Energy Storage Label

A method for comparing storage systems over all ranges

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Summary

This report describes the creation and use of a database for energy storage technologies which was developed in conjunction with Netbeheer Nederland and the Hanze University of Applied Sciences. This database can be used to make comparisons between a selection of storage technologies and will provide a method for ranking energy storage technology suitability based on the desired application requirements. In addition, this document describes the creation of the **energy storage label** which contains detailed characteristics for specific storage systems. The layout of the storage labels enables the analysis of different storage technologies in a comprehensive, understandable and comparative manner. A sampling of storage technology labels are stored in an excel spreadsheet and are also compiled in Appendix I of this report; the storage technologies represented here were found to be well suited to enable flexibility in energy supply and to potentially provide support for renewable energy integration [37] [36]. The data in the labels is presented on a series of graphs to allow comparisons of the technologies. Finally, the use and limitations of energy storage technologies are discussed. The results of this research can be used to support the Dutch Renewable Energy Transition by providing important information regarding energy storage in both technically detailed and general terms. This information can be useful for energy market parties in order to analyze the role of storage in future energy scenarios and to develop appropriate strategies to ensure energy supply.

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1) Introduction

Considering the objectives of the European Union regarding climate change mitigation, renewable energy production will likely increase over the next few years, while fossil energy production will likely decline. A big part of this renewable energy production will likely be made up of intermittent energy sources, such as solar and wind energy. One concern with this scenario is that energy will not necessarily be available when there is demand. Storage technologies can help solve this problem by storing peak production from intermittent sources and filling demand during production lows. This enables energy storage technologies to provide balancing services to help meet energy demand. Therefore, energy storage could play an important role in the future energy mix by providing energy flexibility.

There is a considerable amount of research available regarding the properties of different methods of energy storage. By reviewing available literature, it is possible to gather highly detailed information regarding energy storage technologies. There are many studies which summarize important properties of energy storage technologies[1]. Other reports delve into the importance of energy storage for particular applications[2]. Still other reports provide a thorough analysis of the current use and future potential of different storage technologies, particularly with respect to renewable energy integration[3]. However, since energy storage technologies vary greatly in their properties and applications, it can be difficult to make comparisons between these different technologies.

Many studies focus on either thermal or electric energy storage without drawing a clear link between the two. Broadly speaking, energy consumption is centered on three energy end-uses: **thermal energy**, **electric energy** and **transportation**. By linking the thermal, electric and transportation energy systems, we can create a more versatile and resilient energy sector. Energy storage can help achieve this aim by enabling thermal energy to help meet electric or transportation demand and vice versa. For example, stored hydrogen gas can be used to produce electricity, heat, transportation or a combination of these. Gas storage in particular is considered to be closely linked with both thermal and electric energy storage, with a notable focus on the application of combined heat and power (CHP) systems. [1]. In summary, energy storage can provide the support required to help match energy production with energy demand for a variety of energy end-uses.

The intention of this project was to develop a label system which presents a standardized presentation of storage technology characteristics in an easy-to-interpret way. These **storage labels** were then compiled in a database. An Excel-based application was developed to enable easy access to the information contained within the database. The storage label system provides the ability to interpret the advantages and disadvantages of various energy storage technologies based on the desired storage application, with a particular focus on the integration of the electricity and natural gas networks. This information will be valuable for evaluating future energy scenarios and determining the potential of energy storage to help ensure energy supplies in the future.

This report is divided into the following sections: Section 2 describes the methodology used to develop this report and the **storage label**. Section 3.1 describes the operating characteristics which were analyzed in this study. Several different storage technologies were researched in this study; a brief summary of these technologies is presented in Section 3.3. Section 3.4 explains a number of comparisons which have been made between different storage technologies. Section 4 presents important considerations and limitations of the storage label system. In Section 5 some general conclusions from this study are set out and Section 6 provides recommendations for future work in this area.

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[1] [4], [5], [7], [9], [13], [15], [30], [31], [36]
[2] [3], [8], [34], [38], [43]
[3] [1], [6], [21], [37], [39], [42]

2) Methodology

The aim of this project is to accurately summarize data regarding different energy storage technologies. A study of current literature regarding storage technologies provided the basis for this project. Fundamental characteristics of different energy storage technologies were determined based on this literature review. This selection of characteristics was then refined through discussion with energy professionals and project stakeholders within Netbeheer Nederland. With this information, a **storage label** is designed which contains the fundamental operating characteristics of energy storage technologies. Storage labels for various storage technologies are created in an Excel database. Using the Excel application (which draws on information from the database), the user can generate interactive graphs can be developed which allow an easy comparison of different technologies. All of the storage labels which have been developed are also available in Appendix I.

3) Energy Storage Systems

The information presented in this study includes: A description of the key operating characteristics discussed in this study; a detailed overview of the storage label which was developed; a brief description of the different storage technologies that were analyzed in this study; a thorough comparison of these technologies utilizing the results obtained from this study.

All data presented in this report and the Excel database are derived from publications. Where a range of values is presented regarding an operating characteristic, the storage label notes a lower and an upper limit. In this way, the data presented in this study is representative of all the literature which has been reviewed during this study. References for all cited values are indicated in the Excel storage labels and all references used are summarized at the end of this report.

3.1) Key Operating Characteristics

The first aim of this study was to determine the key operating characteristics of energy storage systems, which are closely linked with the energy services (i.e. applications) different means of storage can provide. Below is a description of the storage system **key operating characteristics** and **expert properties** considered in this study, with pumped hydroelectric storage used as an example case to help illustrate what these characteristics represent:

1. **Discharge power** refers to the rate at which energy can be removed from storage per unit of time. For instance, a pumped hydro facility with a discharge power of 5 MW is able to produce 5 MWh of electricity every hour [2].

2. **Charge power** refers to the rate at which energy can be placed into storage per unit of time. For instance, a pumped hydro facility with a charge power of 5 MW is able to store 5 MWh of electricity every hour (by pumping water into the storage reservoir) [2].

3. **Energy storage capacity**[4] refers to the total amount of energy which can be placed in storage. For instance, a pumped hydro facility may be able to store several hundred MWh of electricity in the form of potential energy of water [3]. The energy storage capacity is often a physical limitation. In the case of a pumped hydro facility, the larger the water reservoir, the larger the energy storage capacity.

4. **Discharge time** is the amount of time during which a storage system can provide energy at the maximum power level. Looking over the range of storage technologies, discharge time can range from a few milliseconds to several months. For example, a pumped hydro facility with a discharge

[4] It shoulb be noted that energy storage capacity refers to the amount of energy which can be held within a storage system. This is not to be confused with the capacity of energy which can be extracted from storage.

power of 5 MW and an energy storage capacity of 20 MWh would have a discharge time of 4 hours. It is important to note that the discharge time presented above is a strict relation between discharge power and energy storage capacity; it is the amount of time required to fully discharge a storage system.

5. **Charge time** is the amount of time it takes to completely refill the storage system at maximum charge power. Looking over the range of storage technologies, charge time can range from a few milliseconds to several months, and energy storage capacity must reflect these requirements. For example, a pumped hydro facility with a charge power of 5 MW and an energy storage capacity of 20 MWh would require 4 hours of continuous pumping in order to completely refill an empty water reservoir.

6. **Operational Time** is the amount of time for which a storage system can be expected to provide a reasonable (i.e. average) discharge power. It is not always desirable or practical to discharge a storage system at maximum discharge power. For example, a gas storage facility is expected to provide gas throughout the winter, though it may be fully emptied within a few weeks if discharged continuously at maximum output. Operational time reflects this tendency by indicating the amount of time for which a storage system can typically provide energy, but gives no indication as to the *amount* of energy provided. The amount of energy provided is simple a ratio of the energy storage capacity and the operational time of the storage system.

7. **Energy density** refers to the physical space required to store a given amount of energy. This is particularly important for mobility and household applications, where space can be limited and excess weight is undesirable. In the case of pumped hydro, energy density is relatively low and is proportional to the density of water and the elevation at which the water is stored. For example, 1000 m^3 of water elevated by 10 m can store roughly 25 kWh of energy.

8. **Discharge response time** refers to the amount of time required between the request for energy from the storage system and the actual delivery of energy from the storage system. For some applications (especially in the electricity sector), response times must be within a few minutes to being nearly instantaneous, whereas in other areas (especially in the thermal sector) response time can be postponed up to several days. A storage system's response time severely restricts its suitability for certain applications. For example, a pumped hydro facility requires approximately 15 minutes to begin producing electricity. This makes pumped hydro potentially suitable for hourly or daily energy balancing, but not for uninterruptible power supply where response times must be nearly instantaneous.

9. **Charge response time** refers to the amount of time required between the request to deliver energy into storage and the actual delivery of energy into the storage system. A fast response time can ensure that surplus energy is stored as soon as it becomes available. A slower response time will likely result in some energy losses since surplus energy must be disposed of until the storage system comes online. A pumped hydro facility can begin storing electricity within a few minutes of its availability and is therefore an effective means of storing surplus electricity.

10. The **energy carrier** is the form which energy takes when it is extracted from storage. In this study, storage technologies are considered which can provide energy in the form of electricity, gas, heat or liquid fuel. Typically, energy is converted to another form when it is stored and is converted back when retrieved. For example, in a pumped hydro facility electricity is used to pump water into a reservoir: the electricity is considered to be stored in the potential energy of the pumped water. When the water is released from the reservoir, potential energy is converted back into electricity. In this case, the energy carrier is considered to be electricity because electricity is delivered to and retrieved from the pumped hydro storage system.

11. **Costs** are generally evaluated in terms of the cost per unit of power as well as the cost per unit of stored energy capacity. While costs do not directly affect the suitability of a storage technology for a particular application, they are an important parameter when considering which technology to invest in. With the example of pumped hydro storage, costs per unit of power and per unit of energy are approximately 2,050 €/kW and 360 €/kWh respectively [3] [4] [5].

12. **Ramp up / Ramp down speed** is the capability of a storage system to change its power output over a given amount of time. Ramp up / ramp down speed is indicative of how well a storage system can react to fluctuations in demand. For example, it takes 10 to 60 minutes to change the power output of a pumped hydro facility by 1 MW [5]; this flexibility is significant, but it may not be fast enough to respond to sharp peaks in demand or steep drops in production.

13. **Cost projection 2020** is the predicted cost per unit of power and cost per unit of energy by the year 2020. In the case of pumped hydro, a mature and developed technology, costs are likely to remain fairly consistent. This characteristic is more relevant to technologies currently under development, such as lithium-ion batteries, where increases in production efficiency and product quality are expected to reduce costs significantly in the near future.

14. **Self-discharge rate** is the amount of stored energy lost per unit of time. For a pumped hydro facility, stored water is lost to evaporation. It is important to note that with thermal storage technologies, self-discharge rates are highly variable and situation-dependent. Therefore, by convention, self-discharge is not considered in these cases; instead, energy losses are accounted for in the **roundtrip efficiency** (described below).

15. **Roundtrip efficiency** is the percentage of energy lost when inserting and later extracting energy from storage. For example, pumping water into a reservoir has an efficiency of approximately 75%; producing electricity from water in a reservoir has an efficiency of approximately 90%. Therefore, the roundtrip efficiency (converting electricity to potential energy then back to electricity again) is approximately 68%.

16. **Lifetime** is the number of years or cycles a technology is designed to function for. A pumped hydro facility can have a lifetime of 50 years or more. Cycle lifetime is not applicable to all technologies, but has a strong effect on the performance of batteries and supercapacitors. Cycle lifetime indicates the number of times a storage system is designed to be fully charged and discharged without adverse effects on system performance.

17. **Storage time** is the amount of time energy is typically stored for. In other words, storage time represents the average amount of time for one full storage cycle (i.e. completely charging and discharging a storage system). This parameter is directly related to self-discharge rate and ranges from several seconds to several months. A pumped hydro facility can have a storage time of several months (though it is typically cycled more frequently) without losing significant amounts of energy. Storage time is more relevant for technologies such as flywheels which can lose up to 40% of their stored energy per hour.

3.2) Additional Properties

The **key characteristics** and **expert properties** mentioned above are important for determining the suitability of a particular storage technology for a given application. However, there are some additional points of interest when investigating storage technologies, which are described below:

1. **Suitable applications** describe the services which a particular storage technology is able to provide. Suitable applications can be broadly divided into four categories (depending on time scale) and further divided into specific services [3] [6]:
   a. Sudden (i.e. several seconds), unexpected deviations in energy supply. Examples include:
      - Frequency control in the electricity grid
      - Reactive power provision in the electricity grid
      - Uninterruptible power supply (e.g. for server banks and hospitals)

   b. Predictable, short-term (i.e. several hours) deviations in energy supply. Examples include:
      - Hourly balancing of energy demand
      - Daily balancing of energy demand
      - Congestion relief of the transmission and distribution grids during peak demand
      - Off-grid / Micro-grid support (this includes a variety of services, but is a general term used to indicate increased resilience of an isolated energy grid).
      - Off- to on-peak shifting and firming of loads (storage can store energy when excess production is available and provide energy when demand increases).
      - Demand shifting and peak demand reduction (storage can indirectly reduce demand during peak hours by allowing consumers to shift their demand to off-peak hours).
      - Energy arbitrage (i.e. buying and storing energy when costs are low, selling energy when costs are high)
      - Waste heat utilization

   c. Predictable, long-term (i.e. several weeks or months) seasonal deviations in energy supply. Examples include:
      - Seasonal balancing of energy demand
      - Energy arbitrage

   d. Special circumstances (e.g. calm weather or cold snaps) which limit the production of energy. Examples include:
      - Hourly balancing of energy demand
      - Daily balancing of energy demand
      - Black start capability for power plants
      - Transportation, which can be enabled by energy storage systems

   For example, pumped hydro storage is best suited to support predictable, short-term deviations in energy supply. These include hourly balancing, daily balancing, off- to on-peak shifting and firming, energy arbitrage and reactive power. Pumped hydro storage is also able to provide frequency control, black start capability and off-grid / micro-grid support, although it is not ideally suited for these applications.

2. **Sector for use** describes in which sector of the grid a particular energy storage system is likely to be used. Energy grids can be described as an interlinked set of energy producers and energy consumers. Historically, energy producers have been large-scale and centralized, whereas energy consumers have been small-scale and decentralized, with the transmission and distribution network providing a link between these sectors. Typically, grid capacities are quite large (MW to GW range) closer to energy producers and gradually diminish (kW range) closer to consumers. The advent of small-scale renewable energy and other technologies (such as micro-CHPs) has altered this conventional grid structure by allowing the decentralized, small-scale production of energy. Today, the energy grid can be broken down into 4 main sectors, distinguished by their location in the grid network and the typical grid capacities they are limited to [6] [7] [1]:

   a. Supply (100 MW – 100 GW)
   b. Transmission and distribution (15 kW – 100 MW)
   c. Consumer / Demand (<15 kW)
   d. Renewable energy integration (kW – MW)

   For example, a pumped hydro facility will almost always be located in the supply sector since these facilities are typically large-scale (i.e. several MW) and centralized.

3. **Technology Maturity:** When investing in a technology, it can be important to understand the technology's maturity. In this study, maturity ranges from research-phase to demonstration-phase to deployed-phase to commercial-phase. Research-phase implies that the technology is still being developed and is not readily available. Demonstration-phase implies that the technology is currently being tested and used in research. Deployed-phase implies that the technology is being used and produced, though it may still have some reliability issues and a high cost. Commercial-phase implies that the technology is proven and sees regular use throughout the world. Pumped hydro is considered to be a mature technology because it has been in active use for several decades and has seen little new development in recent years.

4. **Reliability**: Reliability can be difficult to measure, especially with new technologies where system lifetime is still unclear and experience is lacking. However, when the information is available, this study indicates a technology's reliability by recording the average number of days per year during which the technology cannot be used due to unplanned shutdowns.

5. **Downtime** is a measure of the percentage of time during which a storage technology is unavailable for use due to scheduled maintenance.

6. **Safety**: It can be hard to measure safety in absolute terms, so this report simply records any notable safety considerations associated with a given technology. For example, pumped hydro dams can have catastrophic failures if they are not properly maintained.

7. **Sustainability** is also indicated, although this is very difficult to determine accurately. In the current report, when information is available, technologies are given a high or low rating based on their recyclability, environmental impact and worldwide effect on resource depletion. This ranking is very abstract and must be considered in the context of the source being cited. For example, pumped hydro facilities can have large environmental impacts when they are constructed. This is due to the potential flooding of large areas of land and disruption of natural waterways [8].

8. Finally, all technologies have certain unique traits (referred to as **final remarks**) which must be taken into account. This report summarizes notable technology characteristics which may not be readily apparent from their properties alone. For example, pumped hydro storage is highly dependent on the presence of appropriate geographic conditions: a pumped hydro facility cannot be constructed without natural formations for creating a lower and an upper reservoir within close proximity.

3.3) Storage Label

The collection of storage labels produced during this project is presented as a separate Excel document. Each label refers to one technology and provides a range of properties which were found in literature. Different technologies can be directly compared based on their characteristics and suitability for certain applications. It is important to note that some features are only accessible in the digital excel-based library. Specifically, the sources used for each characteristic and the ability to change the units for various characteristics can only be seen in the excel spreadsheet. Below, the details of the storage label are shown and described. A detailed description and examples of the storage label can be found in Appendix I.

3.4) Storage Technology Overview

Several different storage technologies were chosen for this study. Below, we give a brief description and some important features of the technologies which were analyzed. The Excel application can provide technical details for each technology, and Section 3.4 of this report provides a summary of the different technologies present in the Excel application. More detailed information for each of these technologies can be found in the Excel application.

1. **Flywheel** - Mechanical Storage: A flywheel is a rotating mass which is connected to the electricity grid via a motor/generator. Energy is stored and retrieved by speeding up or slowing down the speed of rotation [9]. Flywheels are typically used for frequency regulation, reactive power generation and short-term uninterruptible power supply in electricity grids. Their fast reaction time (near instantaneous) and high reliability make flywheels an ideal technology for managing power quality, especially as the energy sector moves away from traditional turbine generators towards renewables, which are less able to regulate grid frequency and reactive power [1] [3] [9]. However, flywheels are limited by their high self-discharge rate (3-40 %/hr) and high initial cost [8].

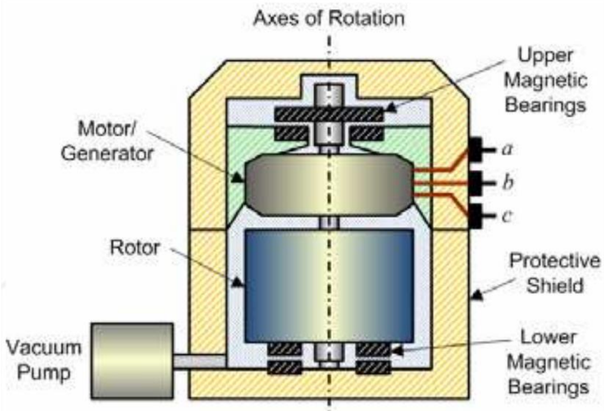


Figure 1 – Flywheel [10]

2. **Pumped Hydro Storage** - Mechanical Storage: Pumped hydro storage is a hydro electricity generating station with an upper and lower reservoir. When there is surplus electricity available, water can be pumped from the lower to the upper reservoir. When there is a demand for electricity, water is released from the upper reservoir to spin turbines and generate electricity [9]. Pumped hydro is able to provide the same services as many conventional electricity generation technologies (i.e. frequency control, reactive power, daily and hourly balancing power and off- to on-peak shifting and firming [3]). Pumped hydro storage is a highly efficient, low cost form of energy storage with a long lifetime and low cycling degradation [9]. This technology has a limited continuous operating time (1 to 100 hours [2] [9]). Pumped hydro is restricted by geographic requirements [8] [9]. Pumped hydro storage differs from traditional hydroelectric dams because energy must be invested into the system (i.e. by using electric pumps) before energy can be extracted.

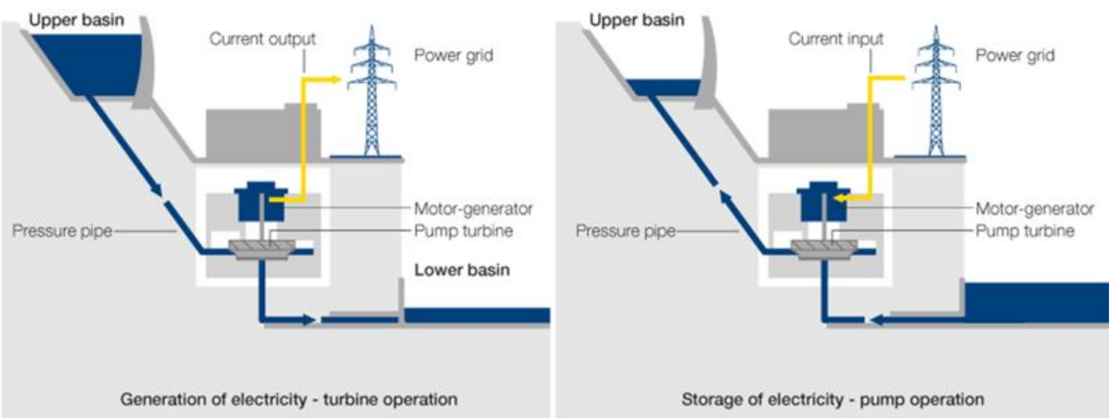


Figure 2 - Pumped Hydro Storage [11]

3. **Compressed Air Energy Storage (CAES)** - Mechanical Storage: Air is compressed and stored in underground caverns using surplus electricity. This compressed air is later released and passed through a conventional gas turbine to produce electricity [9]. CAES has a high storage capacity (115 to 360 MWH [9]), high power output (50 MW [8]), fast response time (5 minutes [1]) and can provide many energy services [3]. However, it should be noted that air must be heated when it is decompressed and this heat is typically derived from combusting natural gas, which greatly reduces the efficiency of the overall system [12] [13]. Also, it can be difficult to obtain an appropriate storage area for the compressed air due to the physical requirements of storing large amounts of air under pressure [9]. There is research being done to store the heat extracted when air is compressed and use this same heat to decompress the compressed air. Heat storage will improve the CAES system efficiency, although this idea is still in the development stage [12].

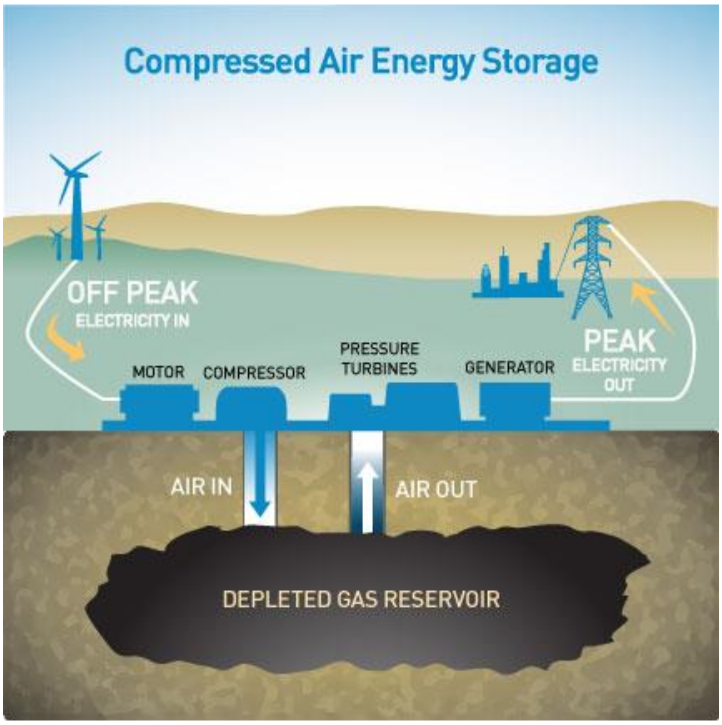


Figure 3 – Compressed Air Energy Storage System [14]

4. **Lead Acid Batteries** - Electrochemical Storage: Lead acid batteries store electricity by charging an electrochemical cell composed of a metallic sponge lead anode, a lead-dioxide cathode and sulfuric acid solution electrolyte [15]. Several cells can be connected in parallel or in series to significantly increase power output and energy storage capacity [15]. Lead acid batteries can be used for emergency uninterruptible power supply and black-start capabilities, as well as off-grid and micro-grid support, hourly balancing, demand shifting and peak reduction and transportation [3]. Lead acid batteries are often paired with photovoltaic panels to provide electricity in off-grid regions [3]. Lead acid batteries are a common, low cost and relatively simple method of storing electricity [15]. If used correctly, these batteries have a good life cycle and good reaction kinetics (i.e. fast response time and high surge-to-weight ratio) [8] [15]. In addition, lead acid batteries are highly recyclable where such infrastructure exists [8]. Some drawbacks include a very short lifetime if not operated correctly (e.g. deep discharging) [8], the use of toxic materials and hazardous chemicals (e.g. lead and sulfuric acid [9]) and the potential for producing explosive gas mixtures in enclosed areas [5].

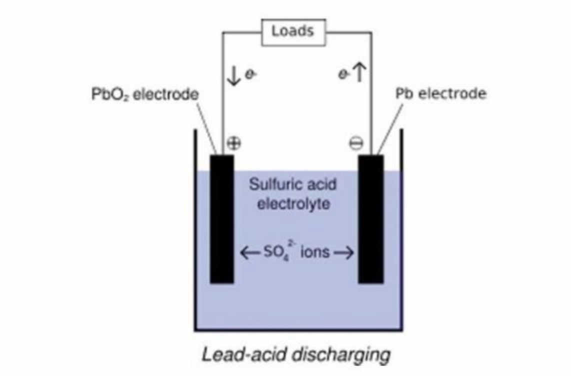


Figure 4 - Lead Acid Battery Discharge Diagram [16]

5. **Lithium Ion Battery** - Electrochemical Storage: Lithium batteries store electricity by charging an electrochemical cell composed of a graphite cathode and lithium metal anode [15]. Several cells can be connected in parallel or in series to significantly increase power output and energy storage capacity [15]. Lithium ion batteries have many useful applications, including black start capability, off-grid and micro-grid support, hourly balancing, demand shifting and peak reduction and transportation [3]. Compared to other batteries, lithium ion batteries have a high energy density (currently the highest energy density in commercially available batteries, making them ideal for electric transportation), low self-discharge rate and high roundtrip efficiency [5] [9]. In addition, lithium ion batteries are highly recyclable where such infrastructure exists [15]. Unfortunately, this all comes at a relatively high cost [8]. Lithium ion batteries require over-charge protection and can be flammable if exposed to air [8]. Due to their increasing lifetimes and quickly decreasing costs, lithium ion batteries are becoming increasingly prominent in the battery market [4].

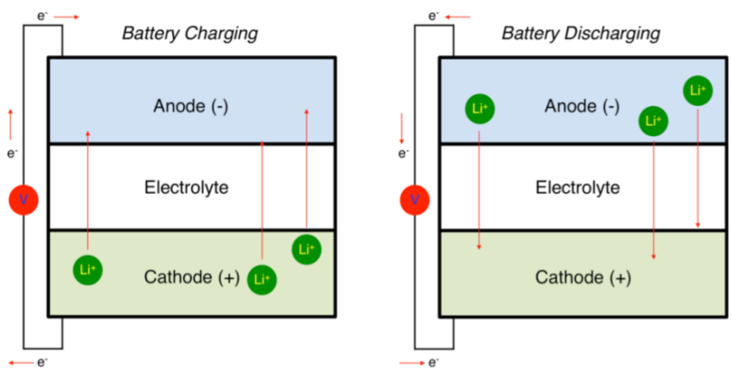


Figure 5 – Lithium Ion Battery Charge and Discharge Diagrams [17]

6. **Vanadium Redox Flow Battery** - Electrochemical Storage: Flow batteries employ a reversible fuel cell with the electro-active components dissolved in an electrolyte [9]. This feature allows the decoupling of power and energy ratings, which allow power output and energy storage capacity to be completely independent [15]. This enables the system to be easily customized for specific power and energy requirements, making vanadium redox flow batteries suitable for hourly balancing, black start capabilities, off-grid and micro-grid support, off- to on-peak shifting and firming, demand shifting and peak reduction and uninterruptible power supply [3] [9]. Currently this technology is still in development and has high costs and space requirements, although costs are expected to drop in the coming years [9].

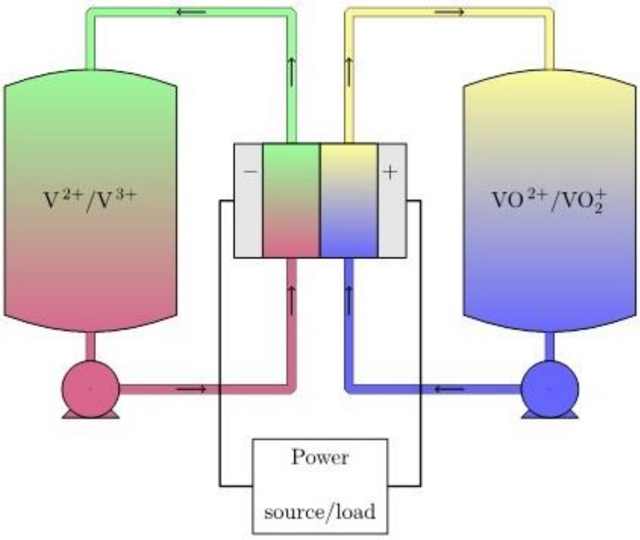


Figure 6 - Vanadium Redox Flow Battery [18]

7. **Supercapacitors** - Electrical Storage: By storing electricity in large electrostatic fields between two conductive plates, supercapacitors allow electricity to be quickly stored and released in order to produce short, high bursts of power [6]. Supercapacitors can be continuously charged and discharge with a low amount of degradation (they can perform up to 100 million cycles [1]), and can charge or discharge almost instantaneously [15]. This makes supercapacitors ideally suited for grid frequency control [9] and transportation (specifically regenerative breaking and acceleration) [15]. This technology is still in development and is not currently commercially available [2].

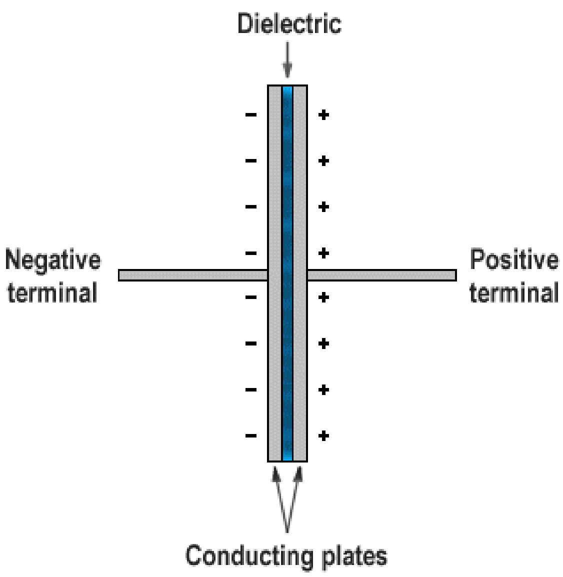


Figure 7 - Supercapacitor [19]

8. **Superconducting Magnetic Energy Storage (SMES)** - Magnetic Storage: SMES stores flowing electric current in a superconducting coil [5]. This technology can be used to effectively manage power quality in the electricity grid and provide short-term uninterruptible power supply [2] [6]. SMES is extremely efficient, fast reacting and easily scalable [5]. SMES has low losses except for the parasitic losses required to keep the coil cooled [5]. Also, there are concerns regarding the effects of strong magnetic fields on human physiology [5]. Currently, this technology is still in development [9] and costs are relatively high [1] [6] [5].

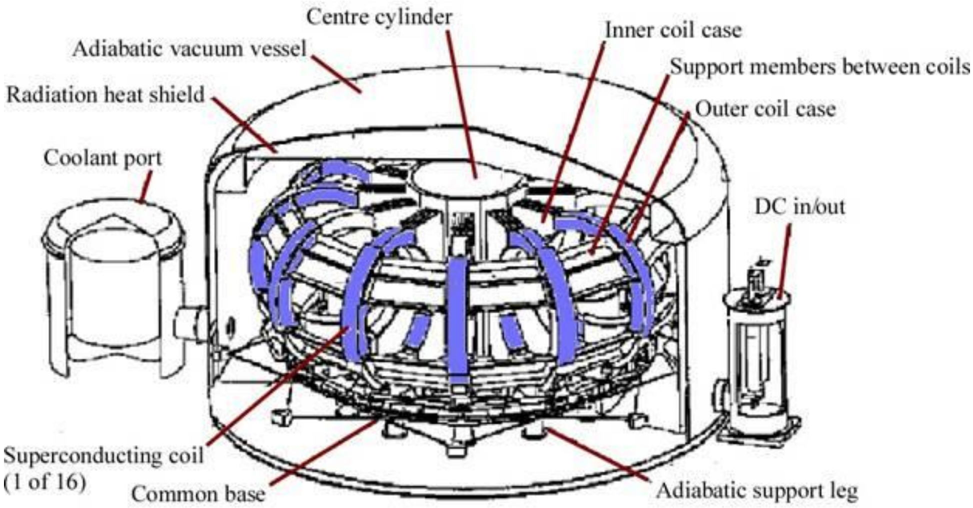


Figure 8 - Superconducting Magnetic Energy Storage [20]

9. **Hydrogen Gas Storage** - Surplus electricity can be stored in the form of hydrogen gas using an electrolysis process [7]. Hydrogen can be readily stored in and extracted from appropriate facilities such as salt caverns [7] or gas grids (current gas grids can accommodate up to 5% hydrogen content (equivalent to 1.8 TWh in Germany) without a significant impact on performance [8]). Hydrogen can be fed into a fuel cell or combusted to provide a combination of heat and electricity. This energy can provide grid frequency control, hourly, daily or seasonal balancing, transmission and distribution relief, energy arbitrage and transportation [8] [21]. Hydrogen electrolysis is considered to be a relatively clean energy if the surplus electricity used to produce it comes from a renewable source [8]. Hydrogen electrolysis allows the storage of large amounts of energy (several GWh) over a long period of time (several months) [8]. This storage system has a high roundtrip efficiency (70-80%) if hydrogen is combusted to produce thermal energy, although this number drops significantly (to 40-45%) if hydrogen is re-electrified [8]. This technology is currently in the demonstration phase, although much work is being done and it may be deployed in the near future [8].

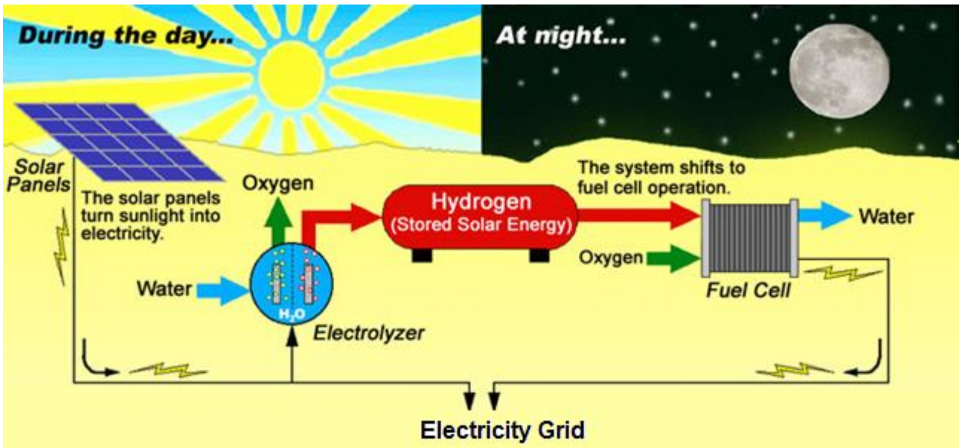


Figure 9 - Hydrogen Gas Storage [22]

10. **Salt Caverns (Methane Storage)** - Salt caverns can be used as gas storage facilities which typically have less working volume than larger aquifers and depleted gas/oil fields [23]. Salt caverns are used mainly for trading purposes, peak supply, hourly and daily balancing [23] [24]. This storage system is a proven technology and is very safe and reliable [25].

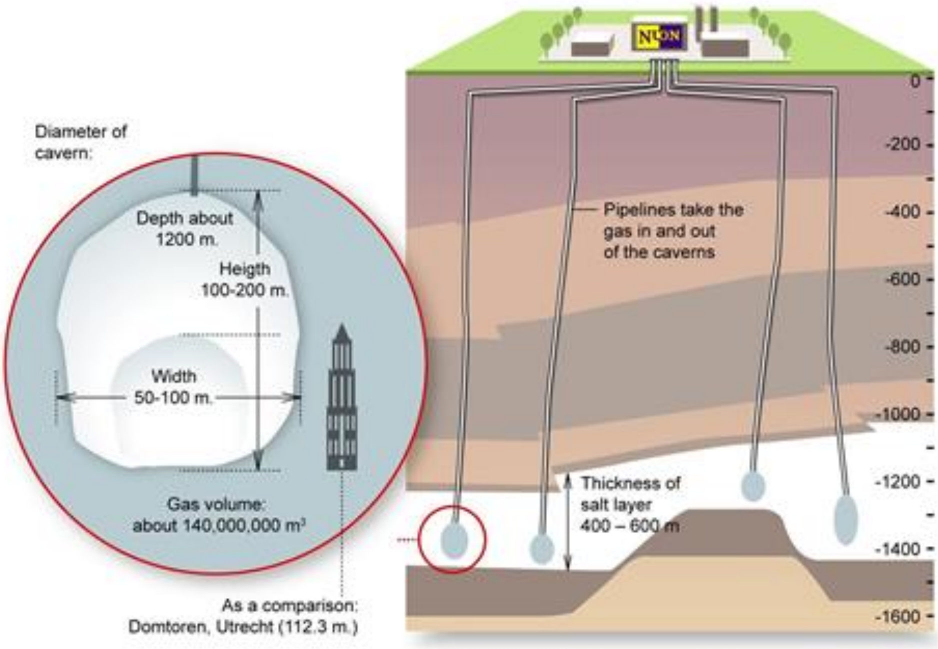


Figure 10 - Gas Storage in Salt Caverns [26]

11. **Aquifers & Depleted Gas/Oil Fields (Methane Storage)** - Aquifers and depleted gas/oil fields are typically used for seasonal gas storage or as a strategic stock to support low levels of natural gas production [23]. This technology is well established and reliable and can store several TWh of natural gas (up to 45 TWh in the Netherlands [27]). These large storage facilities require a cushion gas (i.e. the gas which is intended as a permanent addition to a storage system to maintain pressure) of 50-80% which makes initial costs highly dependent on the price of natural gas [23].

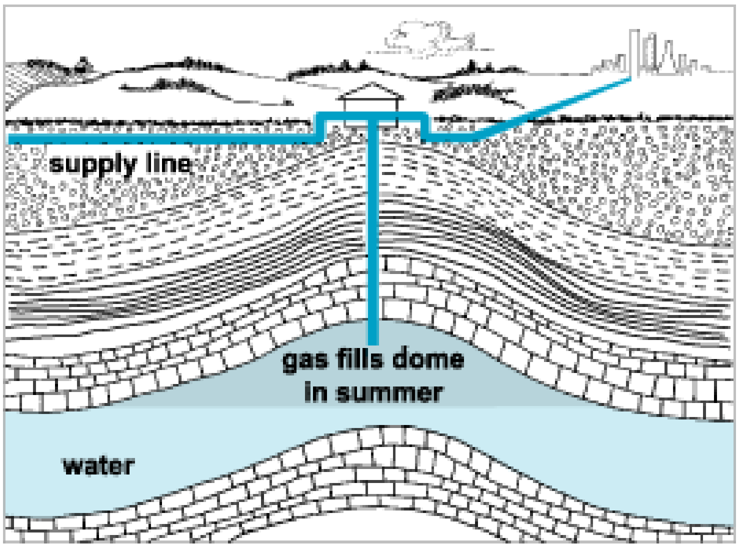


Figure 11 - Gas Storage in Aquifer [28]

12. **Liquified Natural Gas (LNG) Storage** - LNG storage involves storing natural gas under high pressure and low temperature to change its phase to liquid. LNG storage is used when high deliverability (i.e. a large amount of energy delivered in a short amount of time) is required with a small working volume. This makes LNG ideal for daily or hourly balancing [23]. Also, due to its high energy density, LNG is easily transportable when pipeline infrastructure is not available, and has potential to be used in the transportation sector [23]. LNG is significantly more expensive and less efficient than other gas storage technologies and is typically used only to cover rare winter peaks [23] [24].

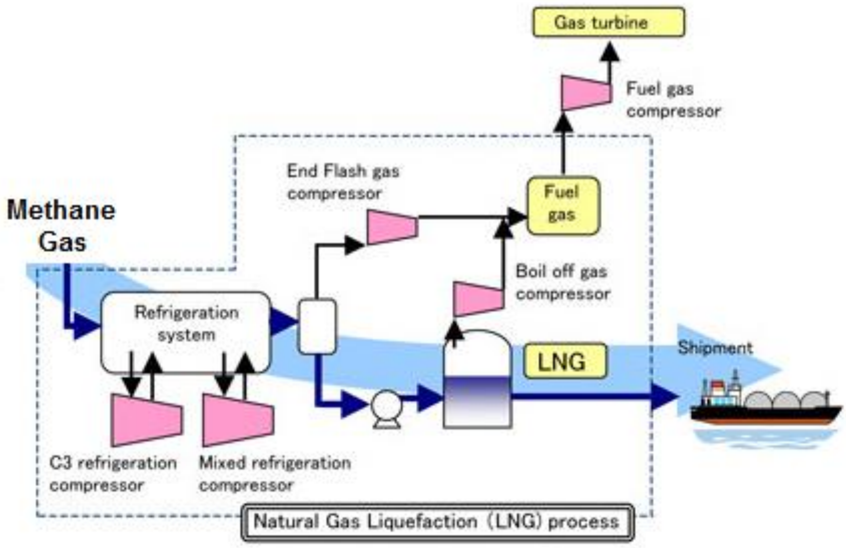


Figure 12 - LNG Storage [29]

13. **Hot Water (Sensible Heat)** - Thermal Storage: Thermal energy is stored by heating water in a highly insulated storage tank [15]. Hot water storage can be used to effectively and significantly reduce daily and seasonal thermal energy demands [30]; in France, peak heating demands have been reduced by 5% (5 GW) due to hot water storage implementation in households [31]. Hot water storage is a simple, low cost, mature technology which is highly reliable [30].

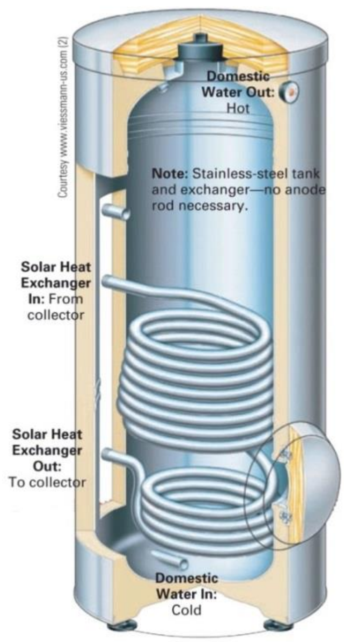


Figure 13 – Hot Water Storage [32]

14. **Underground Thermal Storage (UTS) (Sensible Heat)** - Thermal Storage: Thermal energy is stored by heating water and pumping it underground to store in porous rock or an aquifer [15]. Like hot water storage, underground thermal storage can be used for daily and seasonal thermal balancing and can utilize waste heat [30] [31]. Underground storage is a simple, mature technology which is highly reliable and requires less infrastructure and direct use of space than hot water storage [30]. However, underground storage can be significantly more expensive and requires appropriate geological conditions to be installed [30].

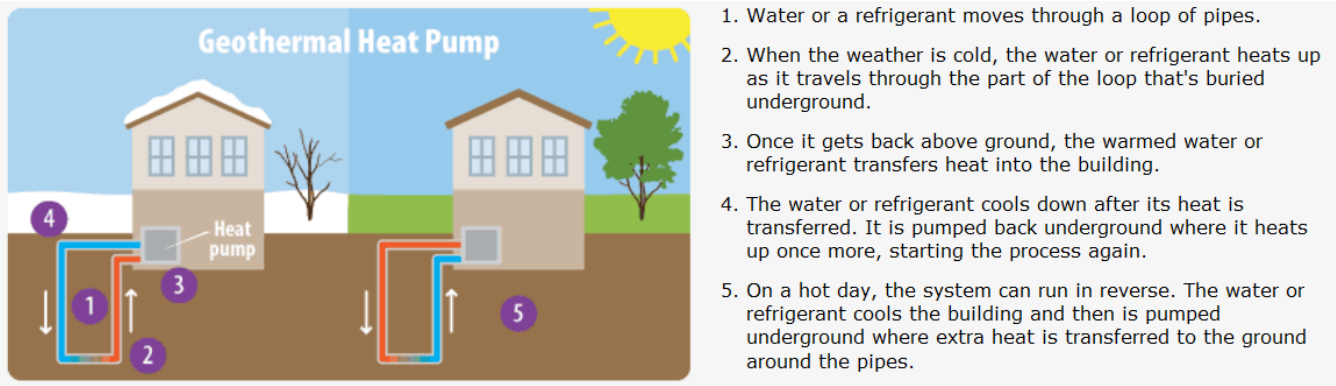


Figure 14 - Underground Thermal Storage [33]

15. **Latent Heat (Phase Change Materials)** - Thermal Storage: Latent heat is stored by releasing or absorbing heat during material phase changes [15]. Latent heat storage has the potential to provide daily and seasonal thermal balancing, demand shifting and peak reduction and waste heat utilization [31]. Latent heat storage has a much higher energy density than other methods of thermal storage [31]. However, these systems are currently still in development and are much more costly than alternative means of thermal storage [31] [34]. There is currently much research being done to develop cheap, reliable phase change materials, which will allow latent heat technologies to provide significant amounts of thermal energy storage [30].

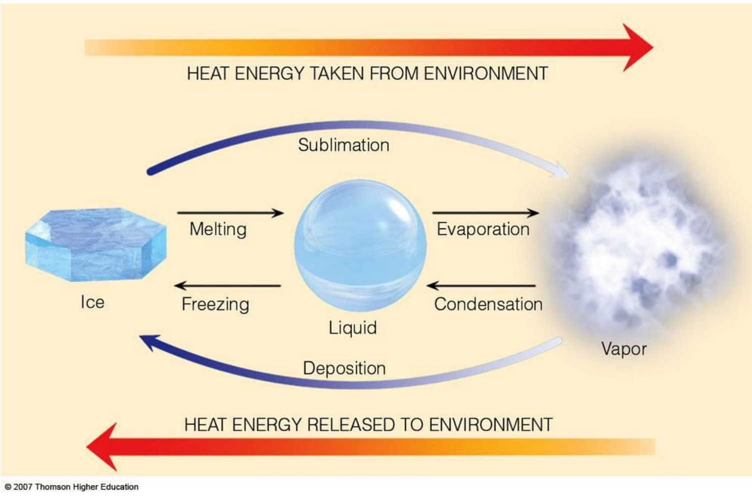


Figure 15 – Latent Heat Storage [35]

16. **Molten Salts (Sensible Heat)** - Thermal Storage: Thermal energy from a solar thermal power plants is often stored by heating molten salts [34]. Currently, molten salts are being employed in solar thermal power plants to enable electricity production 24 hours per day. This can be achieved due to the high heat capacity of molten salts, which allows the continual release of heat throughout the night when there is no solar input [34]. Compared to other storage materials, molten salts are very stable under high temperature and pressure, are non-flammable and non-toxic [34]. The use of molten salts as storage is a relatively new technology, so costs are still high and there is little knowledge about system reliability and lifetime.

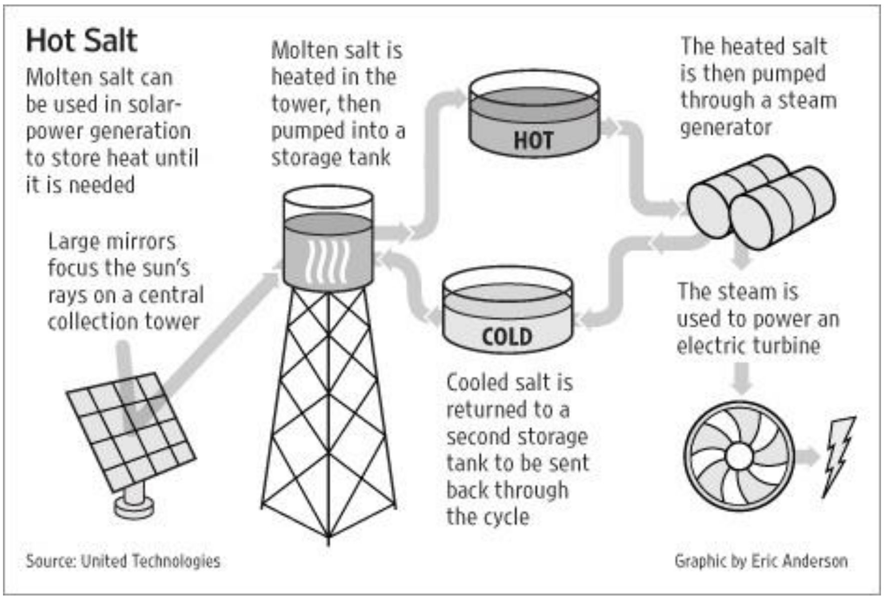


Figure 16 - Molten Salts Storage [29]

3.5) Energy Storage System Analysis

In broad terms, it is clear that energy storage technologies have a range of properties and functionality. It is equally apparent that **energy application** is the key to determining which technology is most suitable for a given situation. What we want our technology to do determines the required storage properties, and these properties determine which storage technology is most suitable. Based on which application the stored energy is intended to be used for, one can easily judge which technologies best meet their needs and should be studied further.

The Technology Suitability Table (see Table 1) presents a clear distinction between the requirements and capabilities of thermal and electric energy storage technologies. Gas and liquid fuel storage are considered separately because they can readily provide thermal energy, electric energy or a combination of these. The suitability of a given technology for a given service is indicated with a coloured dot:

● A green, filled dot indicates a technology is highly suitable

◑ A yellow, half-filled dot indicates a technology is moderately suitable or requires further development in this region

○ A red, empty dot indicates no suitability.

It is notable that storage technologies cover a wide range of operating characteristics and are able to provide a variety of services. Table 2 shows an overview of the potential services (described is Section 3.2) which different storage technologies can supply. This table is similar to others found in literature, though it is far more comprehensive than previous studies. The information presented in Table 2 is essential for determining which energy technology to pursue for a given task and is a key foundation for the storage label which has been developed.

An analysis of various storage labels leads us to many conclusions and can allow us to compare different storage technologies in a variety of ways. Many graphs have been developed which help to summarize the data collected in this study. Many of these graphs show a resemblance to graphs presented in other studies, although those presented here are more comprehensive, providing details on thermal, electric, gas and liquid fuel storage technologies. The diverse range of operating characteristics means that a given storage technology may be ideally suited for one application, but completely impractical for another. It is clear that several storage technologies must be employed in combination in order fulfill energy storage requirements during the energy transition.

Using the Excel application, it is possible to select which technologies are displayed in the following graphs to allow for an easier comparison. Note that some technologies have a large range of operating characteristics (e.g. lead acid batteries have an energy storage capacity of anywhere from 1 kWh to 50 MWh [9]), while others have range at all (e.g. molten salts, which is currently represented by only one installation). It is important to note that the ranges in operating characteristics presented here are generally, but not necessarily, dependent on one another. For example, some technologies (e.g. vanadium redox flow batteries) have independent, scalable energy storage capacity and power output. However, other technologies (e.g. traditional batteries) may have an energy storage capacity and discharge powers which are proportional to one another, since discharge power and energy storage capacity can be closely linked and must adhere to physical limitations.

In the following graphs, please note the following abbreviations:

Table 1 - Storage Technology Abbreviations

Aquifers & DGF	Aquifers and Depleted Gas/Oil Fields
CAES	Compressed Air Energy Storage
Li+	Lithium Ion Battery
LNG	Liquified Natural Gas
Pb Acid	Lead Acid Battery
SMES	Superconducting Magnetic Energy Storage
UTS	Underground Thermal Storage
Vd Redox	Vanadium Redox Flow Battery

Table 2 - Technology Suitability Table

Technology Name	Frequency Control	Hourly Balancing	Daily Balancing	Seasonal Balancing	T&D Congestion Relief	Black Start	Off-grid / Micro grid	Waste Heat Utilization	Off- to On-Peak Shifting & Firming	Demand Shifting & Peak Reduction	Energy Arbitrage	Reactive Power	Uninterruptible Power Supply	Transport
	Application													
Electric Energy														
Flywheel	●	○	○	○	○	○	○	○	○	○	○	●	◐	○
Pumped Hydro	●	●	●	○	○	◐	○	○	◐	○	●	●	○	○
CAES	●	●	●	○	○	◐	○	○	◐	○	●	◐	○	○
Pb Acid Battery	○	●	○	○	◐	●	●	○	◐	●	○	○	●	●
Li+ Battery	○	●	○	○	◐	●	●	○	◐	●	○	○	●	●
Vd Redox Flow Battery	○	●	○	○	◐	●	●	○	●	●	○	○	●	○
Supercapacitors	●	○	○	○	○	○	○	○	○	○	○	○	○	◐
SMES	●	○	○	○	○	○	○	○	○	○	○	○	●	○
Thermal Energy														
Hot Water	○	○	●	●	🟡	○	●	●	○	●	○	○	○	○
Underground Storage	○	○	●	●	◐	○	●	●	○	●	○	○	○	○
Molten Salts	○	○	●	○	○	○	○	○	○	○	○	○	○	○
Latent Heat	○	○	●	●	◐	○	○	●	○	●	○	○	○	○
Gas and Liquid Fuel														
Hydrogen Gas	●	●	●	●	●	○	○	○	◐	○	●	◐	○	◐
Salt Caverns	○	●	●	○	●	○	○	○	○	○	●	○	○	○
Aquifers & DGF	○	○	●	●	◐	○	○	○	○	○	○	○	○	○
LNG	○	●	●	○	◐	○	○	○	○	○	○	○	○	○

● indicates full suitability

◐ indicates potential or moderate suitability

○ indicates no suitability

Figure 17 - Discharge Power vs. Energy Storage Capacity

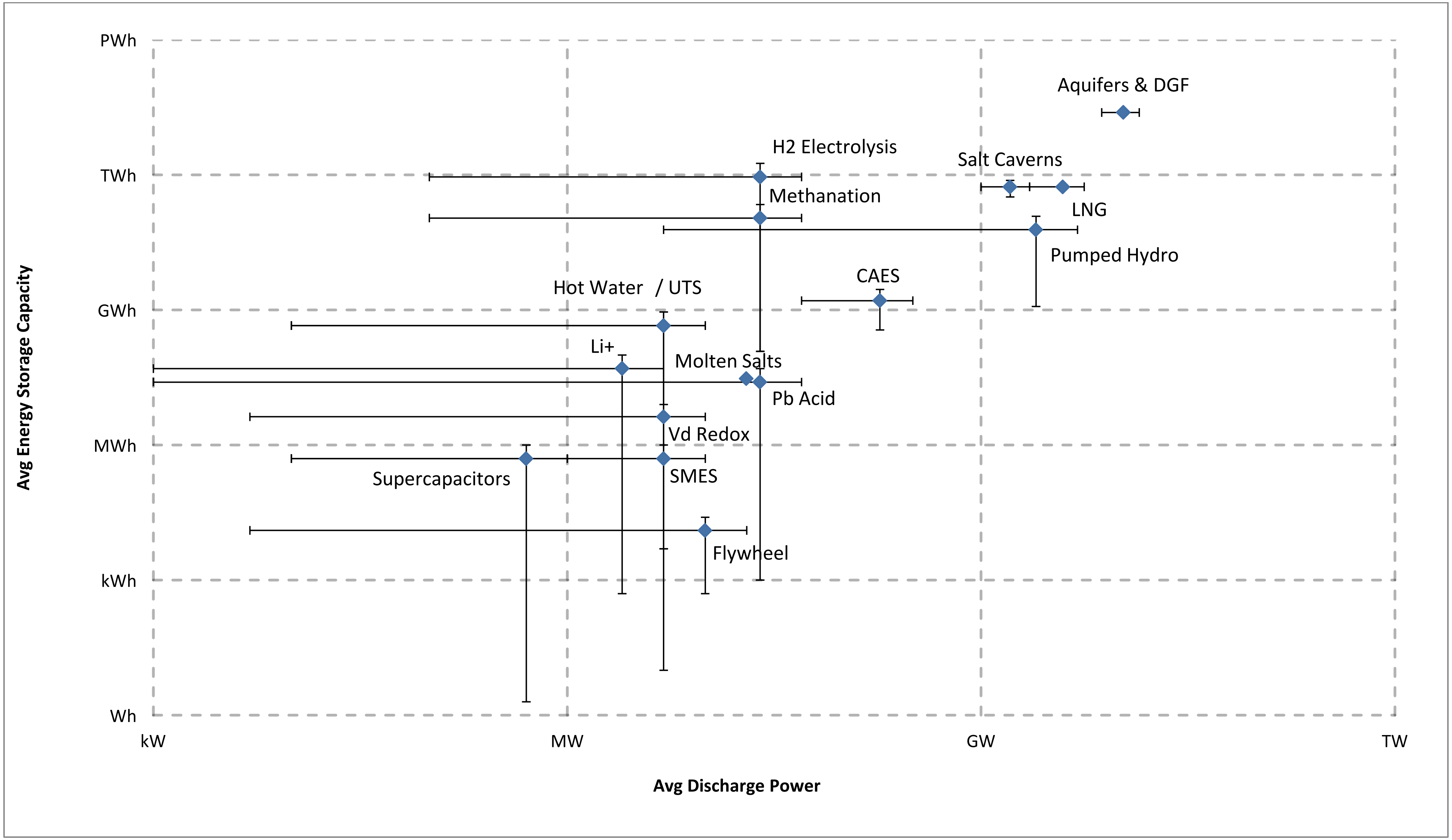


Figure 18 - Energy Costs vs. Energy Storage Capacity

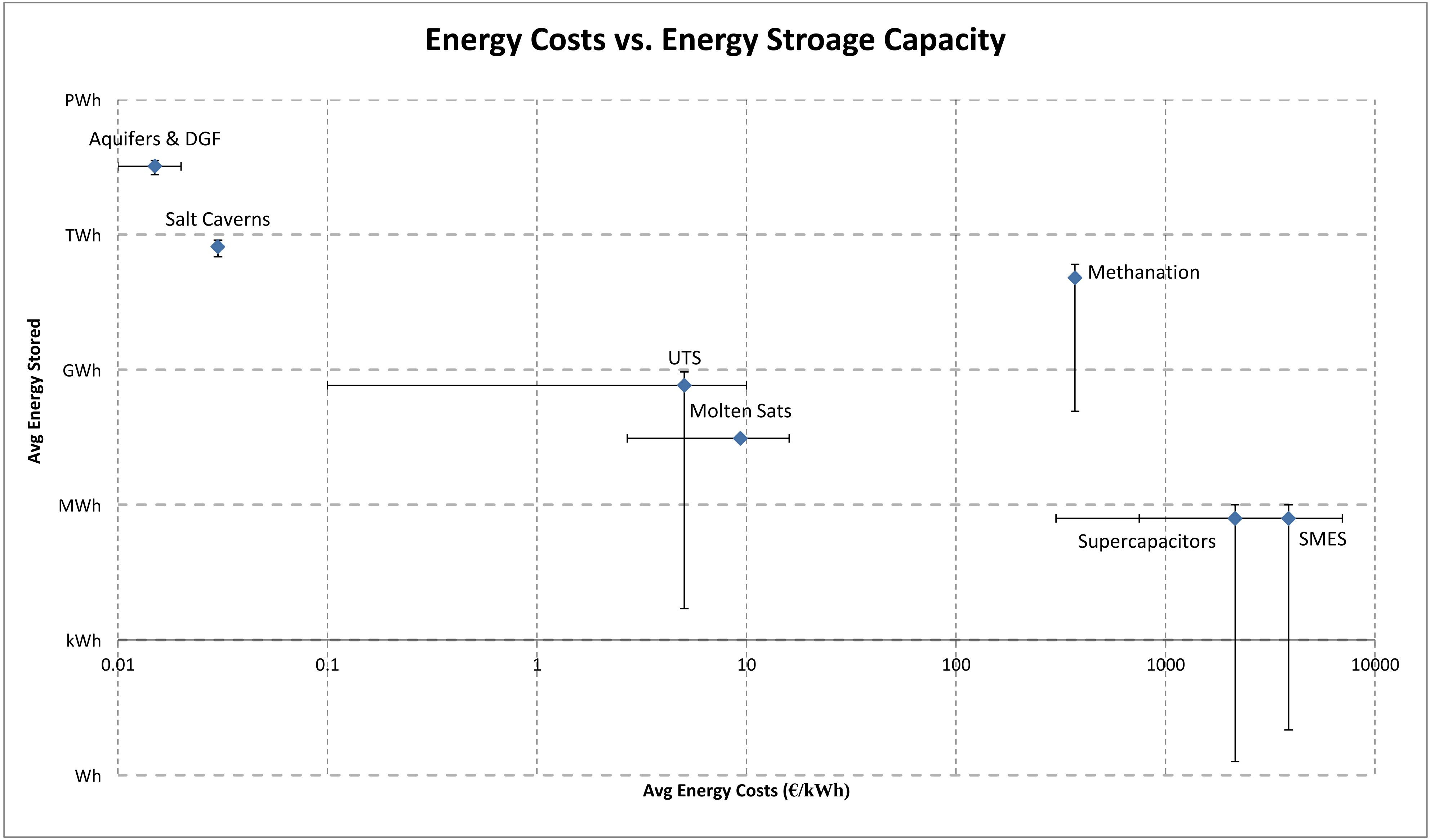


Figure 19 - Discharge Time vs. Energy Storage Capacity

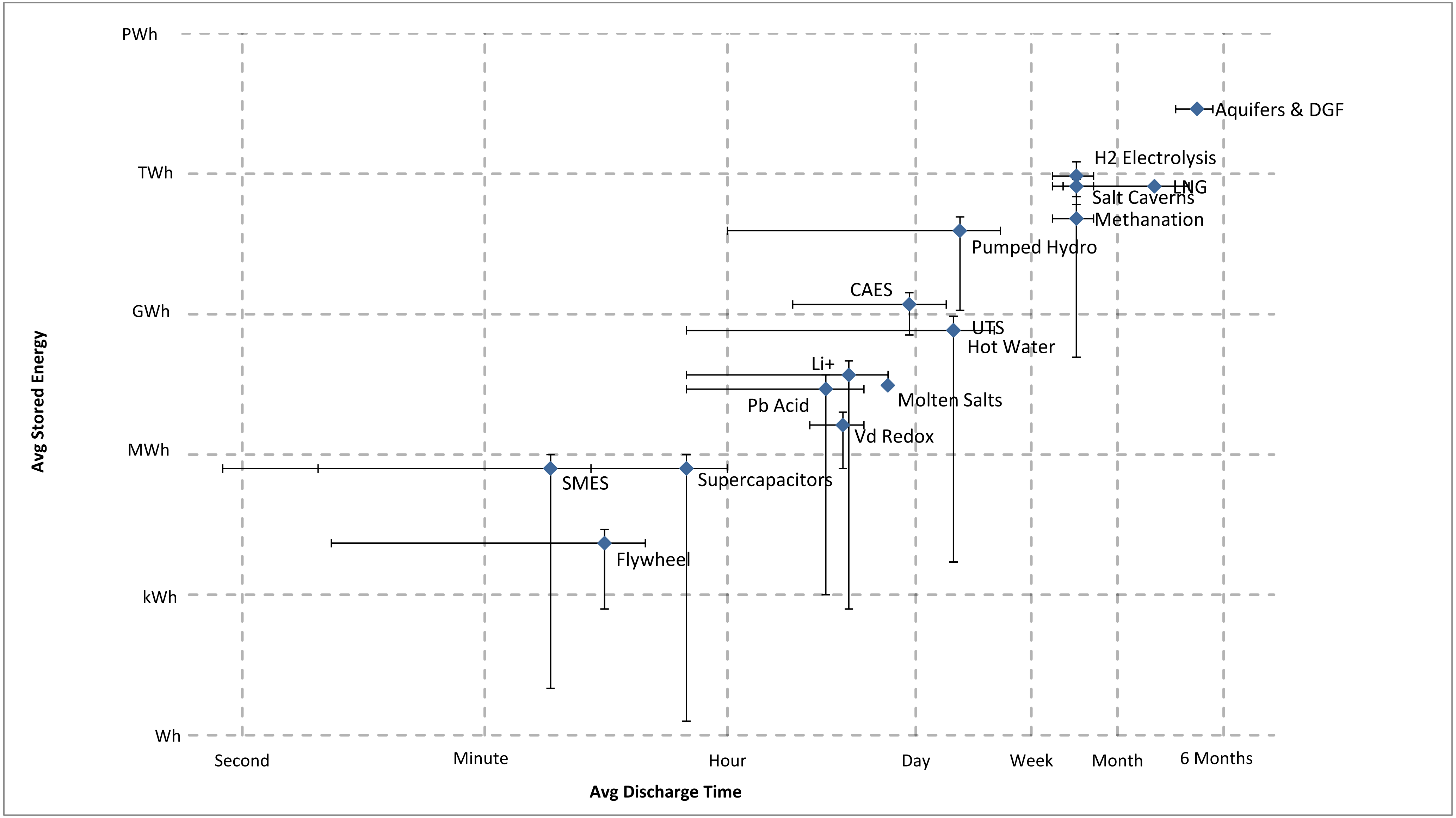


Figure 20 - Discharge Time vs. Discharge Power

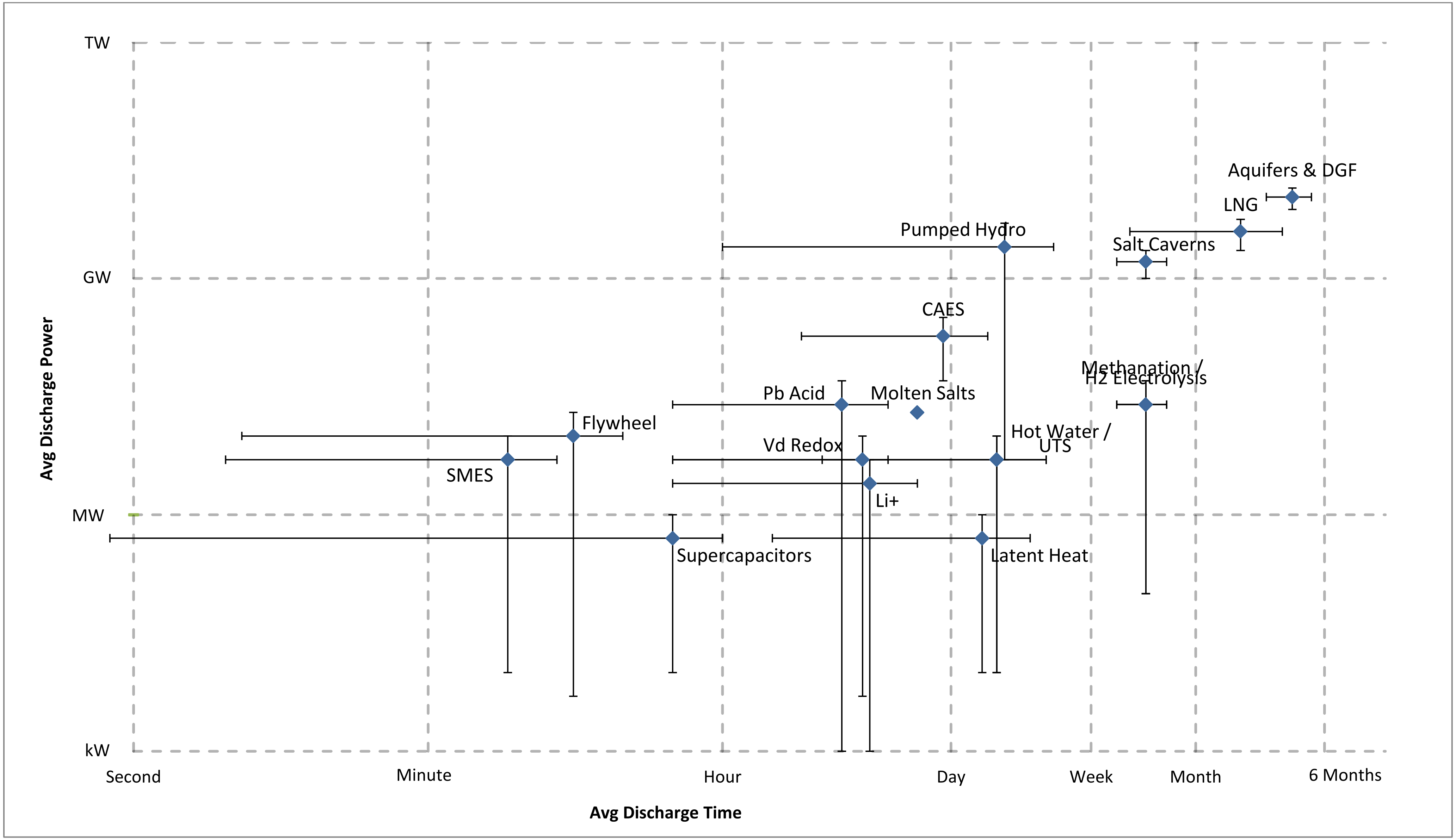
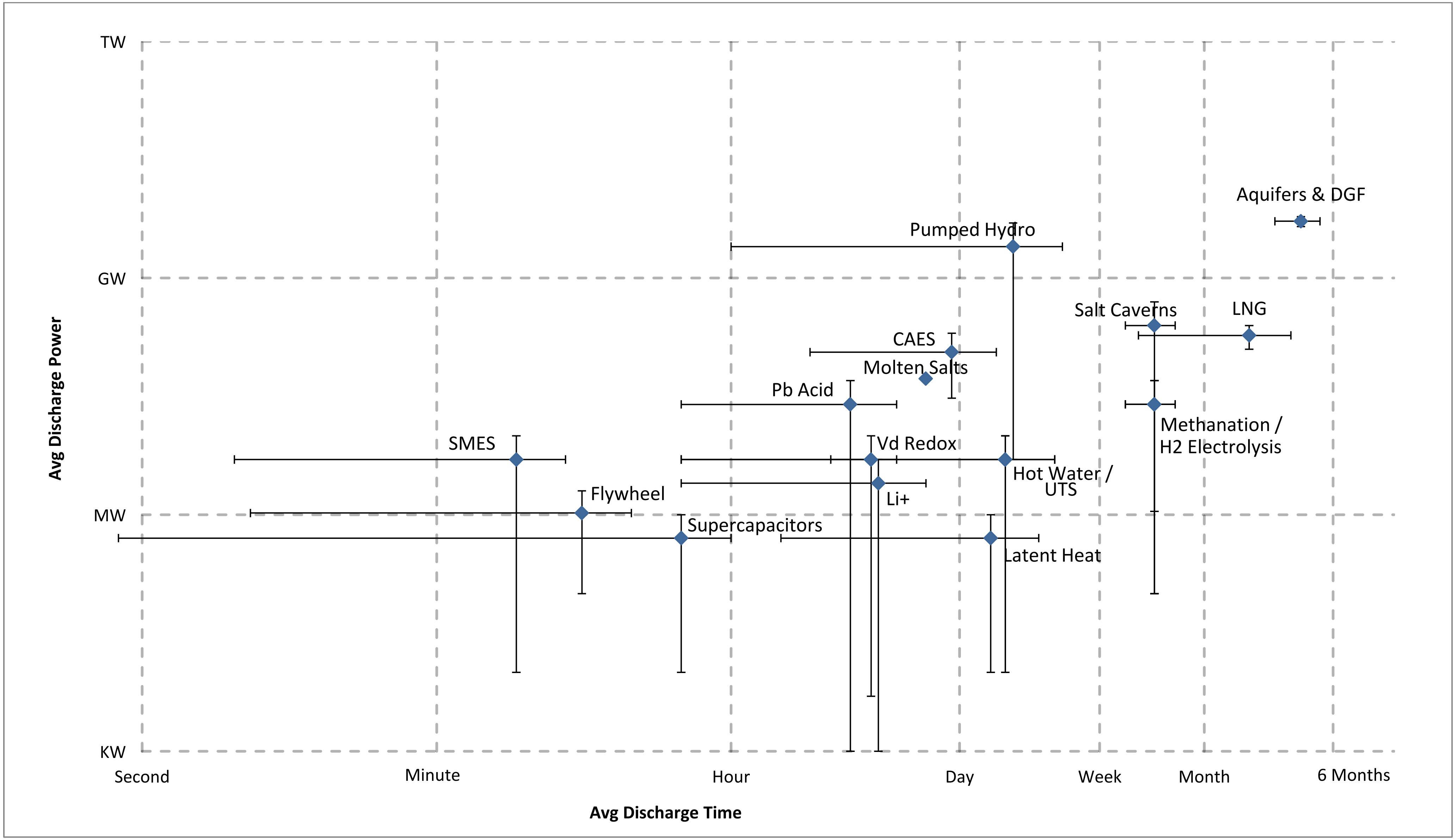


Figure 21 - Charge Time vs. Charge Power



4) Discussion

The intention of the label system was to form a standardized presentation of storage technology characteristics in an easy-to-interpret way. The advantage of this system is that it allows for straightforward comparison between technologies and allows for the addition of new and improved technologies to the database. However, there are some important limitations with this system which must be addressed.

It is important to note the vast differences between different technologies: For example, a bank of lead acid batteries can store up to 2,000 times more energy than a flywheel. It can be very difficult to properly compare data on this huge range, where logarithmic scales (and their interpretation) are essential for direct numeric comparisons. However, highly-trained experts who understand these implications can use this application to effectively compare energy storage technologies. By breaking down storage technologies to their fundamental properties, this report hopes to provide transparency and clear indicators for what makes a technology suitable for a given application. The label system is not intended to provide concrete solutions to problems, but to provide a guideline for a proper course to pursue. When properly used, this system can refine which storage technologies bear further consideration for a particular dilemma and should be studied in further detail.

Currently, the database does not consider geographic limitations or social impacts. For example, pumped hydro storage may appear to be a valuable storage technology. However, pumped hydro storage is so dependent on appropriate geographic conditions that it does not even bear consideration in many countries. In addition, the social impact of creating a hydro dam is very difficult to measure and present in a meaningful way. In fact, the environmental impact of many technologies is still largely unknown. Studies do exist, although the results are highly dependent on how a technology is used. Returning to the example of pumped storage, this technology will have a much lower environmental impact if it is used frequently to offset fossil fuelled power plants and is only ever filled using surplus renewable energy. This is not to say that the label system is flawed, only that more research is needed in several areas.

One important consideration is the standard unit of measurement in different sectors and institutions. For instance, natural gas can be measured in terms of m^3, MJ of kWh. When comparing different storage technologies, it is important to take these standards under consideration. While the current label allows the user to switch freely between units of measurement, it is important that all units are the same when comparing different technologies.

It is also important to note that all data presented in this handbook is subject to interpretation. For instance, while solar thermal storage may be able to store 900 MWh of energy, this is not necessarily true in all climates or for all solar thermal facilities. It is therefore important to consider that a specific energy storage facility may not be able to provide all of the services implied by this study. Continuing with the above example, a large solar thermal facility may be able to provide effective seasonal storage but may not be suitable for peak demand shifting. In contrast, several small solar thermal facilities may be effective at distributing thermal loads on the short term (i.e. several days), but not on the long term (i.e. several weeks).

5) Conclusions

This study characterizes the properties and capabilities of various energy storage technologies. It is clear that energy application is the key factor for determining the appropriateness of a given storage technology. The storage labels can provide a guideline for which technologies are best suited for a given application, as well as a simple, quick reference for comparing different storage technologies. In addition, technology labels can be examined to provide a more detailed view of individual storage technology properties. In summary, this project provides an overview of available storage technologies (as well as a method for comparing them) and their potential uses.

While this project has achieved its intended goals, there are some areas which could be expanded upon in future studies. Specifically, environmental and social impacts should be studied further and a clear ranking system should be developed. In addition, new technologies and more specific technologies (i.e. specific brands and models) should be added to the database in order to gain a better perspective on the potential of a given technology. This would provide a more distinct ranking and reduce the required interpretation when using the storage label system.

Storage technologies will play an important role in future energy scenarios, particularly in terms of renewable energy integration and the increasing interdependence of thermal and electric energy consumption with the introduction of CHP systems, electric heat pumps and other technologies. Current storage technologies offer a broad range of operating characteristics and potential applications. This report emphasizes the importance of choosing the correct technology for the correct application and intends to provide a clear guideline in this decision-making process.

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