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Calculation of Renewable Electricity Storage Cost for Future

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Abstract

Electricity systems in remote areas and on islands can use electricity storage to integrate renewable generation and help meet continually varying electricity demand. Electricity storage technologies vary widely in design, technological maturity and cost. There is no single best storage technology, and storage is not necessarily appropriate for all island electricity systems. The most competitive energy storage technologies had LCOS of 50-200 $/MWh. By 2030, a much wider range of technologies offered LCOS below 100 $/MWh. Looking to 2030, it is particularly striking that battery technology becomes much more competitive. The levelized costs are higher for the wind-storage case than the solar-storage case, because of the high sensitivity of the LCOS to the number of discharge cycles per year, and the suboptimal energy-to-power ratios required for the wind-storage case as defined. An important aspect about the LCOS of storage is that it will always depend on the load factor for discharging and therefore the way it is used cannot be ignored. Battery technologies followed by sensible thermal, latent thermal and supercapacitors show the greatest reduction in cost. Battery technologies show a reduction from around 100-700 $/MWh to 50-190 $/MWh in 2030 is a reduction of over 70% in the upper cost limit in the coming years. Pumped storage shows the lowest cost reduction, due to the current maturity level of the technology, followed by compressed air energy storage.

Keywords: Electricity storage; Storage materials; Levelized cost of storage (LCOS)

1. Introduction

The mature technology of lead-acid batteries has moderate costs and high reliability. However, these batteries have a relatively short lifetime (typically, three to ten years) and must be disposed of or recycled properly [1]. Lithium-ion batteries are common for mobile applications (such as cell phones and laptop computers) and may make their way into the electricity grid market in the next five years. They have higher first costs than lead-acid batteries but longer lifetimes and lower losses. Flow batteries (notably, vanadium-redox and zinc-bromine) hold the promise of long lifetimes and low operating costs [2]. However, they are just entering the commercial market and thus do not have an established record of operation for electricity storage applications. Flywheels are best suited for short-duration storage (less than one minute), but they are still at an early stage of technical development. Compressed air energy storage (CAES) and pumped hydro are generally suitable only for large (500 MW+) electricity systems. There are numerous other storage technologies in earlier stages of technical development [3].

In addition to helping integrate renewables, storage can also contribute significant value by increasing the operating efficiency of diesel generators. These generators are much more efficient when operated at high load factors, and the addition of storage can significantly reduce the number of hours they operate at low or minimum load factors. Storage can also be of value in systems that are transmission capacity–constrained or that suffer from low power quality at the end of the distribution system. Storage is generally not appropriate, in contrast, for solving problems such as chronic supply shortages or poorly performing transmission and distribution systems [4]. Detailed modeling of a typical diesel-based island electricity system shows that storage can be cost-effective even in the absence of renewables through its ability to increase diesel generator efficiency and thereby reduce diesel consumption. The rampant oversizing of diesel generators contribute to these potential savings. A combination of renewables,

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storage and diesel generators can yield the lowest cost solution. However, such systems are complex. “Pure” renewable systems, such as photovoltaic (PV) plus storage, are relatively expensive due to the need for PV system and storage oversizing to meet loads during extended cloudy periods.

Power systems have to be flexible to allow supply and demand to be balanced at all times. As the deployment of wind and solar generation increases globally, the challenge of managing the increased volatility of generation grows and hence, the need for increased system flexibility is becoming more urgent. Electricity storage is an important option to provide this additional flexibility. Energy storage technologies can be defined to incorporate all forms of energy. For the purposes of this report, it is defined as a system installed within a power system that can, given an independent control, store electrical energy generated within the power system, and release when required. This energy can be stored in various forms. The application of renewables alongside storage is one of many models which are being pursued. Energy storage is also being deployed in stand-alone grid-level applications and in electric vehicles.

2. Electric storage technology

Energy storage is not a single technology, but rather refers to a suite of diverse technologies. Due to the wide range of technologies, it is important to begin by outlining the types of technologies which can be deployed and the different roles that they can play within the energy system. Each technology and category has advantages and disadvantages which can be mapped to the applications that are most suited to each specific technology. The technologies have a range of different performance characteristics, summarized in Figure 1 below, based on their energy capacity and discharge time at rated power. These are considered the most relevant characteristics for the purposes of this report, though other characteristics may of course be relevant, depending on the application. Supercapacitors and batteries are associated with the characteristics of lower energy capacity and shorter discharge time at rated power and are therefore more suited to higher power applications [5-7]. By contrast, power-to-gas (P2G) technologies are associated with the characteristics of higher energy capacity and a longer discharge time at rated power. These are better suited to storing large amounts of energy which is discharged over longer periods of time [8-10].

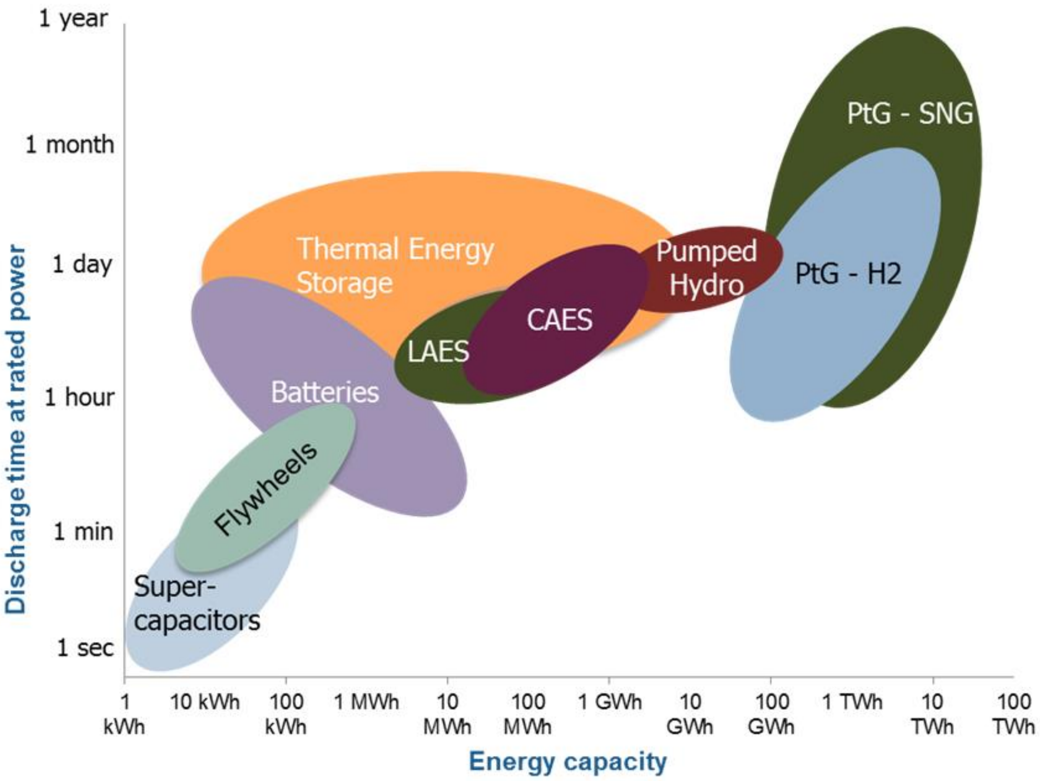


Figure 1. Mapping storage technologies according to performance characteristics.

The following two examples emphasize that not all storage devices are suitable for all applications: a grid-connected storage system co-located with renewables may need a combination of both the ability to shift energy on an hourly basis, whilst also supplying high power at other times of the day to deal with the inherent volatility problems associated with renewable energy. As a comparison, to support the balancing of national power systems and in order to supply adequate reserve capacity, storage devices are able to time-shift large amounts of energy over daily time periods are required; in this case technologies such as pumped hydropower storage are more pertinent. Figure 2 gives capabilities of existing electricity storage technologies and Figure 3 shows experience curve for Lithium-ion battery.

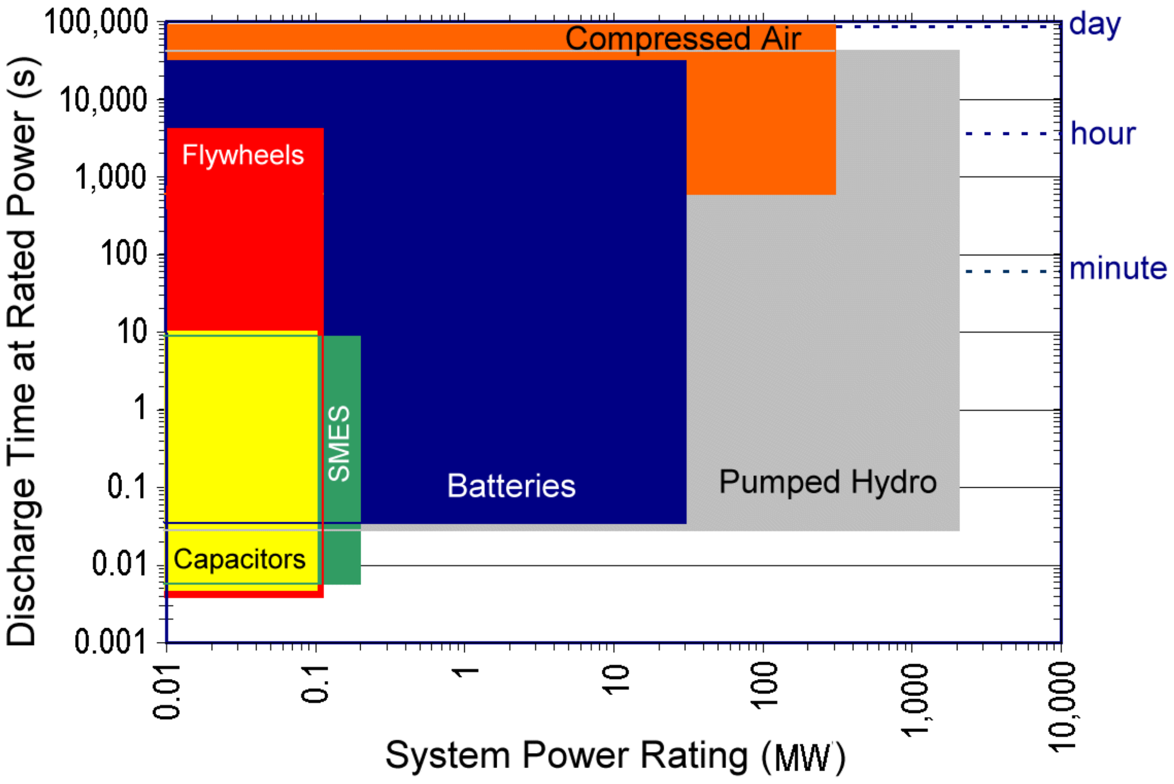


Fig. 2. Capabilities of Existing Electricity Storage Technologies.

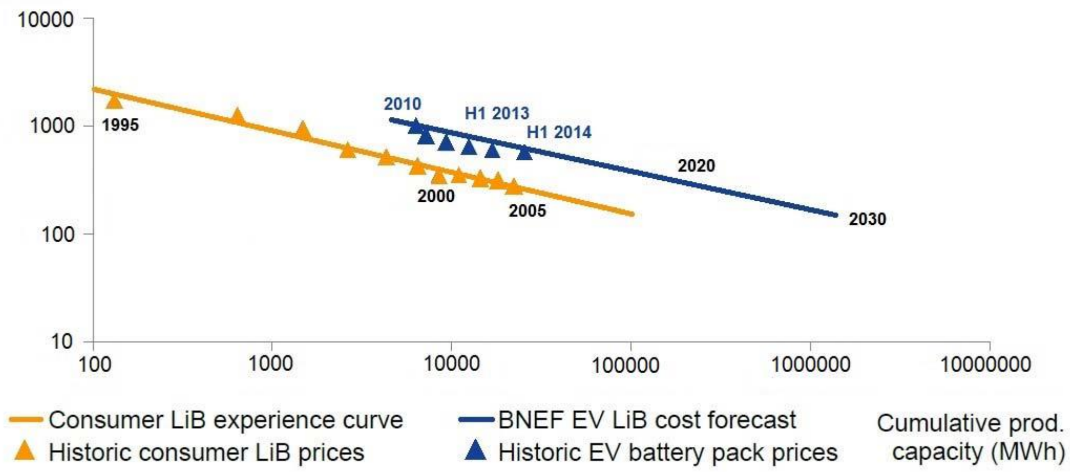


Figure 3. Experience curve for Lithium-ion battery.

3. Cost modeling

The cost analysis has been developed based on a literature review and cost modeling status. The two key metrics considered in the analysis are specific investment costs and levelized cost of storage (LCOS). These are estimated based on recent cost data and 2030 conditions. LCOS in particular, raises methodological difficulties, which are discussed in detail. The modeling of levelized cost is applied to two hypothetical, but standardized application cases, namely solar storage and wind storage. Assuming daily cycles and six hours discharge time at rated power, the most competitive technologies have LCOS of 50-200 \$/MWh, though these are technologies which are not necessarily suited to all PV projects. Battery technologies are next, around 200-400 \$/MWh. By 2030, a much wider range of technologies offer LCOS below 100 \$/MWh. Looking to 2030, it is particularly striking that battery technology becomes especially more competitive, with sodium (NaS), lead acid and lithium-ion technologies leading the way. This application assumes a two-day cycle structure and 24 hours discharge time at rated power. Few technologies appear attractive. Levelized costs are much higher for the wind storage case than the solar storage case because of the high sensitivity of the LCOS to the number of discharge cycles and the sub-optimal energy-to-power ratios required for the wind storage case as defined.

3.1. Specific investment costs

The metric of specific investment costs (SIC) describes the installation costs for power and energy storage capacity. In the following work, we refer to the specific investment costs in \$/kW, i.e. the investment cost per installed discharging capacity (\$/kW). The individual energy capacity is reflected in the assumed E2P ratio (hours) as per the table above.

3.2. Levelized cost of storage

The metric of LCOE is typically used in the industry to assess the cost of electricity from different power plant types. In this analysis the formula has been transferred to storage technologies, as an economic exploration of the discharging side of energy storage. Because storage plant does not generate power and depends on another generating technology, the formula is referred to as the levelized cost of storage (LCOS). It still enables comparison between different types of storage technologies in terms of average cost per produced / stored kWh. The levelized cost calculation used is summarized as follows:

$$LCOS = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{M_{el}}{(1+i)^t}} \qquad (1)$$

Where;
LCOS : Levelized cost of energy (\$/kWh);
I_o : Investment costs (\$);
A_t : Annual total costs in year t (\$);
M_{eI} : Produced electricity in each year (kWh);
n : Technical lifetime (years)
t : Year of technical lifetime (1,…,n)
i : Discounted rate (%)

Note that the annual total costs A_t consist of annual fixed costs and other variable costs. When applying the LCOS metric, it is important to understand the implications for the assumed application case of the Energy to Power Ratio (E2P). In the cost modelling conducted in this report, where the potential E2P Ratio of a storage plant does not cover the requirements of the application case, the rated power has been increased, to increase the energy capacity. As a consequence, potentially higher investment costs are derived. In the case of lithium, lead acid and redox flow batteries, an E2P Ratio of 4 is applied for each application case. This represents the upper limit applied in the calculation of the general LCOS and is most suitable for the application cases.

Another critical issue is the assumption on usage, i.e. cycles per year. For PV, a daily cycle is fully justified. However, for wind in north-western Europe which has a relatively high penetration of wind generation for example, weather cycles are typically in the order of three to four days. This is driven by the passage of large weather systems eastwards over the Atlantic. Assumptions being used are a four-day cycle for wind applications and usage of the storage device at 90 times per annum. Therefore, the LCOS results will be around twice the level for a two-day cycle. This strong effect shows the importance of understanding the application assumptions behind any cost estimate. Table 1 gives the E2P ratios used within the calculations and Table 2 shows explanation of Levelized Cost of Storage (LCOS) calculation.

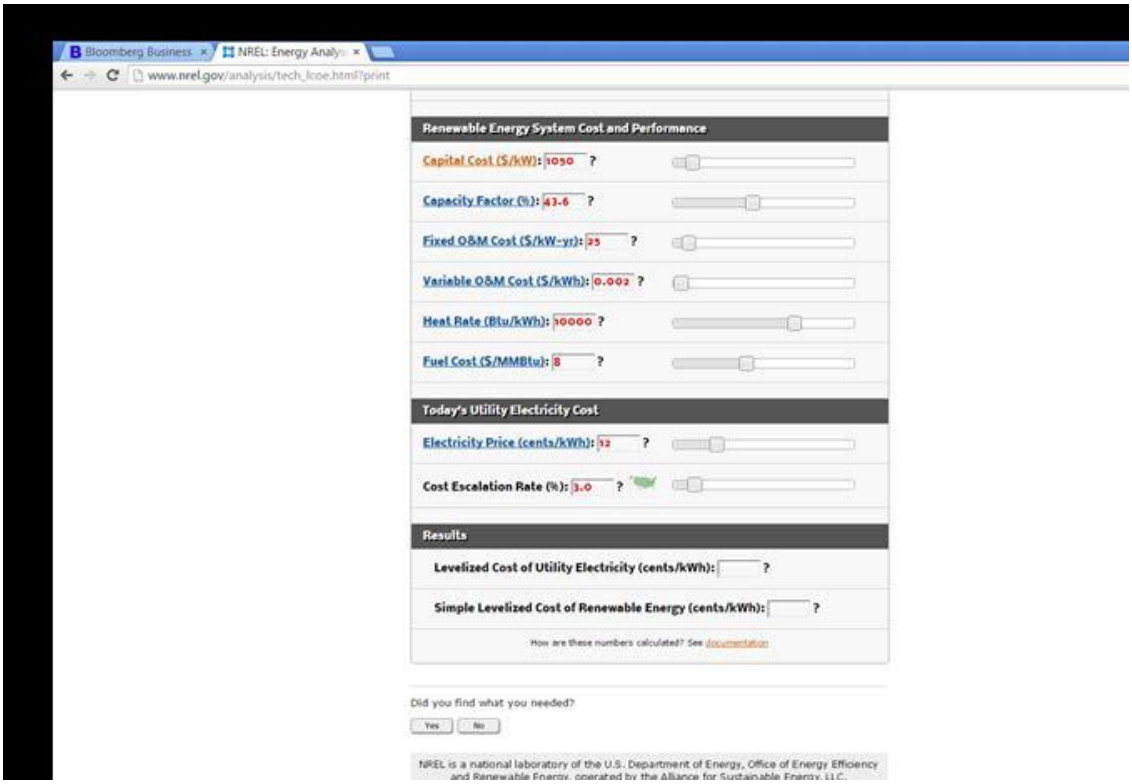
Table 1. The E2P ratios used within the calculations.

Storage technology	E2P ratio min. (h)	E2P ratio max. (h)
Pumped Hydro	100	100
Compressed air (adiabatic)	6	6
Lithium	1	4
Sodium Sulphur (NaS)	6	6
Lead Acid	1	4
Redox Flow	1	4
Thermochemical Storage	6	6
Supercaps	0.25	0.25
Flywheels	0.25	0.25
Sensible Thermal Storage	200	200
Latent Thermal Storage	200	200
Power to Gas H_2	200	200
Power to Gas SNG	200	200

Table 2. Explanation of Levelized Cost of Storage (LCOS) calculation.

Input Variables	Elements	Example Values
Investment cost ($)	Specific investment cost * rated power	700-1500 $/kW * rated power
Annual total costs in year t ($)	Operational costs (in %) * Investment costs	4% Investment costs
Produced electricity in each year (kWh)	Rated power * Equivalent full-load hours * Efficiency	
Technical lifetime (years)	Technical lifetime	50 years
Discount rate	Discount rate	10%

Note: We accepted that in our calculations 1$ = 1€



Renewable Energy System Cost and Performance

Capital Cost ($/kW): 1050 ?

Capacity Factor (%): 43.6 ?

Fixed O&M Cost ($/kW-yr): 25 ?

Variable O&M Cost ($/kWh): 0.002 ?

Heat Rate (Btu/kWh): 10000 ?

Fuel Cost ($/MMBtu): 8 ?

Today's Utility Electricity Cost

Electricity Price (cents/kWh): 12 ?

Cost Escalation Rate (%): 3.0 ?

Results

Levelized Cost of Utility Electricity (cents/kWh): ?

Simple Levelized Cost of Renewable Energy (cents/kWh): ?

How are these numbers calculated? See documentation

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Figure 4. The computer screen for LCOS calculation given by NREL-DOE-GOV [1].

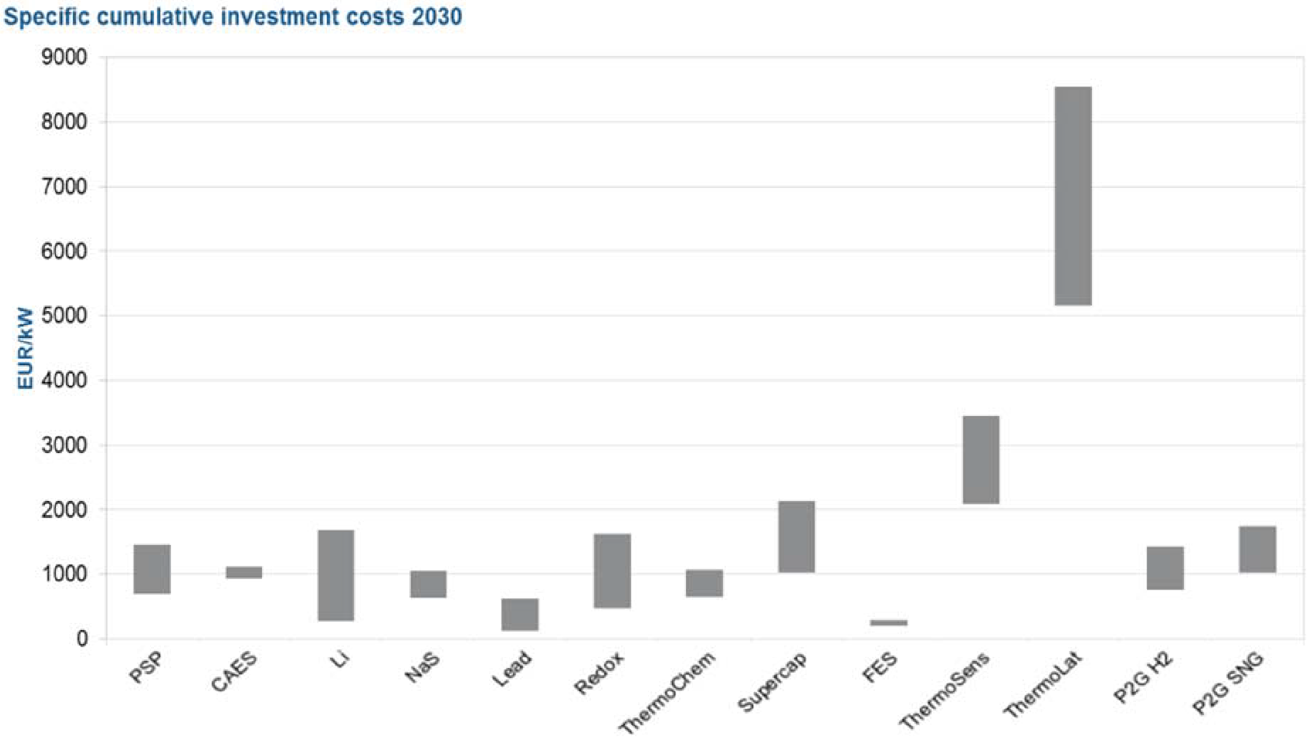


Figure 5. Specific investment costs, 2030 ($-2022).

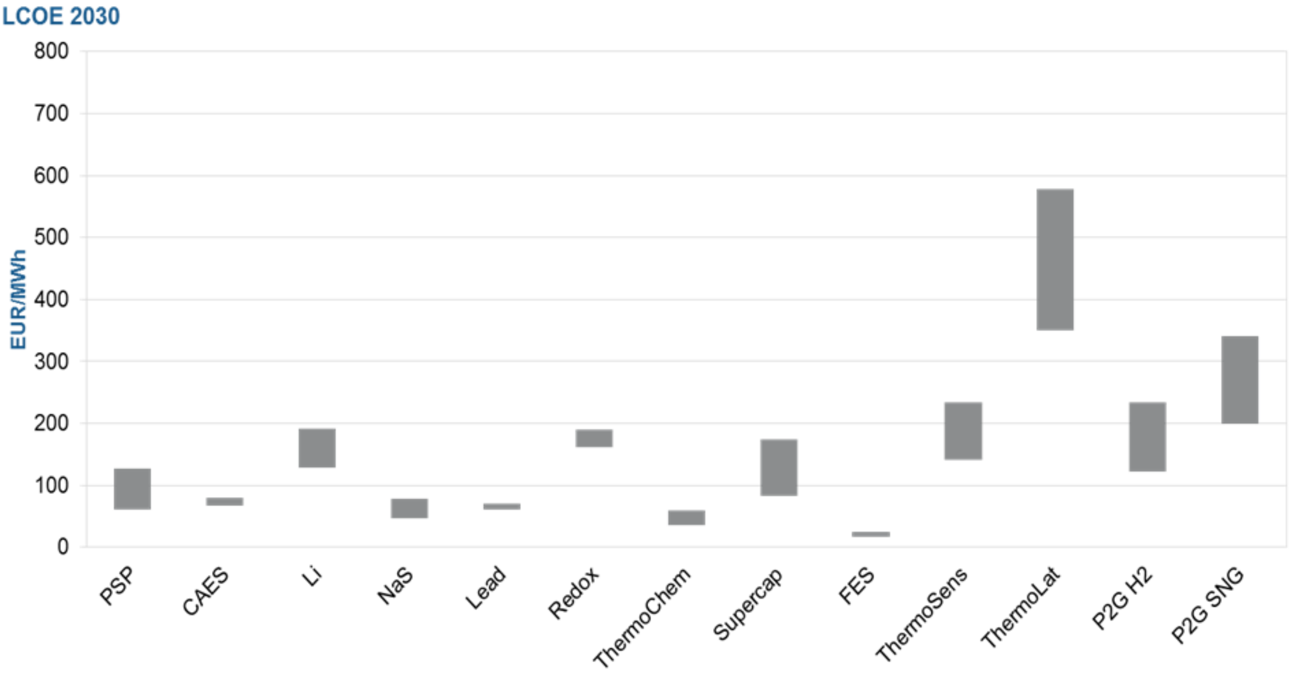


Figure 6. Levelised cost of energy in 2030 (€-2022)

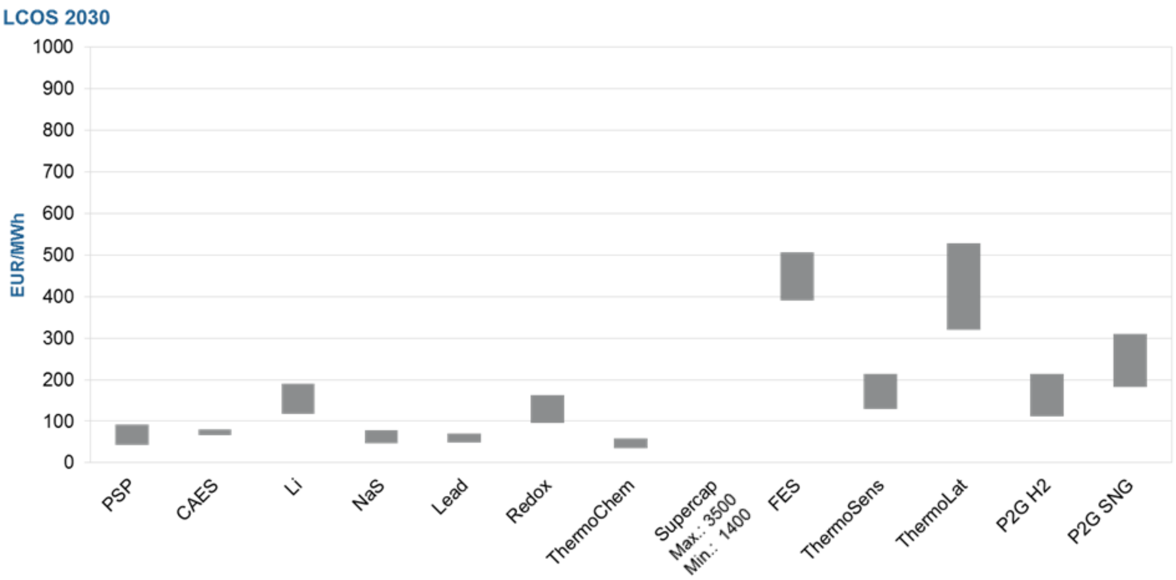


Figure 7. Levelized Cost of Storage co-located with PV in 2030

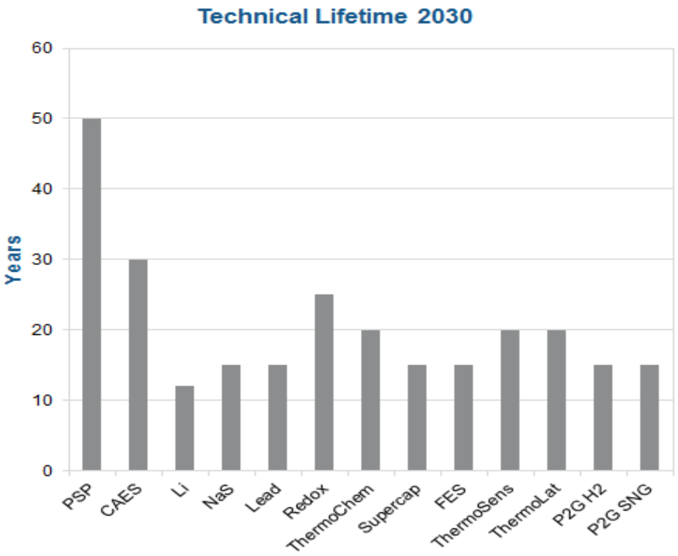


Figure 7. Technical lifetimes assumed in LCOS modeling in 2030

4. Conclusions

Measures lifetime costs divided by energy production and calculates present value of the total cost of building and operating a power plant over an assumed lifetime. Allows the comparison of different technologies (e.g., wind, solar, natural gas) of unequal life spans, project size, different capital cost, risk, return, and capacities. Levelized cost of electricity (LCOE) and levelized cost of storage (LCOS) represent the average revenue per unit of electricity generated or discharged that would be required to recover the costs of building and operating a generating plant and a battery storage facility, respectively, during an assumed financial life and duty cycle. LCOE is often cited as a convenient summary measure of the overall competitiveness of different generating technologies. Although the concept is similar to LCOE, LCOS is different in that it represents an energy storage technology that contributes to electricity generation when discharging and consumes electricity from the grid when charging. Furthermore, LCOS is calculated differently depending on whether it is supplying electricity generation to the grid or providing generation capacity reliability. In order to calculate the renewable electricity storage cost, we used Eq.

(1) and Table 1 and 2. Also we use the LCOS calculation method given by NREL DOE-GOV [1]. The method of LCOS is very useful for determining of renewable electricity storage systems. The calculated results are shown in Figs. 4-7.

Both wind and solar PV are volatile renewables technologies, and it is important to understand the characteristics of that volatility. Other renewable technologies are also volatile. Tidal energy is highly volatile but is highly predictable; wave energy has characteristics very similar to wind. However, both are currently at relatively low levels of penetration and so are not considered in this study. Run-of-river hydro is also volatile, but is a mature technology and is well understood in any specific location.

The dominant component of volatility is the daily cycle. The duration and peak value of this cycle can readily be calculated for any geographical location, panel orientation, and site shading characteristics. Cloud effects are more random: they can cause rapid fluctuations in output of a single installation, but over distances of around one kilometer they are uncorrelated on timescales of tens of seconds or minutes, and when spread over the area of an electricity distribution system they are only correlated on timescales of hours. Periods of cloud cover can be forecasted with relatively good accuracy. Therefore, when considering storage co-located with PV installations, the applications are:

- Storage of tens of seconds or a few minutes, to remove fluctuations due to cloud cover, if this is important for the electricity sales agreement or the grid connection agreement.
- To provide ancillary services such as frequency response or reserve, if a market or a mandatory requirement exists.
- Storage of a few hours, in order to time-shift production to times of the day when the price is higher. Electricity systems with a high penetration of PV already show a strong impact on spot prices.

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