Ciências ULisboa | Engenharia Geográfica, Geofísica e Energia

# Energy Systems

## Batteries as energy storage

**Integrated Master in Energy and Environmental Engineering**
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# 1 Introduction

Due to the highly fluctuating production times of renewable energy systems and their rapid growth in share, grid operators are facing intensified difficulties. Because of the poor match between generation and consumption, problems such as voltage rise triggered by reverse power flow occur. One way to prevent grid problems is to curtail production. Another option that maximizes the share of renewables and to match the production and consumption is the storage of surplus electricity. In addition, a private self-generation system in combination with a battery storage system can increase self-sufficiency and independence of private consumers as well as reducing their payback times (Ranaweera, I. et al., 2016).

The objective of this paper is to compare the characteristics of different battery storage systems to see which has the best price-performance ratio and is best suited for our island. For this purpose, the following options were considered:

- The use of the battery capacity of electric cars, the so-called vehicle to grid principle.
- Using conventional car batteries as storages.
- The purchase of domestic storage systems for the individual households.
- The utilization of old, still functioning batteries from electric cars as external storage in households.
- As well as centrally operated large community battery storages.

As an approximation, a capacity factor of 50% was assumed for all calculations. Since we do not know how often the batteries will be charged and discharged, because it depends on the discrepancy between supply and demand, which is data we don’t have yet reliable information on.
After the comparison of the different technologies, the current socio-economic aspects of this area will also be discussed, as well as some issues and advantages of battery reuse. At the end of our work, the results are compared in a table to show which technology is most relevant for our project.

# 2 Technology

## 2.1 EV battery systems

One of the options for storing electricity is to use electric vehicle (EV) batteries in a vehicle to grid (V2G) solution, since electric Vehicles (EV) are emerging due to ever increasing concerns on the energy issues and greenhouse gas effects. (Sujitha, N. et al., 2017). Vehicle-to-grid (V2G) refers to the reciprocal flow of power between an electric vehicle (EV) and a recipient that could be, among other possibilities, the grid, a low voltage microgrid or a building. In addition to demand-shifting and the associated reduced electricity costs attained by avoiding peak tariffs at times of high demand, it also introduces the prospect of financial incentives for the consumer, through offering frequency regulation and energy storage facilities to the grid. (Uddin, K. et al., 2018)

For continuity purposes, the data already available in the mobility report was considered. With this case, for this scenario, it was analyzed the electricity storage capacity of the 40-kWh, 110 kW battery of a 2018 Nissan Leaf, which has a round trip efficiency of 91%. Since the cars still need to be drivable and capable of daily duties, it was estimated that only 20% of the total battery capacity was used for storage. This means that daily the battery is charged and discharged 10%, which will have an impact on the lifetime of the battery. Uddin, K. et al., 2018 on his critical analysis of the Hawaii V2G study wrote that results showed that this additional usage of the batteries, even at constant power, is detrimental to cell performance and that it could shorten the lifetime of battery packs to less than five years. While Banguero, E. et al., 2018, in his paper presented a table, on which was the range of the lifetime of a lithium battery represented, being the lowest value 5 years. So for the lifetime of the battery on our paper we considered that would be 5 years and also that battery degradation would be linear, since we don't have enough data to use a battery degradation model.

In terms of the battery price, it was considered the price of replacement, 7000 €, (UVE, 2019) and with this value, if the cost of storage in 5 years would be half of this, we estimated a cost of storage per year of 700 €. The table 1 presents the key data of the analysis of storing using EV batteries, including the total storage costs. We considered a 5% discount rate, for congruency purposes.

*Table 1 - EV battery key data.*

| | | |
|---|---|---|
| power density | 0,36 | kW/kg |
| energy density | 0,03 | kWh/kg (capacity) |
| | 65,77 | kWh/kg (stored) |
| specific density | 10,00 | kWh/m3 (capacity) |
| | 8303,75 | kWh/m3 (stored) |
| Investment cost | 87,50 | €/kWh (capacity) |
| Operation cost | 0,07 | €/kWh (output) |
| Total storage costs | 0,17 | €/kWh (output) |

## 2.2 Traditional car battery systems

When looking at car storage options, besides the usage of EV.batteries there is still the option of using traditional car batteries. These batteries with 12V and 40Ah are commonly used in any kind of electrical device. These are not made for large scale energy storage, and as expected are not a viable option at all. Reusing such batteries for an energy storage system, apart from their original purpose, is simply not feasible. The batteries have too low capacity at about 0.48 kWh, even with a lifetime of 5 years, which is the usual time its used, the cost of this type of storage would be too high. Too many batteries would be needed to achieve usable capacities. Even considering the low cost of a single battery of about €60, realistic use would require too many batteries that are not ready for this rapid discharge and recharge. Overall, it is simply not a viable option, especially because of the size of the battery and its carrying capacity. In the table 2 we can analyse the traditional car battery key data.

*Table 2 - Traditional car battery key data.*

| | | |
|---|---|---|
| power density | 0,09 | kW/kg |
| energy density | 0,04 | kWh/kg (capacity) |
| | 34,07 | kWh/kg (stored) |
| specific density | 75,51 | kWh/m3 (capacity) |
| | 95562,24 | kWh/m3 (stored) |
| Investment cost | 125,00 | €/kWh (capacity) |
| Operation cost | 0,09 | €/kWh (output) |
| Total storage costs | 1,06 | €/kWh (output) |

### 2.3 Domestic battery systems

In this scenario, it was considered that each household would be equipped with an external battery with a capacity to cover approximately two days of self-consumption. The data already available in the electricity consumption report was used for this task. According to this, the annual electricity consumption is 248,000 MWh and the share of the domestic sector 26.5%. The consumption was then divided among the 20,000 households and over the year, resulting in a daily consumption of 9 kWh per household. In order to find the best possible solution for a home battery, we compared the purchase of a new battery with the purchase of an old EV battery and further it´s discussed domestic battery ownership.

#### 2.3.1 New domestic battery

Due to very high investments in research and development resulting in the rapid technical development of lithium-ion batteries, they have become the most prominent domestic batteries. The advantages over other batteries include properties such as good energy density, high efficiency and long lifetimes. Despite a sharp drop in prices in recent years, the investment costs are still high (Schram, W. M. et al., 2018). To get the best value for money, we searched for different home battery systems. We kept coming across the Tesla Powerwall, the LG Chem and the Generac PWRCell. Since the Generac model was the only one with sufficient capacity and also had very good technical properties, we used it for our analysis. The capacity of the selected model is 18.5 KWH with a maximum power of 6.5 kW and is available at a complete price of 12,000 €. According to the manufacturer, the round tip efficacy is 95% and we assumed a lifetime of 15 years. As already mentioned, we used a capacity factor of 50% and thus we were able to determine an annual electricity input of 1643 kWh, which at an electricity price of 0.006 €/kWh results in an annual electricity cost of 98.58 €. We then used this data to calculate the NPV of the investment, which can be looked up in the appendix, in order to obtain other relevant key figures. Some technical data are shown in table 3 and the most relevant figure for our project is the total storage cost marked in green. We obtained this by calculating the NPV through the outputs of the battery, over the entire lifetime of the battery.

*Table 3 - New domestic battery key data.*

| | | |
|---|---|---|
| power density | 0,03 | kW/kg |
| energy density | 0,09 | kWh/kg (capacity) |
| | 117,06 | kWh/kg (stored) |
| specific density | 75,51 | kWh/m3 (capacity) |
| | 95562,24 | kWh/m3 (stored) |
| Investment cost | 648,65 | €/kWh (capacity) |
| Operation cost | 0,06 | €/kWh (output) |
| Total storage costs | 0,56 | €/kWh (output) |

#### 2.3.2 Old car battery for domestic purpose

As the popularity of electric vehicles is fastly increasing, there has also been a rise in the usage of lithium batteries in vehicles. Their lifetime in vehicles is usualy between 8 to 12 years and afterwards they can still be used for up to 5 years for example in households as external energy storage. These batteries are a cheap option, they can be purchased for 10/20% of the price of a new battery and can have higher values of power and capacity compared to new household batteries.

For the old EV battery of the 2018 Nissan Leaf, we assumed that we obtain the battery after 10 years of use, so it already lost 20% of the capacity and now has 32 kWh with a maximum power of 110 kW, the price is 15% of the 7000€ for a new battery so its available for 1050€, the round tip efficiency is 91% and we assumed a lifetime of 5 years. The capacity factor and other electricity information are the same as the new domestic battery scenario, with this data we calculate the NPV of the investment that can be looked up in the appendix and in table 4 the other technical data and the total storage cost are represented.

*Table 4 - Old EV battery key data.*

| | | |
|---|---|---|
| power density | 0,36 | kW/kg |
| energy density | 0,11 | kWh/kg (capacity) |
| | 74,02 | kWh/kg (stored) |
| specific density | 320,00 | kWh/m3 (capacity) |
| | 74756,50 | kWh/m3 (stored) |
| Investment cost | 32,81 | €/kWh (capacity) |
| Operation cost | 0,07 | €/kWh (output) |
| Total storage costs | 0,20 | €/kWh (output) |

### 2.3.3 Ownership discussion

In this subject there are two valid points of view. The first one is from the perspective of the grid operator. Assuming they were installed by the authorized entity, the battery should be charged when there is excess of supply and discharge when it's needed to help match the production and consumption.

The second one is from the point of view of the house owner. Assuming they were installed by the householder that also owns the rooftop PV system, then it would be wiser to manage the battery according to the solar resource. Since a battery storage unit can increase self-sufficiency.

So with these two perspectives we can discuss that domestic battery ownership will depend on who made the installation, and what kind of electricity contract the householder has. But in an utopian society, if every resident can afford the PV system, they should invest also in a domestic battery to use as it an independent storage facility.

## 2.4 Community based battery systems

Due to a strong increase in private energy producers, for example with PV systems on the roof, the role of private households as prosumers is becoming increasingly important. In order to prevent production restrictions and to ensure a stable electricity network, there is always talk about community-based energy storage systems. These systems enable several households to store electricity together at a central location, which is owned and operated by the network provider. In contrast to large storage facilities (e.g. pumped storage power plants), they are significantly smaller in capacity and are distributed in the grid in such a way that they can supply residential customers with lower voltages (El-Batawy, S.A. et al., 2018).

In the case of our island, to prevent production curtailment and the function of shifting supply and demand, we have considered the possibility of community battery storage. When it comes to the size of our storage, we have chosen a capacity that corresponds to the average daily consumption of 100 households. The data we used for the profitability analysis was taken from the study " Techno-economic analysis of battery storage and curtailment in a distribution grid with high PV penetration" by Sevilla Segundo, F. R. et al. In this case, Li-ion batteries were used because of their technical characteristics, such as the capability of efficient charging and discharging with high performance and a long lifetime. The size of the selected storage corresponds to the average daily consumption of 100 households, which is equivalent to 900 kWH and a maximum power of 450 kW. We used 15 years as the lifetime and the typical roundtrip efficiency of these systems which is 90%. The annual electricity input is 164,300 kWh which corresponds to 9858 € and the annual maintenance costs for this storage size is 2876 €. With these data we calculated the NPV, which we attached to the appendix and used for further calculations. The most important data is presented in table 5.

*Table 5 - Community storage key data.*

| | | |
|---|---|---|
| Investment cost | 328150 | € |
| Maintanence costs: | 2867 | €/a |
| Operation cost | 9858 | €/a |
| Anual electricity output | 147870 | kWh |
| Total storage costs | 0,21 | €/kWh (stored) |

# 3 Environment and social economics

The mining of lithium releases toxic amounts of industrial waste to the environment, with serious health risks for fauna and flora, and even for humans.
The processing uses a lot of water, approximately 500,000 gallons per metric ton of lithium. This affects the region's water supplies, some cases consuming around 60% of the region's water, which causes depletion for livestock, agriculture and the water bodies themselves. The processing of lithium also releases toxic vapors, which pollute the air, and also falls down again in the rain, spoiling soil, air, and water bodies in an even wider área.
The greatest bottlenecks can be expected for lithium and cobalt. Bottlenecks there can be alleviated by recycling the lithium from batteries after their lifetime is over, by substituting lithium use in other sectors, and by using less cobalt-intensive cathodes. Also, different battery types may be developed, for example by making use of graphene.

## 3.1 Recycling

Due to the popularity of electric vehicles starts to grow explosively, the industry analysts predict that by 2030, the use of Li-ion batteries in the worldwide will hit 2 million metric tons per year, so now the word had create a new problem and the recycling of these types of batteries has become a vital issue for the near future, because after the end of useful life the batteries can't just be left in normal trash they still can be toxic to the environment.

On the topic of Li-ion batteries production only less than 3% are being recycled nowadays, there are three general methods exist to recycle Li-ion batteries: mechanical, pyrometallurgical and hydrometallurgical processes. These methods are mostly intended to recover different materials (lithium, copper, cobalt, nickel, iron, aluminum and manganese). The recycling of this batteries can bring us a lot of benefits beside contributing to longer life of Li-ion batteries, like in the economical approach due the high price of cathode metals, they can be recovered and used again for less money, recycling can also help to reduce the quantity of dangerous metals and materials going into landfills that can readily leak from the casing of buried batteries and contaminate soil and groundwater threatening ecosystems and human health, contributing to a reduction on emissions and dependence on imported oil products.

In an energetic view it increased need for grid-integrated energy storage to address peak load reduction, grid stabilization and elevate the growth of renewable solar and wind electricity further increasing the value of grid-integrated energy storage and large investment in battery manufacturing for green economy.

Despite these benefits, recycling batteries can have very strong challenges, from the chemistry to the battery structure that further complicates recycling efforts, the major challenge is the high cost of this process, it is still cheaper to recycle than to buy new batteries but for example if the price of the raw material drop the recycle battery would struggle to compete with the new one in terms of price (Dehghani-Sanija, A.R. et al., 2019).

# 4 Conclusion

After examining and comparing all the technologies, we conclude that the vehicle to grid principle is the cheapest storage option with 0,17 €/kWh and has also quite a good annual storage capacity. The traditional car battery, on the other hand, is the most expensive variant and is also unsuitable for our purpose because of its very small storage capacity.

In terms of household batteries, the recycled EV battery is the cheaper option, but it should be noted that only about 2500 batteries are replaced and available each year. This means that after five years, which is the remaining life of the EV batteries, about 12,500 households would be equipped with them and there would not be enough batteries in total to equip every household. The remaining households could either be equipped with new domestic batteries, or community storage systems could be installed in geographically convenient locations to meet the storage needs.

The price per unit of stored electricity of community storage is about one third of that of new domestic batteries, which is clearly in favour of central storage. In table 6, all technologies are summarized below to see which capacities are possible at which prices.

*Table 6 - Final overview for the examined technologies.*

| Type of Battery | Yearly electricity output [kWh] | Total storage costs [€/kWh] (output) |
|---|---|---|
| Traditional Battery: | 12 | 1,06 |
| Domestic Battery: | 1561 | 0,56 |
| Community Battery: | 147870 | 0,21 |
| Domestic Old Car Battery: | 1495 | 0,20 |
| EV Battery: | 1329 | 0,17 |

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# Appendix

NPV EV battery

| NPV | | | | |
|---|---|---|---|---|
| t | Bt | Ct | Bt-Ct | NPV |
| 0 | | € 700,00 | -€ 700,00 | -€ 700,00 |
| 1 | € - | € 87,60 | -€ 87,60 | -€ 87,60 |
| 2 | € - | € 87,60 | -€ 87,60 | -€ 87,60 |
| 3 | € - | € 87,60 | -€ 87,60 | -€ 87,60 |
| 4 | € - | € 87,60 | -€ 87,60 | -€ 87,60 |
| 5 | € - | € 87,60 | -€ 87,60 | -€ 87,60 |
| discount rate: 5% | | | NPV | -€ 1 138,00 |

NPV traditional battery

| NPV | | | | |
|---|---|---|---|---|
| t | Bt | Ct | Bt-Ct | NPV |
| 0 | | € 60,00 | -€ 60,00 | -€ 60,00 |
| 1 | € - | € 1,05 | -€ 1,05 | -€ 1,05 |
| 2 | € - | € 1,05 | -€ 1,05 | -€ 1,05 |
| 3 | € - | € 1,05 | -€ 1,05 | -€ 1,05 |
| 4 | € - | € 1,05 | -€ 1,05 | -€ 1,05 |
| 5 | € - | € 1,05 | -€ 1,05 | -€ 1,05 |
| | | | NPV | -€ 65,26 |

NPV new domestic battery

| NPV | | | | |
|---|---|---|---|---|
| t | Bt | Ct | Bt-Ct | NPV |
| 0 | | € 12 000,00 | -€ 12 000,00 | -€ 12 000,00 |
| 1 | € - | € 98,58 | -€ 98,58 | -€ 93,89 |
| 2 | € - | € 98,58 | -€ 98,58 | -€ 89,41 |
| 3 | € - | € 98,58 | -€ 98,58 | -€ 85,16 |
| 4 | € - | € 98,58 | -€ 98,58 | -€ 81,10 |
| 5 | € - | € 98,58 | -€ 98,58 | -€ 77,24 |
| 6 | € - | € 98,58 | -€ 98,58 | -€ 73,56 |
| 7 | € - | € 98,58 | -€ 98,58 | -€ 70,06 |
| 8 | € - | € 98,58 | -€ 98,58 | -€ 66,72 |
| 9 | € - | € 98,58 | -€ 98,58 | -€ 63,55 |
| 10 | € - | € 98,58 | -€ 98,58 | -€ 60,52 |
| 11 | € - | € 98,58 | -€ 98,58 | -€ 57,64 |
| 12 | € - | € 98,58 | -€ 98,58 | -€ 54,89 |
| 13 | € - | € 98,58 | -€ 98,58 | -€ 52,28 |
| 14 | € - | € 98,58 | -€ 98,58 | -€ 49,79 |
| 15 | € - | € 98,58 | -€ 98,58 | -€ 47,42 |
| | | | NPV | -€ 13 023,23 |

NPV old EV-battery

| NPV | | | | |
|---|---|---|---|---|
| t | Bt | Ct | Bt-Ct | NPV |
| 0 | | € 1 050,00 | -€ 1 050,00 | -€ 1 050,00 |
| 1 | € - | € 98,58 | -€ 98,58 | -€ 93,89 |
| 2 | € - | € 98,58 | -€ 98,58 | -€ 89,41 |
| 3 | € - | € 98,58 | -€ 98,58 | -€ 85,16 |
| 4 | € - | € 98,58 | -€ 98,58 | -€ 81,10 |
| 5 | € - | € 98,58 | -€ 98,58 | -€ 77,24 |
| | | | NPV | -€ 1 476,80 |

NPV community storage

| NPV | | | | |
|---|---|---|---|---|
| t | Bt | Ct | Bt-Ct | NPV |
| 0 | | € 328 149,86 | -€ 328 149,86 | -€ 328 149,86 |
| 1 | € - | € 12 725,37 | -€ 12 725,37 | -€ 12 119,40 |
| 2 | € - | € 12 725,37 | -€ 12 725,37 | -€ 11 542,29 |
| 3 | € - | € 12 725,37 | -€ 12 725,37 | -€ 10 992,66 |
| 4 | € - | € 12 725,37 | -€ 12 725,37 | -€ 10 469,20 |
| 5 | € - | € 12 725,37 | -€ 12 725,37 | -€ 9 970,66 |
| 6 | € - | € 12 725,37 | -€ 12 725,37 | -€ 9 495,87 |
| 7 | € - | € 12 725,37 | -€ 12 725,37 | -€ 9 043,68 |
| 8 | € - | € 12 725,37 | -€ 12 725,37 | -€ 8 613,03 |
| 9 | € - | € 12 725,37 | -€ 12 725,37 | -€ 8 202,89 |
| 10 | € - | € 12 725,37 | -€ 12 725,37 | -€ 7 812,27 |
| 11 | € - | € 12 725,37 | -€ 12 725,37 | -€ 7 440,26 |
| 12 | € - | € 12 725,37 | -€ 12 725,37 | -€ 7 085,96 |
| 13 | € - | € 12 725,37 | -€ 12 725,37 | -€ 6 748,54 |
| 14 | € - | € 12 725,37 | -€ 12 725,37 | -€ 6 427,18 |
| 15 | € - | € 12 725,37 | -€ 12 725,37 | -€ 6 121,12 |
| discount rate: 5% | | | NPV | -€ 460 234,88 |