Electrical Energy Large-Scale Storage, A Possible Application in the Russian Federation

Christophe Savard, Anni Nikulina, and Céline Mécemmène

Abstract—There are many solutions for storing energy, they can be either mechanical, thermal, chemical, electrochemical or electrical. In a context of smart-grid and micro-grid development, it is necessary to be able to store electrical energy at various points in the network: at the source for intermittent resources, in the network itself to have reserves to ensure exploitation and in consumption areas. Each solution is more or less relevant depending on the storage needs in terms of both power and energy. The evolution of electricity demand in the Russian Federation is a good example to illustrate this issue, especially since it is now planned that all new construction will have an energy storage system, so as to contribute to a better overall exploitation of the network. For intermediate storage, on the network, there is definite potential thanks to the old mines, in particular, that can be developed to store energy in the form of compressed air. In high consumption areas, it is also possible to use storage in the form of large energy banks made up of batteries.

Index Terms—Energy Management; Electrical Energy Storage; Arctic Russia.

I. ELECTRICAL ENERGY STORAGE SYSTEMS

A. Electrical energy

Energy represents a force applied at a given point over a period of time. In the electrical field, energy is thus the convolution of an electrical power during its application period.

The theory of relativity teaches us that matter can be considered as a form of energy. Matter stores potential energy, that is, energy that can be released from it. It can be stored in different forms: mainly mechanical, thermal, chemical, electrical or electrochemical forms [1]. It is always possible to transform the stored energy from one form to another. Nature stores energy in chemical form in plants. To extract energy from it, it is always possible to burn an object to extract energy in thermal form. This resulting heat can then be used to heat a fluid contained in a piping system. At its end, the fluid will rotate a mechanical device to recover energy in mechanical form. By using an electric generator, the energy can be further transformed into electrical form. Electricity is a movement of electrons on a conductive support, which does not facilitate its storage. As a result, electrical energy is often stored by using a transformation into another energy form.

In the first chapter, this article presents various current technological solutions for storing electrical energy. In the second part, it explains the current needs by matching them with the most appropriate solutions. It focuses on the example of the Russian Federation in the third part to propose ways of using existing resources, particularly in the northern part of the Federation.

B. Current solutions using natural resources

The article deals with five main modes of energy storage, deployed today: mechanical, thermal, chemical, electrochemical and electrical modes. Some solutions use natural resources as a vehicle for storing energy. Others require the creation of suitable artificial devices.

Among the mechanical storage solutions, two sub-families can be distinguished: potential energy and kinetic storage. For the latter, it consists in storing energy in the form of a movement. The flywheel has been known since ancient times and has come back with the rise of electric mobility. For example, in recent years, London buses have been using flywheel energy storage to reduce their fuel consumption [2]. Other devices use them to ensure an uninterrupted power supply despite a break in the continuity of the catenaries (point break or over long distances). Still others in rail transport use flywheels to recover braking energy [3]. In general, flywheels have a long service life, very high cyclability (number of discharge-recharge cycles), high efficiency (ratio between the energy returned to the energy sent to storage), high power density (expressed in Wh per unit mass) and low environmental impact. They can also, for the larger ones, provide powers of several kW. In addition, they can be combined to produce more power [4]. However, even if flywheels nowadays use magnetic devices to reduce the mechanical friction of rotating parts, they still discharge quickly. They are therefore particularly effective when it comes to replacing a faulty power supply in the short term.

The solution currently deployed almost universally, which represents nearly 99% of the energy storage capacity available on Earth, is hydraulic pumping: Pumped Hydro Energy Storage (PHES). Its good efficiency of around 75 to 80% and its ability to store several hundred GW on a single site have forged its success [5]-[6]. For example, in China, more than twenty sites have powers close to 20 GW and PHES with a capacity of 50 GW are planned for the coming years [7]. This solution uses inertial mechanical energy. Indeed, as shown in Fig. 1, a PHES plant must have two reservoirs located at two different altitudes. To store energy in it, water must be pumped from the lower basin and stored in the upper basin. To recover this energy, all you have to do is let gravity do its job and turbine. The main disadvantage of this storage method is the large space required to install the basins.

Published on March 23, 2019.
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DOI: http://dx.doi.org/10.24018/ejers.2019.4.3.1196
Another way of storing energy in potential mechanical form is to compress a fluid. This fluid can be a gas or simply air. The basic storage principle in a Compressed Air Energy Systems (CAES) is to store air by means of electric compressors, then to recover the energy by expansion through an air turbine, as shown schematically in Fig. 2. Air can be stored in any type of cavity. Mainly, underground cavities are used. Indeed, the hermeticity of these is more easily ensured than in outdoor tanks. On the other hand, tens of thousands cubic meters reservoir is difficult to fit into the landscape. Without the heat recovery at the air compression, the temperature of the compressed air decreases by entropy so that it is necessary to heat the output air. This storage mode is designated as diabatic. CAES store air adiabatically. The heat released by the compression of the air is captured in additional thermal storage devices. It can therefore be reused before expansion of the air to avoid the use of additional heat sources during the discharge phase of the storage system [8]-[10]. The yield of this storage system is between 40 and 50%. If it is lower than for PHES, it requires less space on the ground.

Thermal energy storage uses natural solutions when it is carried out by sensitive heat. The latent heat and sorption variants are at the boundary between natural and technological solutions. Molten Salt Energy Storage (MSES) solutions use special salts which, at the temperatures for which they are to be used, are either pasty or liquid. The salts are heated by an energy source. In the example in Fig. 3, photovoltaic panels produce electrical energy that will be transformed into heat to heat the salts. They are then transferred and stored and retain their heat until it is used, for example via a heat exchanger, to produce steam to power a turbine and produce electrical energy. The main risks of this solution are solidification of salts when they cool and decomposition when they warm up [11]. Some recently commissioned sites have a storage capacity of more than 1 GWh [12]. In thermodynamics, latent heat refers to heat released or absorbed by a body whose temperature remains constant. This latent heat can be stored during phase changes in the material. Only the solid-liquid change is fast enough and does not require too much pressure or volume. This type of solution is currently deployed in some solar storage water heaters [13]. Finally, over the past thirty years, the technique of adsorption and desorption of water in microporous adsorbents has been developed and notably deployed in heat pumps [14]. Research in recent decades has led to new and improved sorption materials such as inorganic crystal frameworks with superior adsorption capacities [15].

C. Current technological solutions

While the chemical form is the most widely used form of energy storage in nature, current technologies make it possible to produce different gases (hydrogen and other synthesis gases) to store electrical energy in chemical form by electrolysis. In this article, this storage method will not be more detailed. Current technologies allow energy to be stored in electrochemical and electrical form [16]-[20]. Electrochemical storage is used in the accumulators. Unlike electric batteries, batteries can be discharged and recharged. Since neither the voltage that depends on the nature of the electrodes nor the intensity that is related to the mass power density is often sufficient to provide the power required by most applications, batteries are combined into batteries. Three major technological families dominate the current market. Other emerging technologies are attempting to develop.

The oldest technology, developed since the end of the 19th century, is lead-acid technology. It retains its monopoly to start automotive combustion engines because of its characteristics. With a lifetime of between 5 and 10 years, lead batteries have an efficiency of around 80%. On the other hand, it suffers from a defect linked to the Peukert effect: the higher the power required from the battery, the lower the capacity returned [20]. The second family is the Nickel-based family. This type of battery has a higher power density and greater cyclability. The first nickel cadmium (NiCd) batteries were developed around 1915. These batteries are still sometimes used because they are the only ones that remain operational for temperatures of the order of -40°C. Cadmium being extremely toxic and banned in the European Union, a second type of nickel-hydride metal-associated battery (NiMH) appeared on the market around 1995. While they are more robust and secure, they have a lower maximum storage capacity. The output voltage of a single battery is also lower: 1.7 Volts compared to 2.1 for
lead-acid batteries. The batteries of the 21st century belong to lithium-ion technology. With an efficiency ranging between 95 and 98% and a cyclability of several thousand cycles, for the best of them, they dominate the battery market despite safety problems. Indeed, they become unstable if they are charged beyond their operating charge (the maximum electrical charge they can contain at any given time).

Overloading can lead to thermal runaway, which in turn can lead to a fire or explosion [21]. To avoid these problems, lithium-ion batteries are never used alone, without a supervisor. Thus, a Battery Management System (BMS) is mainly responsible for monitoring and security missions. To do this, he estimates the characteristic states of each battery in the battery he supervises: state of charge (SoC) indicating the amount of electrical charge contained in the battery in relation to the maximum operative charge it can contain, and state of health (SoH) which traces the evolution of this operative charge, knowing that it decreases with the use and age of the battery [22]. Finally, to avoid disparities in the charges and no-load voltages of the accumulators in the battery, the voltage being linked to the charge by a characteristic relationship [23], additional circuits controlled by the BMS often ensure the balancing of the electrical characteristics between the accumulators [24]. Finally, other technologies exist or are under development, such as metal-air technologies (e.g. Zinc-air), sodium-sulfide (NaS) or flow batteries with electrolyte outside the battery [25,26].

Finally, electrical energy can be stored in its original electrical form either in static or kinetic form. Supercapacitors or double-layer capacitors are capacitors with very high faradic capacities, in the order of several thousand farads [27]. Electrical charges can be stored and extracted in a very short time. They have very low equivalent series resistances. They can operate in a wide temperature range and can withstand up to a few million cycles. They have an efficiency of around 90%. For all these reasons, they are particularly well suited for applications requiring power but are poorly adapted to store energy over a medium to long period of time because they have a much higher self-discharge rate than batteries, which can reach several tens of percent per week [28]. In addition, electricity can be stored in kinetic form in Supraconductor Magnetic Energy Storage (SMES). While this storage technology is very reactive, highly efficient (between 85 and 90%) and can store up to tens of MW, it has a major disadvantage: the materials are superconducting only at very low temperatures, around 100K. A SMES consists of four parts: the superconducting coil which must be kept under vacuum and thermally insulated below the critical temperature ensuring superconductivity, the refrigeration system with its vacuum pump, which operate continuously to maintain the temperature, an electrical regulation system with the network and the control device (equivalent to the BMS) responsible for maintaining the suitable conditions in pressure and temperature, monitoring the deformation of the coil and controlling the current [29].

D. Technological maturity

These different solutions are more or less mature today. They can be classified into three levels.

1 - those whose technological maturity has been proven.
2 - those that are close to maturity, for which it is still necessary to finalize certain aspects in operation and requiring some fine-tuning.
3 - those that are still in an experimental state.

The maturity progress of the different solutions is presented in Table I. CAES and thermal sensitive heat mechanical and thermal solutions are technologies in an intermediate state between experimentation and development.

**TABLE I: STORAGE SOLUTIONS MATURITY**

<table>
<thead>
<tr>
<th>Family</th>
<th>Solution</th>
<th>Maturity</th>
</tr>
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<tbody>
<tr>
<td>mechanics</td>
<td>CAES</td>
<td>2</td>
</tr>
<tr>
<td>mechanics</td>
<td>PHS</td>
<td>3</td>
</tr>
<tr>
<td>mechanics</td>
<td>flywheel</td>
<td>2</td>
</tr>
<tr>
<td>thermal</td>
<td>sensitive heat</td>
<td>2-3</td>
</tr>
<tr>
<td>thermal</td>
<td>latent heat</td>
<td>2</td>
</tr>
<tr>
<td>thermal</td>
<td>sorption</td>
<td>2</td>
</tr>
<tr>
<td>chemical</td>
<td>hydrogen</td>
<td>3</td>
</tr>
<tr>
<td>chemical</td>
<td>synthetic gas</td>
<td>3</td>
</tr>
<tr>
<td>electrochemical</td>
<td>lead-acid battery</td>
<td>1</td>
</tr>
<tr>
<td>electrochemical</td>
<td>nickel batteries</td>
<td>1</td>
</tr>
<tr>
<td>electrochemical</td>
<td>lithium-ion batteries</td>
<td>2</td>
</tr>
<tr>
<td>electrochemical</td>
<td>others batteries</td>
<td>3</td>
</tr>
<tr>
<td>electrical</td>
<td>supercapacitors</td>
<td>2</td>
</tr>
<tr>
<td>electrical</td>
<td>SMES</td>
<td>3</td>
</tr>
</tbody>
</table>

II. ADEQUACIES BETWEEN NEEDS AND SOLUTIONS

Lead made batteries were already used to regulate electricity grids at the beginning of the 20th century. Today, they are also used for emergency power systems, in standalone wind turbine systems, and to reduce fluctuations in power generation. Indeed, connecting to the electrical networks of Electric Energy Storage Systems (EES) solves or mitigates a number of operating problems.

A. Usefulness of storing electrical energy

Submit Unlike fossil fuels, electricity is consumed when it is produced, unless it is stored by one of the solutions described in the previous chapter. In addition, electricity is often produced in a place different from the place where it is consumed, which implies a transport problem. To be an efficient energy carrier, electricity must be produced, transmitted and stored for use remotely in time and space. Such storage may be carried out at source at the place of production or at the place of consumption. It may also be installed on a site intermediate between its place of production and its place of use. This is true in the context of current electricity distribution networks. It may also be possible to build local networks of high power and energy, for isolated areas, such as an island, for example. These networks are then referred to as micro-grid. Simplistically, a micro-grid is described by the diagram in Fig. 4, which shows a single-producer and single-consumer system. From a power grid perspective, several generating sources and several consumption locations are connected by a network, which can have different forms of mesh size. Fig. 5 shows the basic case of a star network between the different production and consumption points. Whether it is a micro-grid or an interconnected network carrying high power, it is still necessary today to use a physical support: conductive cables. On the electricity grid, supply and demand meet. Electricity is produced by m different sources: thermal, nuclear and renewable sources such as hydro, wind or...
photovoltaic. Demand comes from all n consumers, private or industrial, connected to the network. Like any market, it can only remain stable with some form of regulation or management.

The management of an alternating current power grid mainly consists, during the operating phase, in guaranteeing two important parameters: frequency and voltage. Its two parameters must be maintained regardless of supply and demand. At any time, t, it is necessary to adapt the power supplied with the demand. Depending on the physical nature of the electricity grid, congestion may occur on some sections in the event of high local power demands. This congestion will cause the failure of part or all the network, depending on the protection devices inserted and the management methods deployed [12]. One technique commonly used by operators is to isolate the congested part of the network from the rest of the power network. On the other hand, at times when demand is low, lower than production, it is possible to store excess energy, with a view to reinjecting it into the power grid when demand becomes higher.

The instant price per hour kilowatt changes with supply and demand in the electricity market. Thus, it is economically more attractive for surplus electricity produced at a time when its financial value is low due to low demand to be stored. Thereafter, it will be returned to the network at a time when it is more expensive due to high demand. In the absence of energy storage, when the demand for electricity exceeds supply, the grid operator must inject additional energy into the grid, often produced by polluting but highly reactive sources such as gas or diesel thermal power plants.

Today, power grids include renewable energy sources in addition to conventional power plants. The injection of electricity from its sources poses new difficulties in the operation of the networks. Let us pass on the fact that the electricity thus produced requires power converters in order to inject it properly into the power grid [30]. The main difficulty in managing these energy sources lies in the intermittent nature of electricity supply and their weather dependence. Indeed, solar panels do not convert sunlight into electricity at night. Wind turbines sometimes have to be stopped for maintenance, in case of strong winds or when protected migratory bird species pass through [31]. The share of renewable energy produced is increasing everywhere in the energy mix of each country. These energies are produced without greenhouse gas emissions or major environmental pollution around the production sites. However, the higher the proportion of renewable (and therefore uncontrollable) energy injected into the grid, the more the frequency of the grid can fluctuate. Consequently, to regulate this frequency, it becomes necessary to have more power margin. Therefore, it is necessary to have more generators that can quickly inject high powers, i.e. thermal reactors, pollutants. Thus, paradoxically, having a larger share of renewable energy may require more means of regulation and thus increase production costs. Unless you have stored, on hold and quickly available electrical energy.

For all these reasons, it becomes necessary to store electrical energy in power networks. To precisely remedy a failure following congestion and ensure the continuity of the energy distribution service, it is necessary to have access to energy stocks at the ends of the network and in sectors with high demand. To ensure that renewable energy sources provide a more continuous amount of energy, it is necessary to smooth their production through local storage at the place of production. Finally, to reduce peak consumption, it is also necessary to have energy stored at the consumption sites in order to smooth the demand for power on the network.

B. Solutions for the storage of low and medium capacities

Having an interconnected power grid is a good solution for overall energy management. However, it also becomes relevant to manage energy locally when storage systems are present at production sites, consumption sites and within the network itself (Fig. 6). Thus, this results in a smart-grid configuration. In this type of power grid, the supply side combines permanent, intermittent power generation sources regulated by their own storage system and storage systems. The latter are recharged when demand is lower than supply. The demand side includes a multitude of n users, all of whom also store energy in such a way as to reduce their demand at peak times and regulate the flow of electricity to the rest of the network, thereby maintaining the voltage on the network. In the long term, electric vehicles should also be included as consumers. Imagine that all vehicles become electric. It is likely that, like today's heat engine vehicles, they spend more than 90% of their time not driving. Once fully charged, the batteries of electric vehicles remain connected to the power grid. They thus constitute an additional energy reserve, switching to the supplier category as energy stocks [32].

DOI: http://dx.doi.org/10.24018/ejers.2019.4.3.1196
Thus, in relation to the respective performances of the various electrical energy storage solutions described in the first chapter, it appears that some solutions are better suited than others for low and medium capacity uses. The best solutions also depend on the available discharge time. Thus, for short discharge times (less than one hour), the best solutions are supercapacitors, SMES, and flywheels. In terms of power network operation, these solutions make it possible to eliminate small operating defects (temporary overloads, micro-breaks). For needs consisting in providing power for periods of less than a day, flywheels and batteries are the most suitable solutions. Indeed, if a battery can be discharged in one hour when it is operated at its rated current, if it is discharged at a current worth one twentieth of its rated current, it can supply energy for twenty hours. These needs correspond to those of daily operation of the power grid, in order to ensure market regulation and smoothing of both production and demand. Finally, for seasonal, long-term needs (less than a year), chemical storage solutions (hydrogen, synthesis gas), PHES, CAES are relevant. Indeed, these are the only solutions that can store very large quantities of power and can provide high power. This storage method makes it possible to reduce, or even eliminate, major climatic problems (fog permanently installed for several weeks, as was the case in some valleys of the French Alps during the winter of 2017). It also allows use as a troubleshooting tool if all or part of the network fails (following a natural disaster for example). For more regular use, these storage methods make it possible to reduce the disadvantages associated with the intermittency of renewable energies and to regulate the power grid, whether it is a global network or a micro-grid. These choice points are listed in Table II.

**TABLE II: DURATION, NEEDS AND SOLUTION MEETING**

<table>
<thead>
<tr>
<th>Duration</th>
<th>Needs</th>
<th>Appropriate solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>short (&lt; 1 H)</td>
<td>punctual defects removal regulation and smoothing</td>
<td>supercapacitors, flywheels, SMES flywheels, batteries</td>
</tr>
<tr>
<td>medium (&lt; 1 day)</td>
<td>regulation, intermittency, failures</td>
<td>H2, syngas, CAES, PHES</td>
</tr>
</tbody>
</table>

C. Solutions for high-capacity storage

The solutions for storing large energy capacities are the same as for producing intermediate energy levels in the long term: hydrogen and syngas, CAES and PHES. They reduce the overall production cost (economic and environmental) of energy by avoiding the need to build additional thermal power plants. While in the short and medium term, they make it possible to maintain the quality of the network (mainly frequency and voltage), in the longer term, they make it possible to eliminate the nuisances associated with long-term outages (blackout phenomenon).

The PHES solution is the one with the best technical maturity. PHES currently operating have capacities of less than 3 GW [33]. CAES techniques are theoretically mature but are not, to date, sufficiently established throughout the world to be able to benefit from sufficient feedback and offer a lower return. The main reasons come from a non-optimality in energy management [34]. However, they also have the great advantage of being able to reuse previously used areas such as abandoned underground mines and low risks in the event of a major failure. Storage in cavities or old mines is possible. If these are perfectly sealed, the replacement of air by gases that can produce more energy during discharge can also be studied in order to improve the overall efficiency of the operation, by coupling a gas-fired power plant with a CAES.

In PHES solutions, the low reservoir can be both natural (lake, sea itself) and artificial (lake, underground cavity). Its charging time depends on the available water resource and the nature of the reservoirs. In all cases, it requires quite long periods of time, ranging from one to a few days. On the other hand, it allows the energy source to be available for at least equal periods of time. Its major disadvantage is the neutralization of very large areas, even if the level of the upper basin can be raised by dikes and walls. There are not many sites left available to host PHES.

Isolated (mainly island) territories often have their own micro-grid. Although in 2018 a floating nuclear power plant was deployed to supply electricity to part of the Arctic coast of the Russian Federation to open up the territory to energy, currently diesel generators are mainly used to produce electricity on demand in remote territories. Often, it is not very good quality fuel that is used, but rather heavy and viscous oils, which are very polluting when they are burned. Thanks to storage systems, it is now possible to dispense with this mode of electricity production as the main source. Indeed, with renewable energy generators with sufficient cumulative production capacity and high-capacity storage, electricity needs can be covered. Outside isolated territories, there are territories which, either by militant will or by necessity because they are too far from the major production centers, must operate in energy self-sufficiency. For example, storage systems in small PHES associated with photovoltaic production have been implemented on a very small scale in a few houses [33].

D. Operating solutions

When to manage a power network, when it is not possible to use additional production solutions or to draw on the stocks of energy remotely at the points of consumption, there are two possible operating techniques: time-shifting...
and erasure. The first technique consists in postponing non-essential consumption over time. For example, the consumer may be induced (or forced) not to do laundry during peak hours. Generally, electric water heaters are associated with day/night switches that only allow them to operate during off-peak night hours. The second technique of erasure is less comprehensible to the user. It is a question, no more and no less, of not meeting the demand of non-priority users. Even if it is logical to favor the supply of energy to a hospital rather than to residential areas, for the user, this erasure of the network is nonetheless experienced as a penalty. This erasure technique can also be applied to each individual installation, by subscribing to a power level lower than that required at the peak. In this case, an intelligent meter will relieve some circuit-breakers and only keep those considered necessary when the requested power exceeds the subscribed power. In any case, to improve the acceptability of the erasure technique, this implies being able to maintain the expected service through storage directly at the place of consumption.

III. NEEDS IN THE RUSSIAN FEDERATION

Thus, the two technological solutions to be selected are CAES and batteries. To illustrate the best solutions suited for each storage need, this chapter will focus on the example of the Russian Federation issue.

A. Consumption and production evolution

Fig. 7 shows the evolution over the last three decades of the average annual consumption of electricity per capita expressed in GWh for different types of industrialized countries. For countries with a temperate or hot climate, this consumption is between 6 and 9 GWh/year. It includes all consumption items: industry, agriculture, tertiary, transport and residential. Sweden, like the other Nordic countries, consumes more energy per inhabitant. It is important to note that the curves have stopped growing for many countries, and not only because of the various economic crises that have slowed activity. This reduction in per capita consumption also comes from an awareness of eco-responsibility, seeking to reduce individual carbon impacts by reducing energy consumption. This trend is not just a trend in Western countries but is spreading all over the world [35].

In the Russian Federation, consumption fell considerably in the dark years following the end of the communist regime. Since the late 1990s, energy consumption has been on a steady and moderate downward trend. Occasionally, the impact of the economic sanctions imposed on the Russian Federation is felt, but without reversing the curve [36]. In any case, it should grow in the coming years. Today, it is in line with the average consumption of most countries. However, it is still lower than in the industrialized Nordic countries.

B. Resources in the Russian Federation

To meet the forecasts of consumption growth, successive plans and General Scheme of the power industry development have followed one another in recent decades [37]. Projections of consumption growth have been reduced over time to reflect overall trends. The current projections strike a balance between the situation in most Western countries and the Nordic countries. However, as shown in the curves, extrapolated from [37] data in Fig. 8 from 2017 onward, the growth expected for average per capita consumption is similar to that of the population growth trend. It is likely that these two curves will experience a saturation phenomenon before the projection horizon. At the very least, the per capita consumption curve should stop growing, in particular by raising awareness of the environmental impact and improving the energy performance of buildings and means of transport.

In any case, it is clear that, in the near future, it will be necessary to produce more electricity in Russia. Currently, the energy production mix, shown in Fig. 9, shows that fossil fuels (gas, oil, coal) are the main source of electricity production. In the future, the share of nuclear power is expected to increase due to the programming plan for new power plants. Currently, about fifteen new power plants are being programmed to increase the nuclear energy produced by 66% [38]. Above all, these new power plants will make it possible to maintain the share of nuclear production in the energy mix at its current level. On the other hand, a large part of the new demand will be met mainly with the arrival of new and renewable energies (solar, wind, tidal power, geothermal). To simplify, only the first two types of renewable energy will be considered in this paper.

Two scenarios could be considered, taking into account the assumptions made about nuclear production and considering that there is no longer any land reserve left to increase hydropower production. The first is to consider maintaining fossil fuel-based production capacities at their current level, without creating new power plants. This
means using storage to regulate the electricity market. The second, voluntary, reduces this production by 50%, with the closure of several thermal power plants or by keeping them only as backup, to compensate for major failures or exceptional peaks in demand. It will then be necessary to build many solar and wind power plants, as renewable production will then have to cover between 32% and 54% of the total, according to the estimates presented in Table III.

A wind turbine with a rotor diameter of 50 meters is usually two hundred meters away from its neighbor. Thus, it is necessary to count four hectares of land for a single wind turbine. On the same surface, it is possible to install about 1.33 hectares of photovoltaic panels. One square meter of photovoltaic panel can produce about 100 WHc. With normal sunshine in northern Russia, for example over almost the entire territory of the Great Arctic Nature Reserve, this would lead to an average production during the six summer months of 4 kWh/m² per day. Annually, the energy production for a solar power plant would reach just under 0.25 GWh/ha. In the Yukagir sector, for example, in the Sakha region, production would be higher, reaching 0.45 GWh/ha (respectively 0.3 with a solar power plant and 0.6 with a wind power plant).

Moreover, as quickly mentioned above, daily electricity consumption follows a camel like curve, with two bumps: in the morning and in the evening, while a trough in demand appears at night. This curve is directly related to human activities and commuting between home and work. In winter, due to heating and lighting demands, consumption is even higher in both peak periods. To solve the two production peaks in twenty years' time, the easiest way would be to build additional thermal power plants, which would aggravate pollution and consume limited resources that would be much better developed by not simply being burned to be transformed into electricity when electricity can be produced from renewable resources. These two phenomena combined: peak consumption and the share of renewable energy between one third and one half make it essential to add large-scale energy storage devices. In order to begin to remedy this problem, it is now mandatory in Russian Federation to include in any new construction program, the addition of an EESS at the places of consumption.

C. Renewable energy potential

By combining the elements given in [40] on the potential for energy production from solar radiation and wind power, it is possible to draw up the map given in Fig. 10, which measures in MWh the maximum annual potential for energy production, reduced to one hectare, for the most northern territories of the Federation. The southernmost territories benefit from a higher level of sunshine. The map shows an average energy production for both wind and solar technologies, knowing that in some places one would produce more energy than the other.

<table>
<thead>
<tr>
<th>TABLE III: ESTIMATE OF THE ENERGY MIX ACCORDING TO SCENARIOS ON FOSSIL FUEL PRODUCTION CAPACITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossil fuels</td>
</tr>
<tr>
<td>---------------</td>
</tr>
<tr>
<td>current situation</td>
</tr>
<tr>
<td>water runoff</td>
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<td>proactive scenario</td>
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</table>

D. Possible storage options

Number for energy storage, old underground mines can be reused and connected to the electricity grid. Russia has a large share of the mines operating on Earth. Various minerals, including a significant proportion of metals such as copper, aluminum, nickel, lithium or arsenic, are extracted from the subsoil in addition to fossil hydrocarbons. A large part of these mines are located in Siberia or to the North of the Federation. During the Second World War, the Ural Mountains also saw the number of its farms explode. Some mines are no longer in operation, such as the Ural salt mines, which are currently very popular with tourists, or the enormous hole creating by diamond mining in the Mirny underground diamond mine, a hole more than 500 meters deep and 1200 meters in diameter. While the second was mined in the open pit between 1957 and 2005, by digging in the permafrost, this is not the case for all the others. The second option that can be considered is the creation of energy banks, consisting of a large number of batteries. These banks can be located on the network as well as on the production sites and on the consumption sites. Their size depends on the needs when they are located at consumption sites and on storage needs in other ways. A suitable global storage system should include storage at renewable energy production sites in order to smooth production and thus reduce operating constraints. A mass storage system distributed over the network would make it possible to respond to consumption peaks (time-shifting to production). Finally, local storage sites at consumption sites would make it possible to achieve erasure by reducing the nuisance caused to consumers.

To carry out such a project, it would first be necessary to define the investment and maintenance amounts related to the adaptation of storage sites to accommodate compressed energy storage.
air, the construction of storage plants, the installation of high-voltage lines (overhead or underground to reduce exposure to winter stresses). In addition, environmental and operational risks are studied, including the cindynics of the dangers inherent in compression. This multi-criteria analysis would make it possible to determine the best sites that could be located in the North of the Federation [41]. As a result, it also seems relevant to study the relocation of part of the electricity production in this region. Considering planning the construction of renewable energy plants in the medium term could then be a way to improve the attractiveness of these territories [42].

In urban areas, at places of consumption, it seems dangerous to use certain old salt mines that snake under certain urban areas. On the other hand, setting up large-capacity storage banks using lithium-ion, sodium-sulfide or redox flow batteries is a preferred option [40]. It is also necessary to include in the economic calculation used to size these banks the replacement of equipment after obsolescence and to reduce the points that hinder good resource management [34]. The other approach to be developed is to introduce systematic storage in each place of final consumption. In this case, it is necessary to determine the storage capacity carefully, depending on whether the system simply ensures erasure during peak consumption periods or offers the possibility of self-powering during a longer blackout period.

In the coming decades, electric mobility will also make it possible to offer additional storage capacities with the 2-grid vehicle principle, if this technology ultimately prevails.

Finally, for remote regions, it is also possible to give them energy autonomy by designing renewable energy production plants combined with storage centers that can cover periods without production. In this case, a thermal backup system should ensure energy continuity. In this case, using fossil resources to just supplement production for a few days a year helps to reconcile consumer and environmental requirements.

IV. CONCLUSIONS

Several technological solutions are available to store electrical energy, both on the grid as an additional source and at the point of production or consumption. It is conceivable that future consumption in the Russian Federation will increase considerably. Two storage systems seem to be suitable to meet the needs: the CAES because many sealed cavities are available today and the energy banks, made up of many batteries. The implementation of CAES will protect the network from the adventures related to the intermittency of renewable energies, which should see their share in the energy mix increase considerably in the coming years. It will also be necessary to provide energy banks both at production sites and in urban areas. Storage can be done in large quantities to regulate the network and at the end user’s premises to allow erasure at peak hours. In addition, the production and storage of electricity can be located in territories that are currently lacking in attractiveness, such as the northern part of the Russian Federation.

REFERENCES

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