International Journal of
Sustainable Energy Planning and Management

Global Distribution of Grid-connected Electrical Energy Storage Systems

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ABSTRACT

This article gives an overview of grid-connected energy storage systems for electricity worldwide, based on public available data. Technologies considered in this study are pumped hydroelectric energy storage (PHES), compressed air energy storage (CAES), sodium-sulfur batteries (NaS), lead-acid batteries, redox-flow batteries, nickel-cadmium batteries (NiCd) and lithium-ion batteries. As the research indicates, the worldwide installed capacity of grid-connected electrical energy storage systems is approximately 154 GW. This corresponds to a share of 5.5 % of the worldwide installed generation capacity. Furthermore, the article gives an overview of the historical development of installed and used storage systems worldwide. Subsequently, the focus is on each considered technology concerning the current storage size, number of plants and location.

In summary it can be stated, PHES is the most commonly used technology worldwide, whereas electrochemical technologies are increasingly gaining in importance. Regarding the distribution of grid-connected storage systems for electricity reveals the share of installed storage capacity is in Europe and Eastern Asia twice as high as in North America.

Keywords:

Electrical energy storage;
grid-connected energy storage;
pumped hydroelectric energy storage;
compressed air energy storage;
sodium-sulfur battery;
lead-acid battery;
redox-flow battery;
nickel-cadmium battery;
lithium-ion battery;

URL:
dx.doi.org/10.5278/ijsepm.2016.9.4

1. Introduction – the need for grid-connected energy storage for electricity

Consumption and generation of electricity have to be balanced at any point of time. Due to this fact different technologies for generating and balancing with their own special technological abilities and restrictions are used for diverse applications.

Base load power plants (e.g. nuclear power, lignite, coal) should be used constantly with a high amount of full load hours. Intermediate and peak load power plants operate to compensate and cover fluctuations in demand. Photovoltaic (PV) and wind power present an exception in conventional electricity systems, because their power feed-in depends on weather conditions and is less projectable and controllable so that imbalances - between generation and consumption - could increase. [1] investigate an increasing disparity between generation and consumption and thus an increase in energy balancing demand when increasing fluctuating capacities. In addition, a methodology has been developed and applied in [1] to estimate flexibility required to integrate fluctuating renewables in selected regions. As Germany pushes the energy transition until 2050 [2], within this scope there are several studies investigating future scenarios and resulting effects. Hence [3] gives in that context a survey and an analysis of current studies regarding national and European level. As well, [4] carried out a meta-analysis of studies evaluating energy storages. One focus is on studies analyzing the technical need of energy balancing capacities regarding Germany and Europe.

According to energy balancing technologies, energy storages for electricity are one option to balance disparity by charging or discharging. In the grid-connected case storage systems have to compete with

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other balancing options e.g. demand side management, curtailment or grid extension. [5] gives an overview and classification of balancing technologies, [6] takes a closer look on storage technologies and their development according to their role in the energy system, whereas [7] provides a comprehensive survey of technologies in 2050.

In addition to technical reasons profitability plays an important role for the use of energy storages. Supplied areas which have a well-developed power grid are central markets like different kind of spot markets or balancing energy markets. These areas are particularly affected and interesting for electric energy storage applications. Apart from this, storage systems can be deployed near to consumers, e.g. to reduce system usage fee or to increase share of PV self-consumption. Extensive overviews of several storage applications and its economic frame conditions are given in [8], [9], [10], [11] or [4], for instance.

2. Methodology

This article focusses on the current worldwide situation of grid-connected energy storage systems for electricity – not considering demonstration or research plants - and offers a detailed reference list based on public available data (see references). The main technologies will be analyzed with respect to storage size and the number of installed systems in all corresponding regions.

The technologies discussed here are pumped hydroelectric energy storage (PHES), compressed air energy storage (CAES), sodium-sulfur batteries (NaS), lead-acid batteries, redox-flow batteries, nickel-cadmium batteries (NiCd) and lithium-ion batteries, all with a minimum size of 10 kW. After an introductory historical overview, the respective technologies will be discussed in relation to installed system size worldwide.

The methodology developed and used in this study is an analysis and evaluation of information obtained from literature. For each technology literature data were researched, selected and evaluated. Thereby the data base includes all systems up to January 2014. Subsequently, the data were analyzed and classified into regions, and consequently relations were developed and considered. A short survey of references used is found in Table 1, whereas a detailed list of literature is found in appendix. Subsequently, the focus is on a survey of systems that can be characterized by power and energy capacity from existing data base. Exception is the analysis of pumped hydroelectric energy storage, because in practice and in the literature as an indication solely power capacity is common.

Table 1: References assigned to technologies

Technology	References
PHES	[12] to [447]
Lead acid	[448] to [455]
Redox-flow	[456] to [483]
NAS	[484] to [498]
Lithium	[499] to [511]
Flywheel	[512]
Capacitor	[513]
CAES	[514] to [515]

3. Worldwide distribution of electrical energy storage systems

The Worldwide capacity of grid-connected energy storage systems for electricity nearly amounts to 154 GW. This accounts for approximately 5.5 % of the installed generation capacity. Eastern Asia (meaning the countries Japan, China, Korea and Taiwan) dominates with an amount of grid-connected storage systems of 54 GW (accordingly more than 30 % of global storage capacity), following Europe[1] with 51 GW and North America (considering the countries Canada, USA and Mexico) with 33 GW. The remaining 16 GW are installed in Australia, South America and Africa. The largest amount of storage in the European context is located in Spain, France, Austria, Germany and Switzerland due to installed pumped hydroelectric power plants.

4. Historical development

To discuss current installed energy storage for electricity, it is useful to have a look at the historical development of installed systems. The installation of the first storage system for electricity was in 1923 when a PHES plant with a capacity of 2.3 MW commenced operations in Hessen, Germany. Until 1978 PHES was the only technology used worldwide.

[1] Database includes the countries: Austria, Belgium, Bulgaria, Croatia Czech Republic, Denmark, Finland, France Germany, Greece, Ireland, Italy, Lithuania, Norway, Poland, Portugal, Romania, Serbia, Switzerland, Slovenia, Spain, Ukraine, United Kingdom

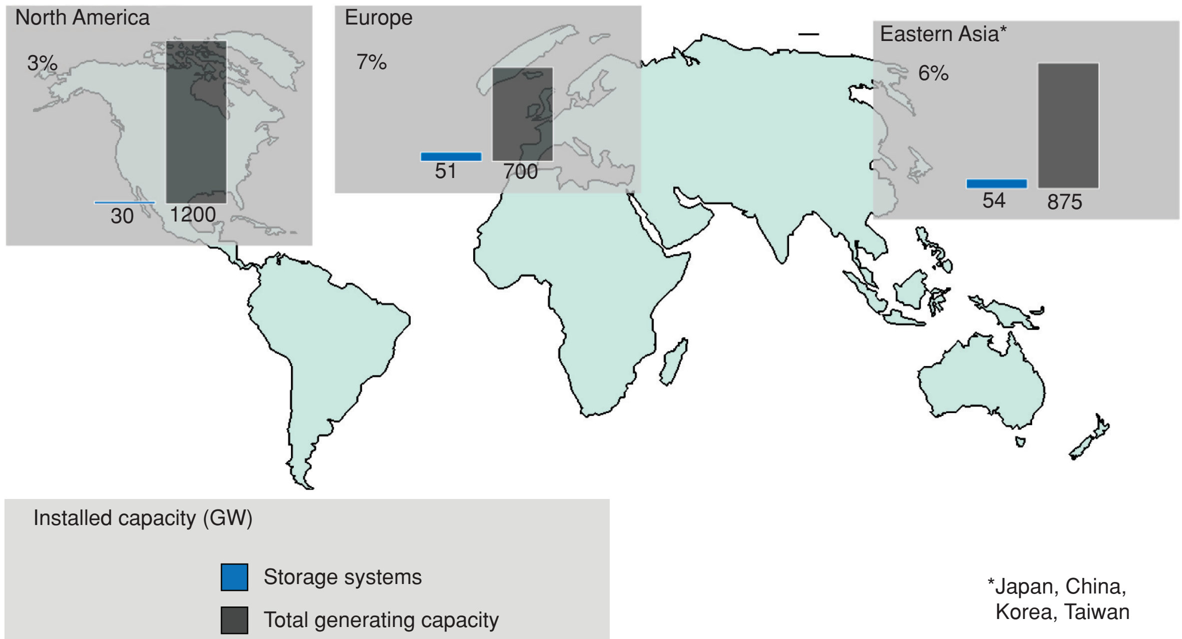

Figure 1: Worldwide distribution of electrical energy storage systems

It was not until then that CAES systems were operated. In 1980 the first lead-acid battery system was established. It is located in the city Selters in the west of Germany. CAES started with a plant size of 321 MW and the first lead-acid battery system was equipped with a capacity of 0.4 MW.

In 1987, the first 0.01 MW system using a redox-flow battery was set up in Alaska, USA. At that time, in 1994, a 5 MW power system with a lithium-ion battery was put into operation in New Jersey, USA. Since 1995 NaS batteries for grid connection are manufactured. However, in the initial phase a system size of only 0.5 MW was installed.

From 1960 to 1980, the number of PHES systems has tripled to 95 systems worldwide, with a doubling of capacity to 1,400 MW. There is a strong correlation to the development of nuclear power plants in this period of time. This increase is due to the fact that the awareness of nuclear energy and safe energy had grown due to the oil crisis in the beginning of the 1970s.

Another rapid increase is observed in NaS battery systems: from 2000 to 2006 the number of systems increased from 7 to 62. This is almost a tenfold increase. Accordingly the installed capacity grew from 18 MW to 119 MW during this period.

Redox-flow systems show a huge increase in number of installations from 2001 to 2012. Here, the installed base rose from 10 in 2001 to 31 plants in 2012. In parallel, the installed capacity of the plants increased by eight times.

However, in the past pumped hydroelectric energy storage was and still is today by far and globally the most widely installed technology with the highest installed capacity.

5. Technologies

The dominant technology in the energy storage market with regard to capacity is pumped hydroelectric storage power. More than 99 % of the globally installed storage capacity is provided by pumped hydro plants.

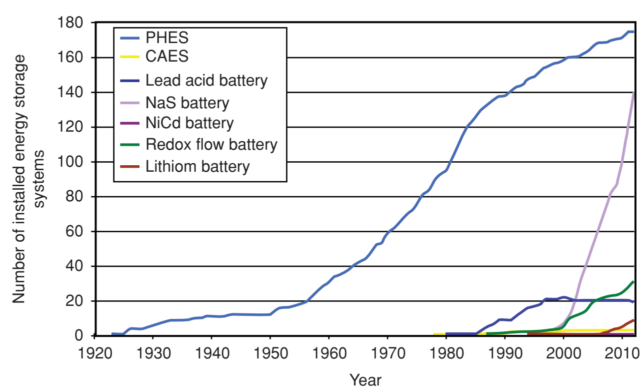

Figure 2: Development of installed electric, grid-connected storage systems

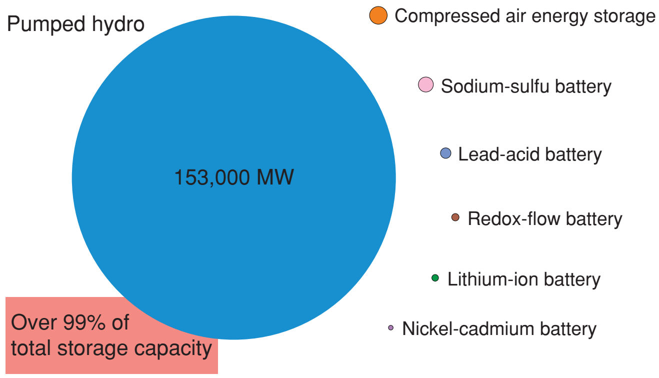

Figure 3: Proportion of installed capacity of various electric storage systems

5.1. Pumped hydroelectric energy storage (PHES)

As far as worldwide capacities are concerned a total of 153 GW are connected to the grid today. In Europe currently approximately 50.7 GW of pumped hydro plants are installed. In Eastern Asia there is a capacity of 54.1 GW with 61 plants installed. In North America the USA is the front-runner with 42 PHES-plants comprising an installed capacity of 32.5 GW.

A closer look at the distribution of storage systems in various countries shows that the majority of the installed capacity of PHES is located in the USA, China and Japan. In Europe the capacity is nearly equally divided between Germany, Switzerland, Austria, Spain, France and Italy. Here the contrast between the USA and Germany is remarkable. Although the number of plants is in the same order of magnitude – in Germany there are 32 and in the USA 42 plants – the average size of plants differs considerably. In the USA the plants have an average size of approximate 774 MW and in Germany they have 204 MW on average.

5.2. Compressed air energy storage (CAES)

On a global view there are just two Compressed-Air-Energy-Storage plants in operation. In Europe, more precisely in Huntdorf Germany, there is a plant that has been in operation since 1978 with a currently net electric power output of 321 MW [501]. The second active facility is in McIntosh, USA, running with an installed capacity of 110 MW and a storable amount of energy of 2,860 MWh. In Eastern Asia a grid-connected plant of CAES-technology is neither in operation nor envisaged. In North America there are currently eight units with a

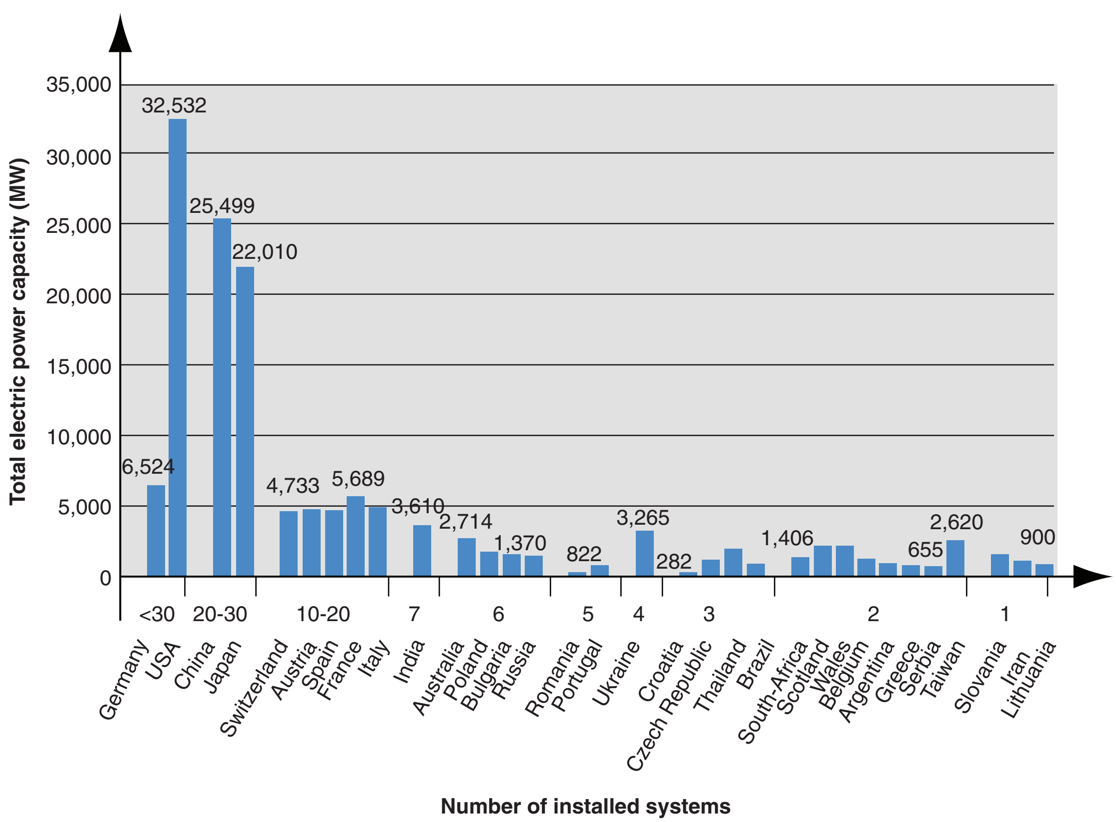

Figure 4: Total electric power capacity and number of installed electric, grid-connected PHES in various countries.

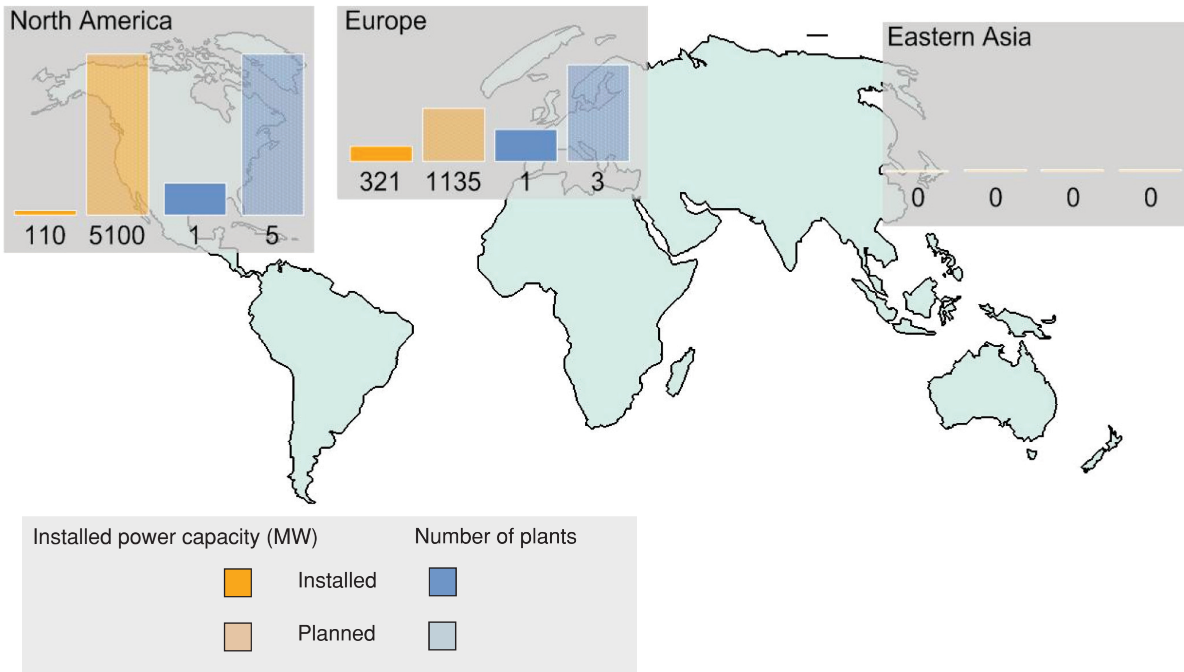

Figure 5: CAES plants installed or planned worldwide (number of installations and total capacity).

total capacity of 5,175 MW in the planning phase. In Europe the capacity of planned CEAS-plants is at 1,100 MW, distributed on five plants.

5.3. Sodium-sulfur batteries (NaS)

Sodium-Sulfur electric storage systems are largely distributed over Eastern Asia. There are more than 180 battery systems installed with a power capacity of 334 MW. Here, Japan is the market leader due to their island grid which requires more options to balance electricity at any point of time than for example in the trans-European grid. This grid is coordinated by the European Network of Transmission System Operators for Electricity (ENTSO-E) has the advantage of balancing

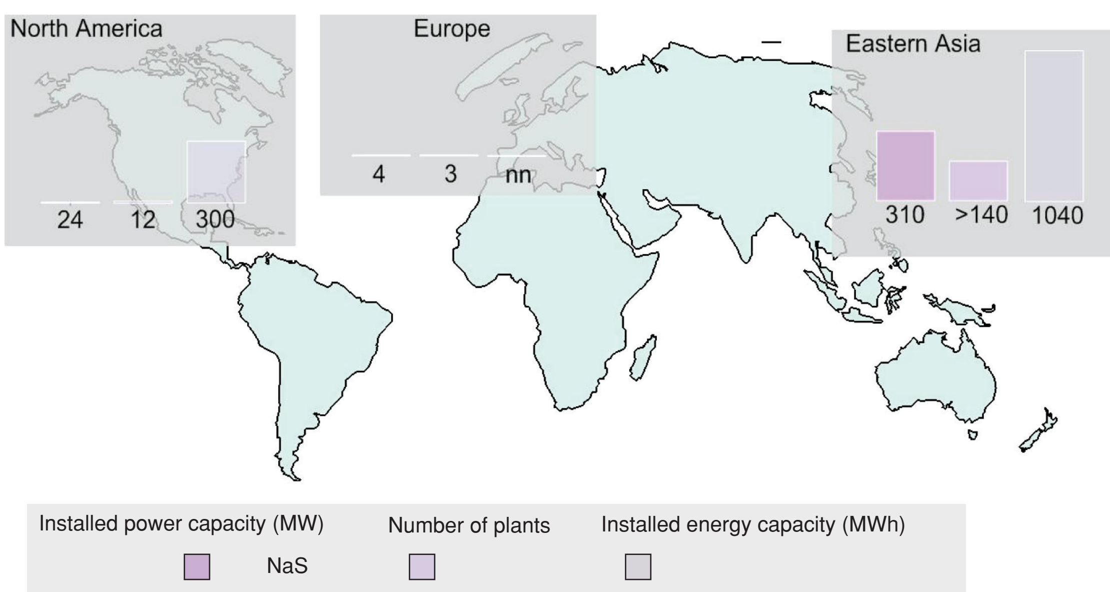

Figure 6: NaS-batteries installed worldwide (number of installations and total capacity).

fluctuations between a range of countries and regions. Besides Japan, there are also 12 grid-connected NaS battery systems with an overall capacity of approximately 23.5 MW in North America. These 12 systems can store 300 MWh of energy.

5.4. Lead-acid batteries

Figure 7 shows the number, the capacity and the worldwide distribution of lead-acid battery systems. The USA has the largest share of installed capacity – 37 MW and eight plants which can store 31 MWh of energy. Three of these eight installed systems are stationed in California, two in Alaska and one each in Hawaii, Indiana and Wisconsin. The lead-acid systems in the USA were constructed between 1987 and 2000.

In Germany there are three plants with an installed power capacity of 1.63 MW and 4.8 MWh energy capacity in operation. The systems in Germany are located in Herne-Sodingen, Selters and Stuttgart. The lead-acid systems in Germany were built between 1980 and 1999. Both, South Africa and Japan also have one installed lead-acid battery system. In South Africa a system with 4 MW and 7 MWh is available and Japan's system has a total power storage capacity of 1 MW with 4 MWh energy storage capacity.

5.5. Various technologies

Apart from bulk storage technologies such as CAES or PHES, there is a minor number of small scale storage systems. The best known of these energy storages will be discussed in the following: redox-flow batteries, lithium-ion batteries and flywheels (see Figure 8).

In the USA there is the largest number of redox-flow systems with 13 batteries and a total capacity of 19 MW and 110 MWh. In Japan a total of 11 redox-flow systems are in operation, hence there is an installed capacity of 13 MW and 29 MWh energy capacity. In Australia and China are 1.5 MW (8 MWh) and 6 MW (15 MWh) overall installed, in each country separated into four systems.

Most of the lithium-ion battery systems are installed in the USA and Chile. The USA has seven systems with an installed capacity of 60 MW (51 MWh) and Chile has two systems with a total capacity of 32 MW and energy capacity of 8 MWh. In the UK a lithium-Ion system with a capacity of 2.9 MW is in the planning phase.

The USA has five plants using flywheel systems, so the amount of installed storage power in this sector is up to 6 MW. This is the only region with a remarkable flywheel system. There is only one NiCd system with a power capacity of 27 MW which can store 7 MWh of energy in the USA, namely in Alaska (see Figure 7).

Ten hydrogen storage systems exist worldwide. Four of them are located in Germany, two in Spain, one in France, two in the UK and one in Canada. Thus, there is a global capacity of 1.7 MW in hydrogen storage systems.

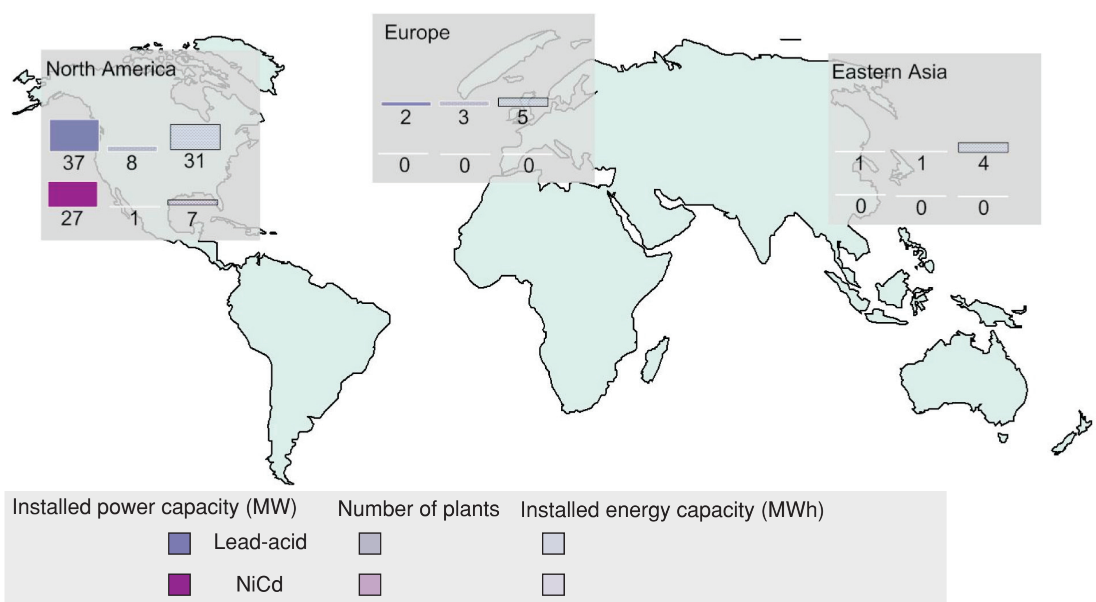

Figure 7: Lead-acid and NiCd-batteries installed worldwide (number of installations and total capacity).

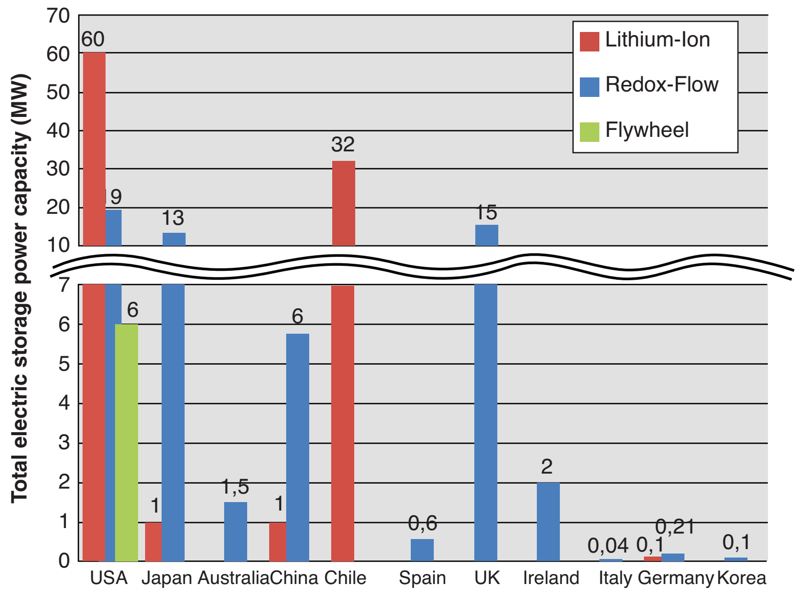

Figure 8: Redox-flow, lithium-ion and flywheel systems installed worldwide (total capacity).

6. Executive summary

Since there is a strong need to store electrical energy, this article gives an overview and detailed data basis (references) on the current situation of worldwide energy storage for electricity. The main technologies are analyzed with respect to storage size and the number of installed systems in all corresponding regions. The technologies treated in this article are PHES, CAES, NaS batteries, lead-acid batteries, redox-flow batteries, lithium-ion batteries and flywheels. It can be noted that the worldwide distribution is divided between Europe, Asia and North America. Europe is the pioneer followed by Eastern Asia and North America.

The historical course of the development of storage devices for electricity shows that the numbers of storage devices grow strongly. Especially in the last 15 years there has been a huge increase of electrochemical storage systems.

However, pumped hydroelectric energy storage systems have in the past been by far and globally the most widely installed technology with the highest installed capacity, and they still are today. The largest number of installed PHES systems can be found in Europe, followed by the USA. In the field of compressed air energy storage there are just two systems in operation worldwide. One system is installed in Germany and another in the USA. Based on the interaction between grid and storage, large grids with less fluctuation are mostly connected to huge storage devices such as PHES or CAES. Therefore fields of application for those systems are among others ancillary services for power plants. Battery systems are often used in small grids, whereas applications are providing balancing power, warranty of power quality and uninterruptible power supply.

The pioneer of installed battery systems is the USA. Most of the existing lead-acid battery systems are installed there. Together with Chile the USA has the highest installed capacity of lithium-ion battery systems worldwide. The USA has seven systems with an installed capacity of 60 MW and Chile has two systems with a total capacity of 32 MW. Furthermore, plenty of redox-flow systems can be found in the USA, besides the UK, Japan and China. The main area where sodium-sulfur batteries are in operation is Eastern Asia. In this region most of the plants and the highest capacity are in operation.

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