginal prices during on-peak hours, thus decreasing equilibrium price.

Marginal pricing (Figure 20) handles the merit order of generation, thus the production with lowest marginal cost is the first to be put in order while the production with highest marginal cost goes the last, thereby determining the price of electricity. Marginal price is an intersection of demand and supply curves. Demand curve is buyer's willingness to pay for commodity based on their power need and supply obligations, forecast etc. Supply curve is producer's marginal price based on type of generation, efficiency, risk management etc.

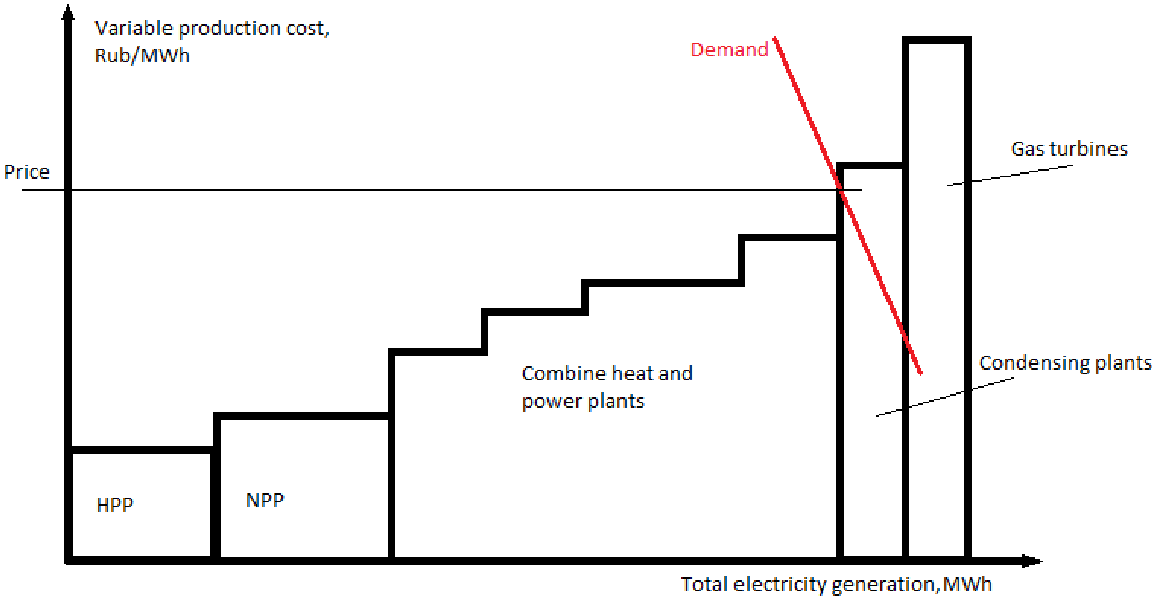

Figure 20. Marginal pricing

Main goal of the model is an evaluation of an influence of batteries implemented on the electricity market by calculating an economic effect. Thereby, it shows an opportunity of improving the grid with new component that promotes many technical and economic effects described earlier. The model is based on assumption of linear correlation between equilibrium price and demand in DAM. Feasibility of storages is determined by application of the arbitrage mechanism.

For the beginning, the option without price impact is estimated. For this work, 2016 year's data is used. Demand and price were assumed from the volume of purchase and equilibrium price of purchasing electricity, correspondingly (Atsenergo.ru, 2017). At first data of demand and price for the year separately for each month were analyzed. For each hour of the month mean average demand and price were defined. Further, graphs of price as a function of demand were drafted based on received values. Finally, a linear equation was found for every month and new price as a function of real demand was defined.

The economic benefits caused by demand shifting are evaluated by calculating the cash flow and the NPV of the investment. The first case is calculated after obtaining all necessary data. This basic option consider only highest and lowest price of each month for calculating average cash flow (no impact of arbitrage). It shows the maximum theoretical profit. However the price variations during separate day are different and that factor influence to the final revenues for battery's owner.

$$Cash\,flow_{month} = (P_{on-peak} - P_{off-peak}/\eta) \cdot Q_{energy} \cdot N_d \tag{1}$$

$$Cash\,flow_{year} = \sum\nolimits_{n=12} Cash\,flow_{month} \tag{2}$$

Where Q_{energy} – amount of energy (dis)charged by batteries;

N_d – number of days during the month;

η – efficiency of the battery;

P on/off peak – price during the hour with highest/lowest demand;

n – number of months.

Capital cost comprises not only energy component but a power constituent (Graditi et al., 2016). Generally, total capital cost includes the per-unit-energy capacity, per unit power capacity, power conversion system (PCS), and balance-of-plant (BOP) costs. The PCS costs relates for all the components linking the storage device to the power grid including control systems, power conditioning equipment, transformers, power lines, system isolation equipment, and safety sensors. The BOP costs encompass construction and engineering costs, land, access routes, permits, taxes, and fees. Thus, the total BESS cost is defined as:

$$C_{tot} = C_{stor}^{unit} C_{BESS} + C_{PCS}^{unit} P_{BESS} + C_{BOP}^{unit} P_{BESS} \tag{3}$$

Where C_{stor}^{unit} - the per unit costs of the storage;

C_{PCS}^{unit}- the per unit costs of the power conversion system;

C_{BOP}^{unit}- the per unit costs of the balance of plant;

C_{BESS} – the energy capacity rating of BESS (in kWh);

P_{BESS} – the power rating of BESS (in kW).

A calculation of a net present value is an objective of the thesis. NPV shows whether it is profitable or not to invest in integrating electrochemical batteries in Russian wholesale market (Equation 4).

$$NPV = \sum_{t=1}^{N} \frac{Cash\ flow_{year}}{(1+j)^t} - C_{tot} \tag{4}$$

Where $j - discount\ rate$;

$t - year$;

N – number of years.

The second case retains the structure of the first one, but it is more comprehensive. The basis of the second case is a condition that model takes into account change of the equilibrium price in wholesale market during peak and off-peak hours depending on amount of batteries operating within zone.

Draft of supply and demand curves with and without batteries can be found in the Figures below where the process during batteries supply electricity to network is called the generation mode (Figure 21). Demand is assumed to be constant when a supply changes from initial condition (s1 in the figure) to the state with batteries (s2) according amount of batteries. Respectively, it is assumed that a presence of batteries reduce a level of peak price from current state - P1 to P2 with batteries.

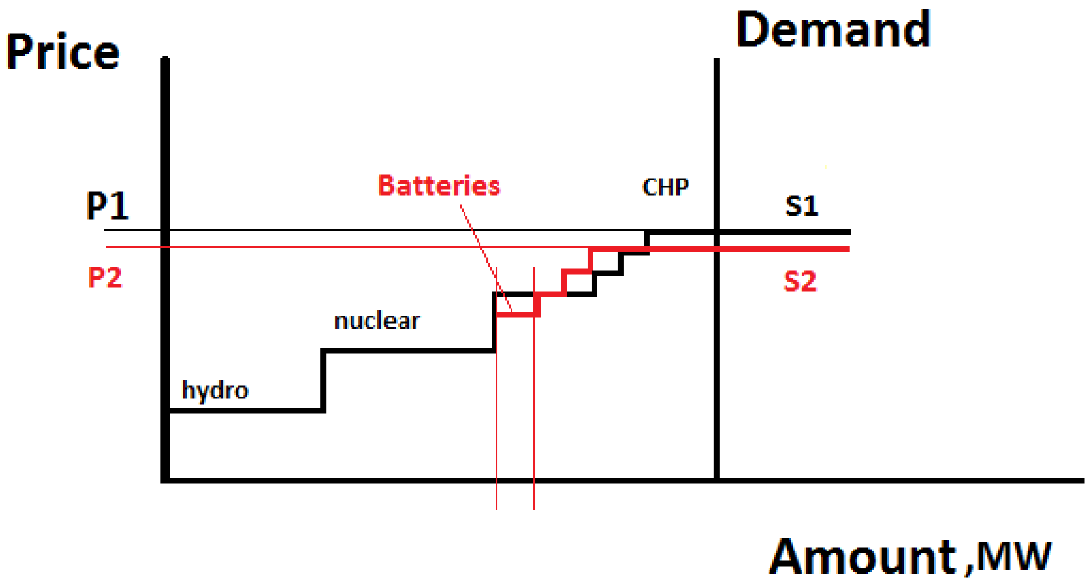

Figure 21. Generation mode

Opposite situation happens while the batteries are being charged. Demand increase from point D1 to D2 and hence price on a market goes up. In the figure 22, so called consumption mode is illustrated. Charge of batteries happens during off-peak hours, where price rising from P1 to P2.

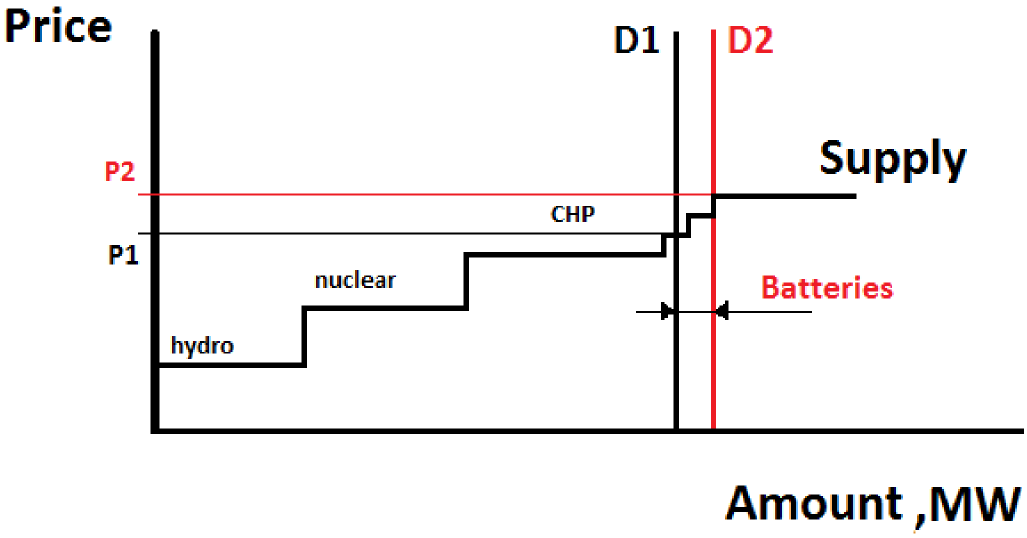

Figure 22. Consumption mode

In the present work, the important place takes defining of charged and discharged energy or defining the battery capacity. For this purpose, at first, the maximum hour demand through the year was found. Amount of energy capacity was then set as a percentage of maximum needed capacity during the year. Sum of capacity was distributed equally between hours with lowest prices – for charging, and between peak hours – for discharging (Figure 23).

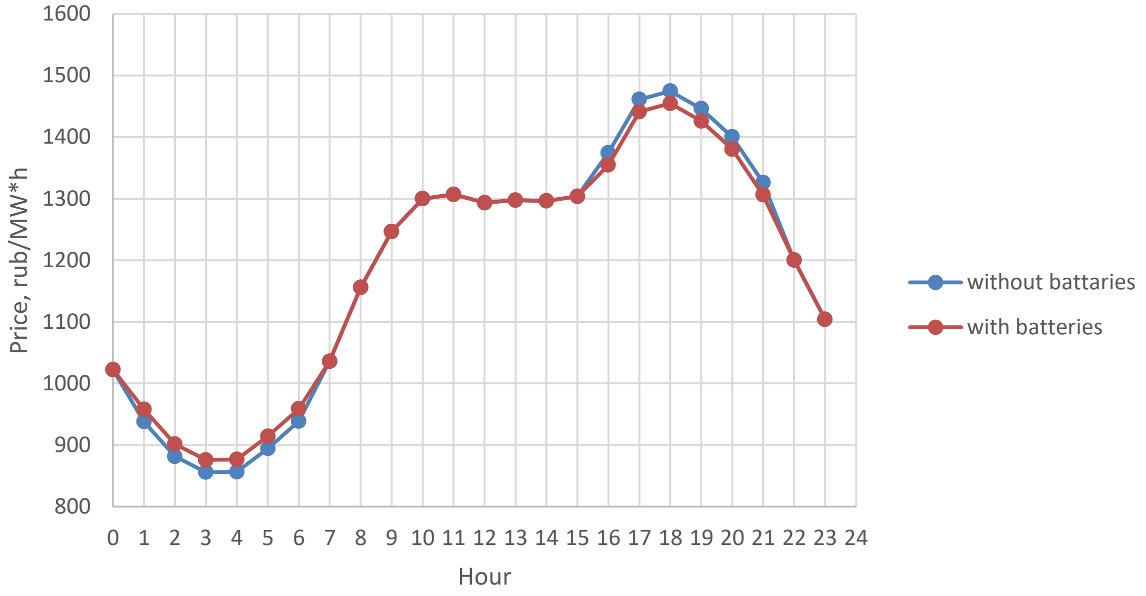

Figure 23. Price as a function of time (January)

$$Battery\ capacity_{hour} = \frac{Amount\ of\ batteries \cdot DOD \cdot \max(\max Demand_{month})}{number\ of\ hours} [MW * h] \qquad (5)$$

Where DOD – depth of discharge.

After a new level of generation is obtained, the higher volume during off-peak hours leads to the price increase. Thus, the surplus should be added to output that was before (new output) (Figure 24). Hour price goes up due to surplus volume is distributed between generators with highest marginal price.

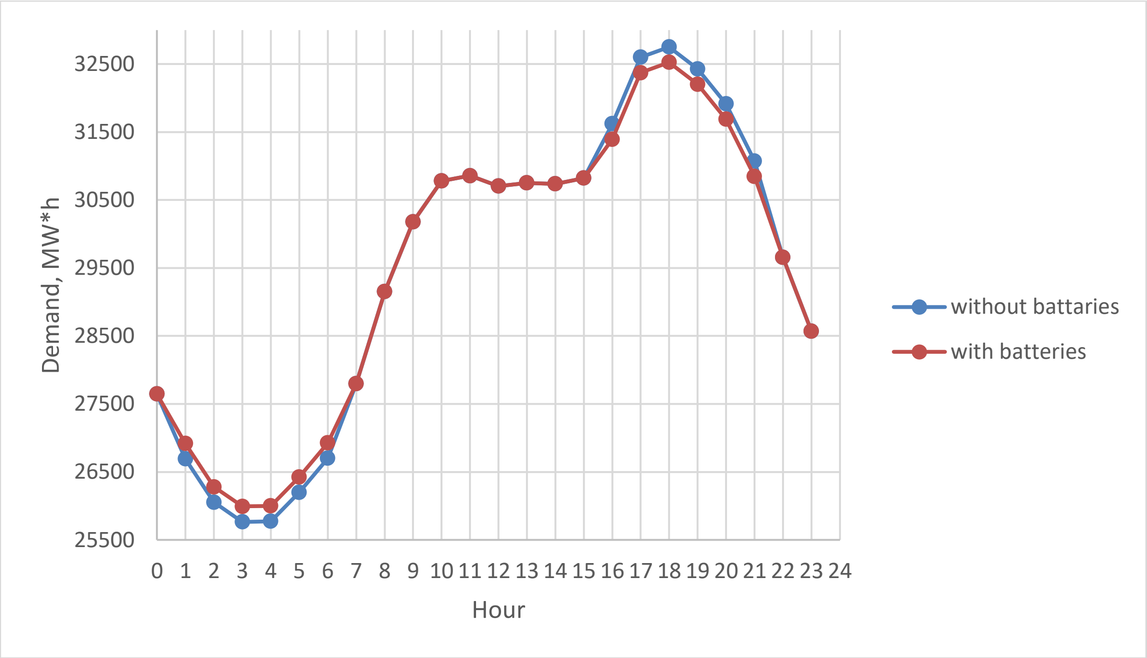

Figure 24. Demand as a function of time (January)

Depth of discharge (DOD) indicates the amount of battery's capacity that has been utilized. Mainly, this is expressed as a percentage of a battery's full energy capacity. The relation between discharge and lifetime is opposite, the deeper a battery's discharge, the shorter the lifetime. This fact is true for some cell-based batteries because of cell degradation, such as lead-acid and li-ion. For instance, if a battery discharges 20% of its full energy capacity, 80% of the full capacity remains unused. Thereby, it corresponds to 20% DOD. This battery is capable of fulfilling more charging cycle than a battery cycle at deep charge. Figure 25 depicts the depth of discharge versus number of cycles (Grothoff, J.M., 2015.)

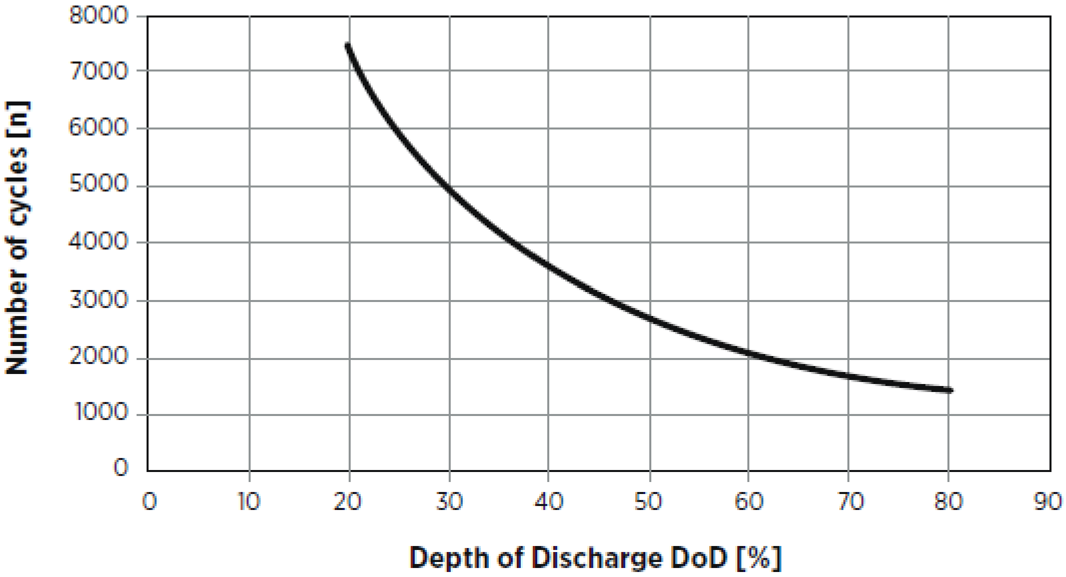

Figure 25. Depth of discharge versus cycle life (lead-acid battery) (Grothoff, J.M., 2015.)

Then a battery volume was summarized with previous demand to establish a new demand curve with batteries for each hour. After that, new price was obtained based on new demand and corresponding equations for price dependency.

$$D_{with\ batteries} = Demand \pm Battery\ capacity \tag{6}$$

$$P_t = A + B * (D_t) \tag{7}$$

Where + is for charging process;

- is for discharging process;

A, B – empirical coefficients;

t – hour of the day (0-23);

D – new demand with batteries;

P – price.

After a new price is defined arbitrage profit/loss for BESS owner can be calculated for each hour separately:

$$Profit/loss = Purchase\ price * (\pm)Battery\_Volume\ [rub] \tag{8}$$

Where + is in generation mode;

- is in consumption mode.

5.1. Assumptions

Assumptions are playing a crucial role in this model due to complexity of market infrastructure and number of influencing factors.

- Linear programming function for cost minimizing is applied;
- Battery is charging and discharging until the same state of charge in a process of using. Thereby, returning to initial state of charge (SoC) at the end of each cycle. SoC is the ratio between remaining in the battery capacity and the full charge, that is 100% when fully charged and 0% when fully discharged;
- Import and export flows are not considered (no electricity flow between close situated zones). Thus, it is assumed that the region is isolated;
- Fixed and variable O&M costs for the BESSs tend to be negligible, so they are omitted (Gonzalez, 2004);
- Self-discharge rate for Li-ion batteries is 5% per month (Simpson, 2011). In the context of the thesis battery is used almost every day. Thereby self-discharge rate is neglected;
- Degradation of battery with time is not considered;
- Temperature dependency in battery operation is not considered. It is assumed that within the operating temperature range from -20 to 60 ºC there is no capacity losses;
- The electricity amount for (dis)charging is equal for every hour during a day;
- Linear price is being used in calculations. Mainly, difference between real price and linear is less than five percent;
- Investments are initially made by a one-time payment;
- Demand and price data are taken for every day (including weekends).

5.2. *Sensitivity analysis*

Sensitivity analysis shows how results change under different circumstances.
Three influencing factors are considered after calculating of the basic option: a forecast of development of li-ion technology, a participation in capacity market, and increasing of price difference in electricity market.

The main things that make Li-ion technology more popular than other options are the forecast of future price decreasing and characteristic's improvement, latter mainly due to increasing of specific energy. John Baker embraces energy storage technologies current characteristics, and future potential development (Baker, 2008). Thus, based on future cost and number of cycles (charge and discharged to the same level) estimated in Baker's publication two more other years (2020 and 2030) are considered. Demand's curves are different during weekdays and weekends, but not so much for chosen area. However number of operating days during each month is assumed that BESS is operating not every day. The data is presented in Table 5. Following equation defines life-time of batteries used in calculations.

$$N = \frac{Cycle-life}{N_d \cdot n} \tag{9}$$

Where N – life-time of battery in years;

$Cycle - life$ – number of cycles during battery life;

N_d – number of operating days during a month (assumed 25 days per month);

n – number of operating months during a year (assumed 12 months per year) .

Table 5. Current and forecasted characteristics for Li-ion battery used in calculation

Year	2016	2020	2030
Cycle-life	3000	6000	9000
Life-time of battery, year	10	20	30
Price, €/kWh	395	300	150
Price decreasing,%	-	24 %	62 %

Two main goods of Russian WEMC are electricity and capacity. According to statistics, payment structure is divided as 70% for electricity and 30% for capacity (Batrakov, 2017). Currently, batteries are not included in the list of capacity market participants. Moreover, they do not have a capacity to produce electricity at any time, when it is needed (what is important for capacity market). However, as a rule, a capacity reserve is needed during peak hour that coincides with time of discharging. In addition, a proper planning and guaranteed availability reduces the risk of shortage and interruptions in energy supply.

Market price for each hour defined as overcrossing of demand and supply. Demand equals to amount of load from customers side. In its turn, production follows established at the moment consumption in traditional system, when controllable generation capacity exist. Supply curve consists of proposals bids by different generators which bid their own marginal price offer. A merit order depends on the plant type, hydro and nuclear go first, and TPP next depended on fuel type and inherent technology features that determine efficiency and specific fuel consumption as consequence. According to investigated data of output by power plant time, nuclear plants decrease output that leads to worsening of capacity factor during off-peak hours. Despite this fact, their share in overall output becomes higher thereby equilibrium price in this hours is less. Consumption of electricity continues to grow, simultaneously price for fuel increasing, as fossil reserves becomes less and extraction is complicated. All of the above is capable to increase difference between peak and off-peak hours in a long-term perspective. Thus influence of this impact on NPV is considered too.

5. IMPLEMENTATION OF ENERGY STORAGES TO CONVENTIONAL MODEL

First, it is important to reveal equation of price as a function of demand. Figure 26 shows linear dependency between price and demand by example of month of August.

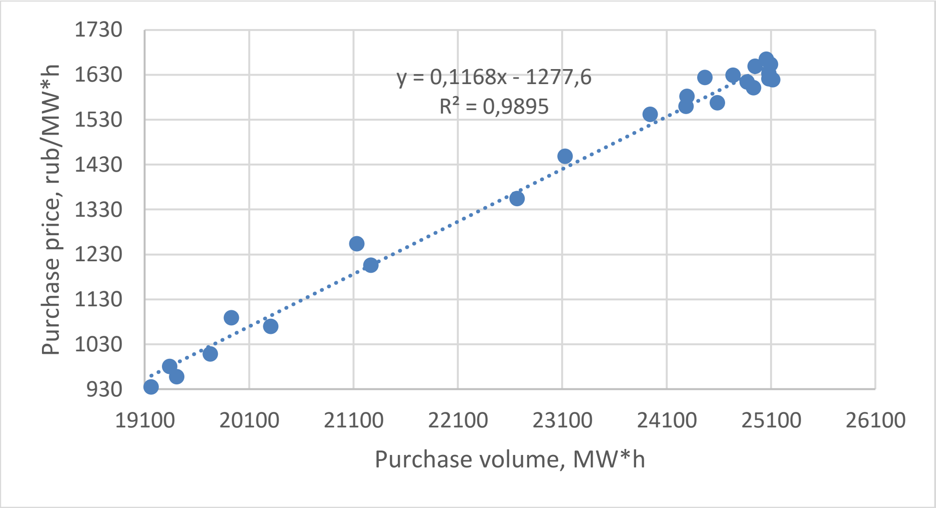

Figure 26. Price as a function of the demand (August)

Based on literature review, initial data was gathered before making a calculation; see Figure 27 and numeric values for the model in Table 6. Number of cycles is taken as 3000. Thus, if battery is used 25 days per month, a lifespan is 10 years. Depth of discharge is assumed to be 80 % due to li-ion battery characteristics and discharge curve. Weighted average capital cost (WACC) is used as a discount rate and assumed as 10% per year. Capital costs of battery components are taken from Graditi report (Graditi et al., 2016). The coefficient that considered participation of battery's owner in capacity market is assumed 1.43 due to payment's amount in WECM (Batrakov, 2017).

Table 6. Initial data

WACC, %	10
DOD, %	80
Participation in capacity market coefficient	1.43
Cycle-life	3000
Number of days of using	25
Euro/ruble ratio	60
Lifespan, years	10
Charge/discharge efficiency, %	91
Per unit costs of the storage, €/kWh	290
Per unit costs of the PCS, €//kW	54
Per unit costs of the BOP, €//kW	51
C-rate	0.5C
Number of charge discharge hours during a day	6

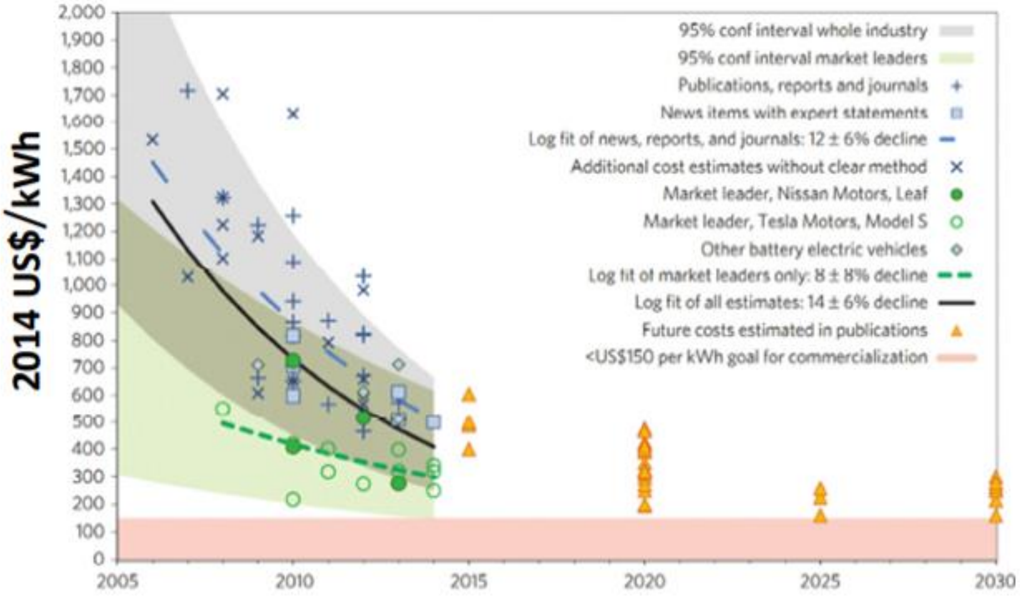

Figure 27. Cost of Li-ion battery packs in BEV (Nykvist and Nilsson, 2015)

Example of investment cost and NPV calculations of 1 MW BESS is presented in equations (10) and (11). Because of C-rate, battery power rating is assumed to be twice lower than energy capacity that reflects at final capital costs.

$$C_{tot} = C_{stor}^{unit} C_{BESS} + C_{PCS}^{unit} P_{BESS} + C_{BOP}^{unit} P_{BESS} = (290 * 1 + 54 * 0.5 + 51 * 0.5) * 100 * 60 * 10^{-6} = 20.55\, million\, rub \qquad (10)$$

$$NPV = \sum_{t=1}^{N} \frac{Cash\ flow_{year}}{(1+j)^{t}} - C_{tot} = \frac{139536{,}1}{(1+0.1)^{10}} - 20.55 * 10^{6} = -19.7\ million\ rub. \qquad (11)$$

Revenue received from 1 MW of energy storage within 1 year is about 140 thousand of Rubbles, see Table 7. At the same time investment of 1 MW storage is 2055 million of rubbles. In this case NPV over 10 years is -19.7 millions of rubbles. As it can be seen, profit is much less than capital costs. Thus, using of BESS in centralized market for electricity only arbitrage is not justified.

Table 7.Year profit (1 MW case)

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Peak price, rub	1436	1390	1436	1526	1585	1567	1605	1665	1554	1455	1410	1429
off-peak price, rub	939	916	905	800	824	970	995	1027	1035	891	891	887
cash flow average, rub	397	379	425	580	609	477	489	510	416	451	416	434
cash flow (month), rub	9929	9464	10617	14503	15228	11927	12214	12747	10393	11278	10391	10845
cash flow average, €	6.6	6.3	7.1	9.7	10.2	8.0	8.1	8.5	6.9	7.5	6.9	7.2
										sum profit, rub*10^3		140

The best case of using batteries for arbitrage is when it does not influence a price. However, second case proposes considering of equilibrium price shifting with increasing number of stored energy.

If there is no price difference with increasing amount of batteries so profit would continue to growth linear. However, with increasing number of batteries in overall composition, profit for each megawatt is decreasing (Figure 28). It means that the more installed capacity of BESS the less profit from each unit from using batteries for arbitrage.

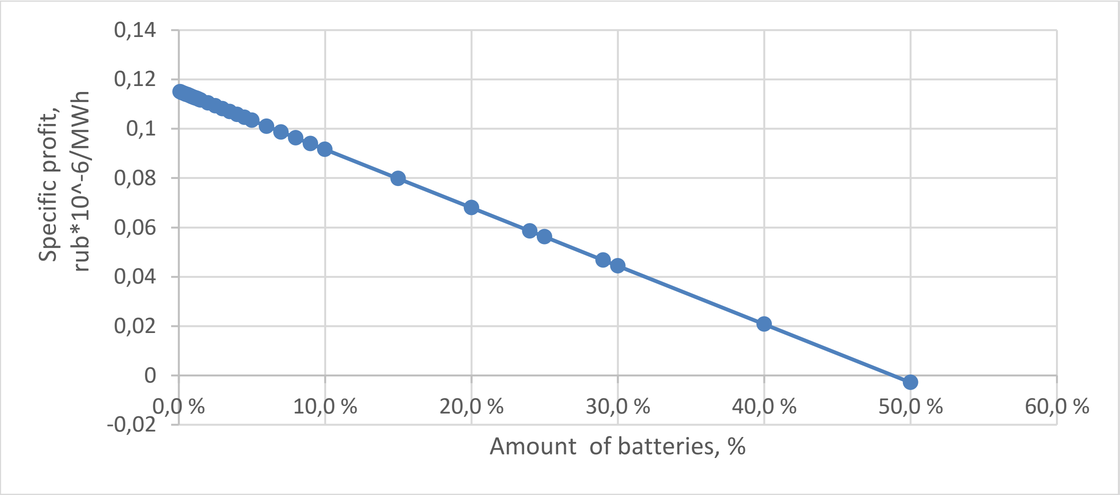

Figure 28. Specific profit as a function of amount of batteries

Energy storage's revenue from arbitrage continues to grow with level of batteries implemented in the market. However, after reaching a tipping point – the profit start decreasing. It means that there is optimal set of storages within each UPS that should be taken into account before implementation. In this work, a tipping point occurs after 24% of batteries in overall composition that equal to approximately 8 GWh (Figure 29). Influence of other storages neglected. Furthermore, the maximum level of battery quantity is restricted by market flexibility and is lower than 24%. However, the definition of maximum possible amount of BESS and its influencing factors is beyond the scope of this work.

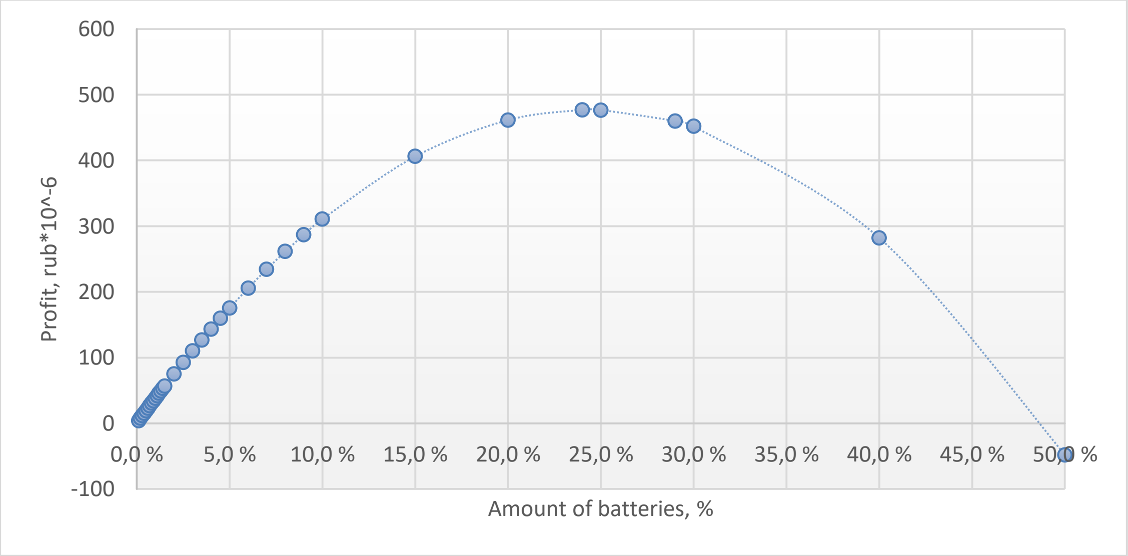

Figure 29. Profit as a function of amount of batteries

Next steps are used to estimate how economic effect is decreasing. Here not only the highest and lowest prices are used, but all stored energy distributed between definite hours. That is why optimal time of using has to be determined. Optimal time of charging and discharging is taken equals to 6 hours. C-rate for li-ion battery was chosen as 0.5 C, which mean 2 hours for full charging or discharging. Thus, three packs of storages are needed. This number of hours is preferable because of characteristics of batteries (Batteryuniversity.com, 2016) as well as a wholesale market equilibrium price trend (Atsenergo.ru, 2017). Another factor that influences on choice of number of hours is recommendations of producers, who point this C-rate as best option for battery usage (Figure 30) (Liotech.ru, 2017). However, the C-rate does not have constant value during operation and is varied due to needs of operator.

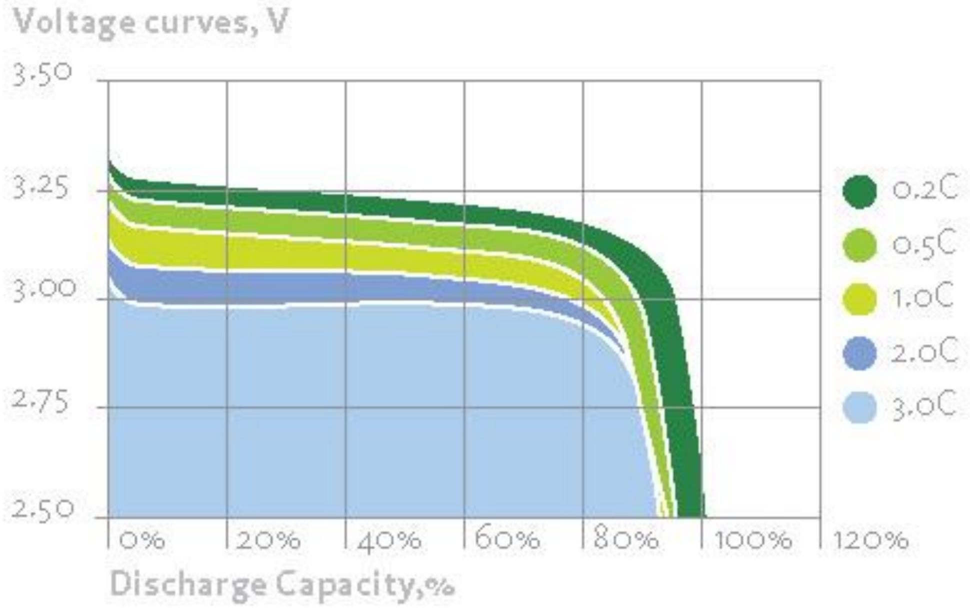

Figure 30. Characteristics of battery at different C-rate (Liotech.ru, 2017)

To find out an optimal hours for using of batteries two graphs were built. All data was taken for UPS Center (Atsenergo.ru, 2017). First graph is a purchase volume as a function of time of a day (Figure 31). For instance, in February the relation of peak hour volume to off-peak hour is about 1.3. It means that power spread between peak and off-peak hours is 7 GWh. An average number during the whole year is a little more than 6.6 GWh. Second graph shows equilibrium price index of electricity purchase and sale (Figure 32). Relation of peak hour electricity price to off-peak hours is about 1.7. It means that electricity is more expensive by 556 Rubles/MWh during peak hour.

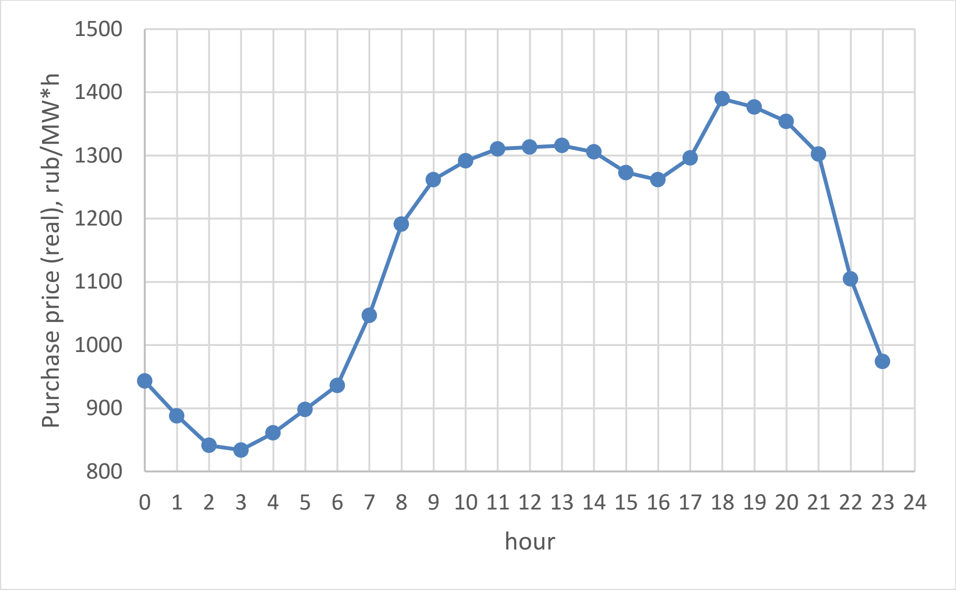

Figure 31. Purchase price as a function of time for February

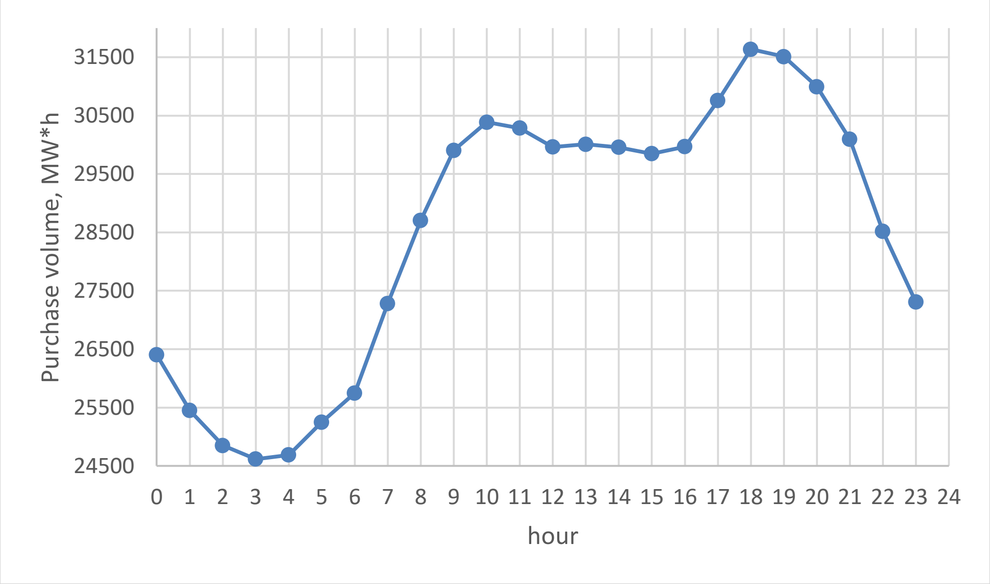

Figure 32. Purchase volume as a function of time for February

The off-peak hours during the year is constant from 1 a.m. to 6 a.m., while peak hours vary during the day. Thus, in this work's calculations on-peak hours were set manually for each month. Finally, NPV is calculated for range of implemented amount of batteries and results are presented in the table 8.

Table 8. Electricity market only

	amount of batteries, %	sum energy capacity, MW.h	total BESS cost, rub*10^6	Total profit, rub*10^6/year	NPV, rub*10^6
case 1 (2016)	0.01	3.39	69.73	0.39	-67
	0.5	169.66	3486.61	19.34	- 3368
	10.00	3393.30	69732.26	310.78	-67823

Figure 33 shows the results of NPV calculation for several cases. The first case is based on current prices and corresponding number of cycles. The second and the third calculations are made regarding forecast for 2020 and 2030, respectively. Three other graphs represent cases where batteries are assumed to participate also in capacity market. The coefficient of 1.43 is assumed due to assumption that producers have 70% profit in electricity market and 30% in a capacity market.

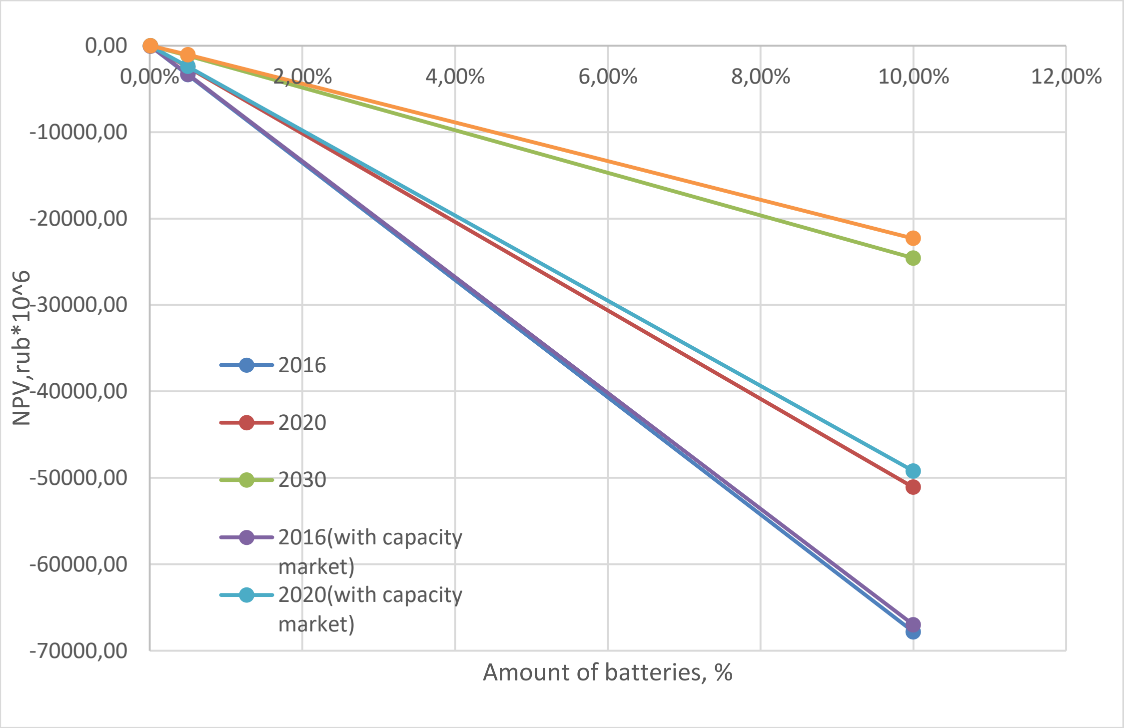

Figure 33. NPV for all cases

The results show that none of the considered cases is profitable for self-participation in the market. Joint participation in capacity market improves result a little. Table 9 shows that with characteristics of 2030, it will be about 3 times more profitable to use BESS than nowadays. NPV difference points how participation in capacity market can improve economic effectivity.

Table 9. Participation on electricity and capacity market

	amount of batteries, %	sum energy capacity, MW.h	total BESS cost, rub*10^6	Total profit, rub*10^6/ year	NPV, rub*10^6	NPV difference, %
case 1 (2016)	0.01	3.39	69.73	0.56	-66	1.53
	0.50	169.66	3486.61	27.63	-3317	1.51
	10.00	3393.30	69732.26	443.97	-67004	1.21
case 2 (2020)	0.01	3.39	53	0.56	-48	2.87
	0.50	169.66	2649.83	27.63	-2415	2.84
	10.00	3393.30	52996.51	443.97	-49217	3.66
case 3 (2030)	0.01	3.39	26.50	0.56	-21	6.92
	0.50	169.66	1324.91	27.63	-1064	6.84
	10.00	3393.30	26498.26	443.97	- 22313	9.25

Influence of increasing the price difference between peak and off peak hour in comparison with current level is presented in figure 34. NPV will change by 4.4 % if price difference is increased by 2 times.

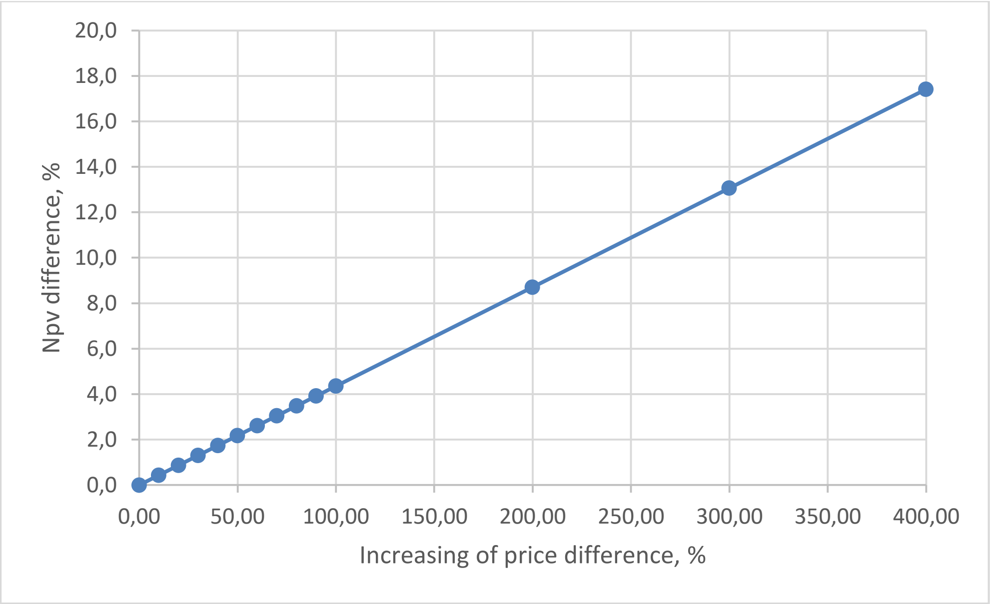

Figure 34. NPV as a function of price difference

6. DISCUSSIONS

A way to store energy is a crucial part of energy systems in future. Stored energy will solve many problems caused by the ever changing demand of electricity and provide a way to easily add more small scale renewable energy generation systems to the electricity network. Pumped hydro storages have set a stable foothold in the current market, but many of the other storage options are still encumbered by high investment costs and poor efficiencies.

Development in the field of energy storage is done every day and, in future, batteries can most likely be found inside of most buildings and single family homes. Most batteries are presumably li-ion based. Lead-acid and flow batteries will be used with on the side for different applications. The world of energy storage is filled with new innovations. It is plausible that we would not even recognize the technology used in the storage systems of the future yet.

To sum up the situation of energy storages a quote from a commentary on Fortune magazine by Scott Nyquist is used. "But the big picture is this. There are many smart people, all over the world, working on energy storage. Investment in their research is growing. Costs are falling. Technologies are proliferating. And people want it. There is one word that sums up the likely consequence of those trends: progress." (Nyquist, 2015)

Notwithstanding, the fast developing in electrochemical industry, namely Li-ion battery market, implementation of energy storages to the grid cannot occurs without changing of legislation and wholesale market model due to economic reason. Market architecture should be changed and adjusted for more efficient fuel and electricity consumption.

Results of the model show that current wholesale market model is not ready for introduction of BESS as independent market player. However, some factors that were not considered within this work can influence the overall result. There is a big percentage of old generating equipment on TPP. In case of substituting old technology or investing in new power plant owner can compare different possibilities where BESS can become prevailing because of market situation where prices for storage decreasing, when in the same time cost of building new power plants is increased. However, feasibility analysis has to be provided before making any decisions. Moreover, availability of ineffective and expensive technologies is required now because of possible boost of demand that should be covered. But in the presence of BESS at a power plant, this demand can be covered by electricity generated during off-peak hours

Usually, a power balance in the system is maintained by changing the output of power to the network by power plants operators. This mode of power plant control not only significantly increases the wear rate of the generating equipment, but also leads to additional fuel consumption. Over expenditure of fuel is especially noticeable, when large blocks of power plants are involved in the regulation of the variable part of the load schedule. In addition, there is not always the technological ability to quickly start or stop the power generating. Also, in case of emergencies, when there are not enough capacity reserves in power plants, limit the load of consumers to restore the permissible frequency level. This can lead to a significant damage associated with the interruption of power supply to consumers.

Environmental aspect should be considered as well since BESS, firstly, increases efficiency of power plants by allowing them to operate in more effective regime, and, secondly, storages substitute inefficient generation.

BESS participation in capacity market has shown its economic advantages. However, there are other places of possible joint use, which effect have not considered in this thesis. In this case, use of the batteries should be considered as mechanism of different markets, such as balancing market, where on-peak prices can reach much higher value than in DAM in certain hours during the day. Other applications are NPP integration for increasing a capacity factor, and frequency regulation on all levels. In addition, technical characteristics of BESS allow them to participate in auxiliary market as they fulfil all needed requirements.

Another development direction for BESS is a distributed generation. There is an exhaustion of the efficiency potential for centralized energy supply systems. Thus, growth of electricity price was estimated to increase by 3.3 – 3.4 times over the past 10 years (depending on price zone and free flow zone). It leads to development of distributed energy (Kozhukhovsky, 2014).

It is also worth noting renewable energy integration. Russian plan is to put into operation 1.5 GW of solar power plants up to 2020 and 3.6 GW of wind power plants up to 2024 (Altenergiya.ru, 2015). This forecast will definitely stimulate integration of storages. Experience of other countries shows that emerging large-scale wind integration is the influencing factor for storages deployment (Popper and Hove, 2017).

7. CONCLUSIONS

The impact of the introduction of BESS on WECM was investigated in the thesis. The contribution from storages shows an increase in price during the consumption mode and a decrease in the generation mode. The main advantage is that due to the generation mode, not only the peak price is lowered, but also the need to use uneconomical generators on the market, which can be replaced by storages charged from basic generation thereby increasing capacity factor of equipment.

The best option for the use of BESS is the case where the influence from them on the prices of the WECM is not taken into account. The use of arbitrage in the network does not make economic sense in the current model of the Russian electricity and capacity market. This approach will reduce the revenue for battery owners when the number of installed batteries increases.

The characteristics assumed in accordance with the forecasts improve the payback index of using storages by increasing the life span, as well as reducing capital costs. Thus, if the market model stay unchanged, the use of BESS with the characteristics of 2020, will be about 1.4 times more profitable than now, and with the characteristics of 2030, in 2.9 times.

Participation in the capacity market undoubtedly increases the economic benefit from energy storage. So the difference for 2016 in comparison with participation only on the DAM is about 1.5%. There is also a decrease in owner’s profit with an increase in the number of batteries in UPS. In turn, for the characteristics of 2030, the difference is about 7% with a small amount of storages.

The case considering the increase in the price difference between peak and off-peak hours in comparison with the level of 2016 showed a linear relationship between the increase in the difference and the increase in the NPV. With an increase in the difference of 2 times, the NPV value improves by 4.4%.

Despite the predictions of improving the characteristics of Li-ion batteries, other energy storage technologies should also be considered. Based on the work done, it was concluded that there is an optimal set of energy storage facilities suitable for the power system and ensuring its most efficient operation.

In the future, it is necessary to evaluate the effect of energy storage in remote areas, in areas with an increase in the number of renewable energy sources.

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APPENDICIES

Appendix 1. Key characteristics of storage system for particular application in the energy system

Application	Output (electricity thermal)	Size (MW)	Discharge Duration	Cycles (typical)	Response Time
Seasonal Storage	e, t	500 to 200	Days to months	1 to 5 per year	day
Arbitrage	e	100 to 2000	8 hours to 24 hours	0.25 to 1 per day	> 1hour
Frequency Regulation	e	1 to 2000	1 minutes to 15 minutes	20 to 40 per day	1 minute
Load Following	e, t	1 to 2000	15 minutes to 1 day	1 to 29 per day	< 15 minutes
Voltage Support	e	1 to 40	1 second to 1minute	10 to 100 per day	Millisecond to second
Black Start	e	0.1 to 400	1 hour to 4 hours	< 1 per day	< 1 hour
Transmission and Distribution (T & D) Congestion Relief	e, t	10 to 500	2 hours to 4 hours	0.14 to 1.25 per day	> 1 hour
T & D Infrastructure Investment Deferral	e, t	1 to 500	2 hours to 5 hours	0.75 to 1.25 per day	> 1 hour
Off- grid	e, t	0.001 to 0.01	3 hour to 5 hours	0.75 to 1.5 per day	<1 hour
Variable Supply Resource Integration	e, t	1 to 400	1 minute to hours	0.5 to 2 per day	<15 minutes
Combine Waste Heat and Power	t	1 to 5	Minutes to hours	1 to 10 per day	< 15 minutes
Spinning Reserve	e	10 to 2000	15 minutes to 2 hours	0.5 to 2 per day	< 15 minutes
Non - Spinning Reserve	e	10 to 2000	15 minutes to 2 hours	0.5 to 2 per day	< 15 minutes

Appendix 2. Technical and economical features of power storage technologies

Storage technology	PHS	CAES	Hydrogen	Flywheel	SMES	Supercap	Conventional batteries		Advanced Batteries			Flow Batteries	
							Pb-acid	NiCd	Li-ion	NaS	NaNiCl Zebra	VRB	ZnBr
Power rating, MW	100-5000	100-300	0.002-20	0.01-10	0.01-10	0.01-1	0.001-50	0.001-40	0.001 -0.1	0.5-50	0.001-1	0.03-7	0.05-2
Energy rating	1-24h				ms - 5min				min-h	s - hours	min - h	s-10h	s-10h
Response time	s-min	5-15 min	min	s	Ms	ms						ms	ms
Energy density, Wh/kg	0.5-1.5	30-60	80-104	5-130	0.5-5	0.1-15	30-50	40-60	75-250	150-240	125	75	60-80
Power density, W/kg			500+	400-1600	500-2000	0.1-10	75-300	150-300	150-315	90-230	130-160		50-150
Operating temp, °C				-20-+40		-40 - +85				300-350	300	0-40	
Self-discharge %/day	~0	~0	0.5-2	20-100	10-15	2-40	0.1-0.3	0.2-0.6	0.1-0.3	20	15	0-10	1
Round trip efficiency, %	75-85	42-54	20-50	85-95	95	85-98	60-95	60-91	85-100	85-90	90	85	70-75
Lifetime, years	50-100	25-40	5-15	20+	20	20+	3-15	15-20	5-15	10-15	10-14	5-20	5-10
Cycles	$2*10^4$-$5*10^4$	$5*10^3$-$2*10^4$	10^3+	10^5,10^7	10^4	10^4 - 10^8	100-1000	1000-3000	10^3-10^4+	2000-4500	2500+	10^4+	2000 +
Power cost €/kW	500-3600	400-1150	550-1600	100-300	100-400	100-400	200-600	350-1000	700-3000	700-2000	100-200	2500	500-1800
Energy cost €/kWh	60-150	10-120	1-15	1000-3500	700-7000	300-400	50-300	200-1000	200-1800	200-900	70-150	100-1000	100-700