A Study of Flow Battery Arbitrage Potential in Two Different Electricity Markets

Xiabing Lou
Chemistry and Chemical Biology

Abstract: The significant increase in renewable energy sector, especially in solar and wind, has elevated the volatility of the electricity price in some regions. Thus the arbitrage potential of an energy storage device is of great interest. In this paper, the PJM and German electricity wholesale market has been chosen to study the economic opportunity of flow batteries in these areas.

Introduction

Renewable energy sources, such as wind and solar, have vast potential to reduce dependence on fossil fuels and greenhouse gas emissions in the electric sector. (Chen, Cong et al. 2009)However, despite the potential low price and high volume, the high volatility of such energy resources would greatly restrict their installation in urban area. One of the most impressive examples would be on June, 16th, 2013, the wholesale price of Germen electricity market fell to minus €100 per megawatt hour (MWh) (Economist). That is due to the large electricity supply from solar and wind due to the sunny and windy weather while the demand at that time was low. The generating companies therefore had to pay for the others to take away energy to maintain a stable grid. In such case, the generation peak of electricity from renewable energy could not match the demand peak of electricity and therefore caused the unusual fluctuation of utility price. Naturally, a cheap, large volume and non-geography dependent electricity storage would be ideal for solving this problem. Moreover, the installation of such storage system would provide an opportunity for making extra profit from the electricity price arbitrage. Previously a lot of work has been done on studying the cost-benefit effect of different storage technologies(Peterson, Whitacre et al. 2010). But seldom any examples were economically attractive. Recently Aziz group (Huskinson, Marshak et al. 2014) has demonstrated an organic-inorganic flow battery system has the potential of being the next generation large-scale storage system. They claimed their flow battery was substantially advantageous over the traditional vanadium flow battery in terms of price per unit weight, but the price per unit energy has not been provided.

In the installation of a flow battery, there are two main sources of cost, liquid electrolytes and solid parts, including storage tank, pump, catalyst and so on. Conceptually, the electrolyte amount and tank size would determine the volume while the pump and catalyst would determine the output and input power. The volume can be expressed as the product of the power times the maximum charging time. In this paper, the power is fixed as 1MW for the ease of representation. In fact, the power can be easily scaled up or down by changing the number of the flow batteries and thus does not affect the profitability study. Therefore, a primitive price model for a flow battery with certain power and volume is proposed in this paper. With this model, two cases, one for traditional area and the other for renewable area, will be studied for their arbitrage potentials.

Methods

The profit of a flow battery can make from arbitraging the fluctuation of the electricity can be studied with a *price taken model* (Sioshansi, Denholm et al. 2009). In this model, the storage capacity was assumed to be small enough not to affect the electricity price during the charging and discharging. The storage device captures arbitrage value by storing low-cost energy and then reselling that energy during higher-priced hours. Such storage device is typically characterized by its power, its energy capacity, and roundtrip efficiency. Thus the profit can be written as:

$$\text{total profit} = \sum_{t=1}^{T} P_t(D_t - C_t); \qquad (1)$$

In equation (1), t is the time in unit of hour, T stands for the total hours that the storage device operates, P_t is price in hour t, D_t is the discharging amount of energy in hour t and C_t is the charging amount of energy in hour t.

The operation of the storage device has a few limits as shown below:

Storage level (S_t) should not exceed the device power (k) times the maximum charging time (h). And every S_t should be equal with the previous storage level (S_{t-1}) plus the change during the t hour. Here we could define the round trip efficiency as ω. Which can be written as:

$$S_t = S_{t-1} + D_t + \omega * C_t \qquad (2)$$

$$S_t \in [0, h * k] \qquad (3)$$

Moreover, the charging and discharging within the hour t cannot be larger than the power times 1 hour. Thus, another boundary condition would be:

$$D_t\,, C_t \ \in [0, k] \qquad (4)$$

In order to study the arbitrage potential of a flow battery, the total profit should be maximized according to the price data. Thus a linear programming solver in MATLA has been employed. In this simulation, the power is fixed as 1 and the hours of maximum charging and the round efficiency can be changed. This is for the ease of programming. In each of the market, a round efficiency from 50% to 100% and a maximum charging hour from 1h to saturate hours (the volume with zero marginal profit) have been employed as the input parameters.

In considering the reasonable computation time, the data was processed in a monthly bases. At the beginning of each month, the storage of the flow battery was assumed to be emptied. This assumption might introduce a small error in calculating the maximum profitability but it should not exceed the profit of one day for each month. Due to the maximizing nature of the model, the flow battery would always discharge completely at the end of each month for maximum profit. Thus this would meet the starting point of the next month.

Electricity Storage Arbitrage Potential in PJM

For studying a region with relatively small renewable energy contribution to the electricity and thus smaller volatility, the PJM is a good candidate. PJM Interconnection is a regional transmission organization (RTO) that coordinates the movement of wholesale electricity in all or parts of Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia and the District of Columbia. As shown in Table 1. In this area, the weighted average of renewable contribution is 5.26%, while the weighted average of renewable without hydro is 2.92%. Compared with the US total electricity from renewable, 13.3% and the renewable electricity without hydro, 6.5%(Wikipedia), the PJM is relatively a less renewable area. Consider the fact that the volatility of the electricity price is primarily from the volatility of energy supply and demand, solar and wind would be the more significant contributors rather than hydro.

State	**% Renewable**	**% Renewable w/o Hydro**	**Renewable electricity (GW•h)**	**Renewable electricity w/o Hydro (GW•h)**	**Total electricity (GW•h)**
Delaware	1.6	1.6	122	122	7616
Illinois	5.1	5.1	10440	10299	202891
Indiana	3.8	3.5	4227	3810	110378
Kentucky	4.1	0.4	3693	327	89935
Maryland	6.9	2.6	2465	934	35487
Pennsylvania	3.7	2.5	8336	5714	227683
New Jersey	2.4	2.4	1549	1549	64848
Ohio	1.8	1.4	2409	1889	136702
Massachusetts	9.3	5.9	3144	1999	33773
Virginia	5.5	3.7	4270	2845	77185
North Carolina	7.5	2.4	9380	2947	124922
West Virginia	4.1	1.8	3119	1402	75927
Michigan	5.8	4.8	6107	5070	104970
Tennessee	16.3	1.4	12819	1082	78669

Table 1. The PJM states energy summary. The renewable energy includes hydro, solar, wind, biomass, geothermal, etc. Among all the sources, hydro is relatively stable in supply of the energy in short runs, while biomass and geothermal contribute much less in the total supply. Due to the nature of wind and solar energy supply, the short run volatility can be significantly elevated with such two sources.

The 2013 all year one-day-ahead auction price data has been acquired from PJM official website as the input data for the price taken model. The mean price of 2013 is $30.89/MWh, the standard deviation is $6.23/MWh. The relative standard deviation (standard deviation/mean price) is 20.16%.

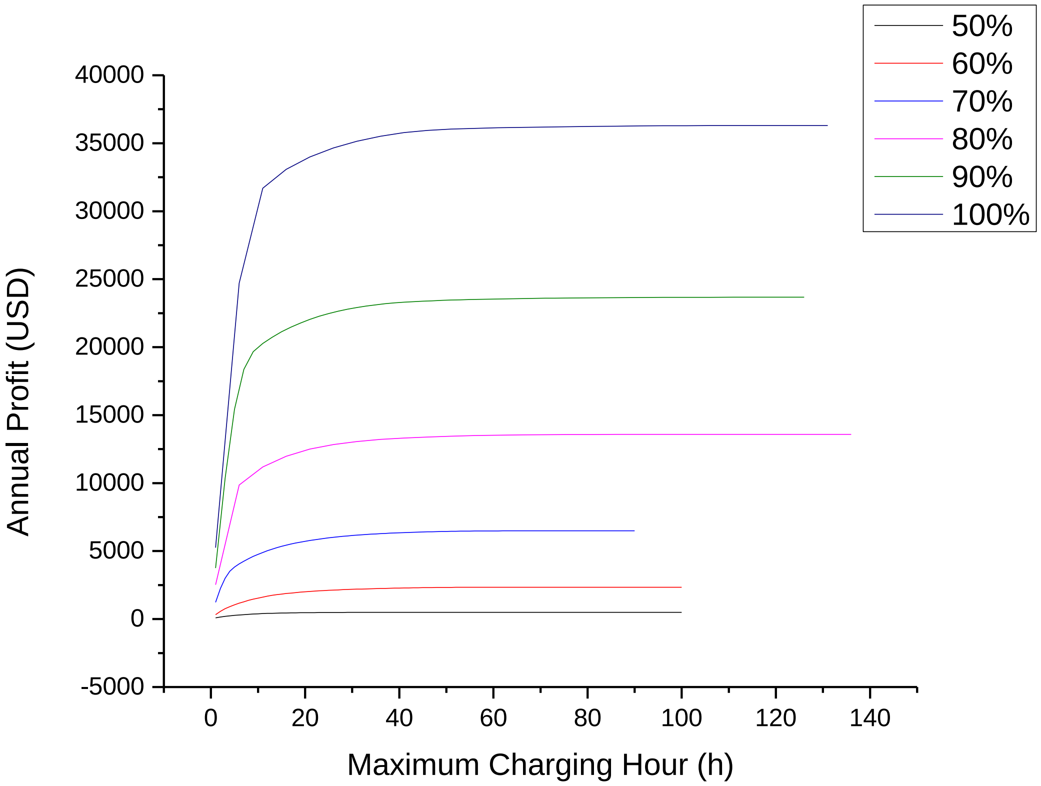


Figure 1. The maximum annual profit of flow battery with different round efficiency and maximum charging hour in PJM.

Figure 1 summarizes the modelling result for the arbitrage profitability in PJM area. It shows that the profitability increase for scaling the storage volume would differ greatly regarding with different efficiency. The higher efficiency the flow battery is, the more meaningful for scaling the volume. Under 50% round efficiency, the profit is only around $100 per year with 1 hours storage and the marginal profit would decrease to zero when storage increase to 30 hours. Even at the saturation profitability, 50% efficient flow battery can only make $500 profit. However, with 80% efficiency, which is the ideal round efficiency for current technology, a $2500 profit can be achieved with 1 hour storage and $13,600 can be achieved with saturation storage. This means that in PJM area, the efficiency is a more critical factor. The profitability increases fast between 1-10h and the marginal profitability decreases significantly in 20-40h. Thus a 10-20h storage capacity would be reasonable for PJM area.

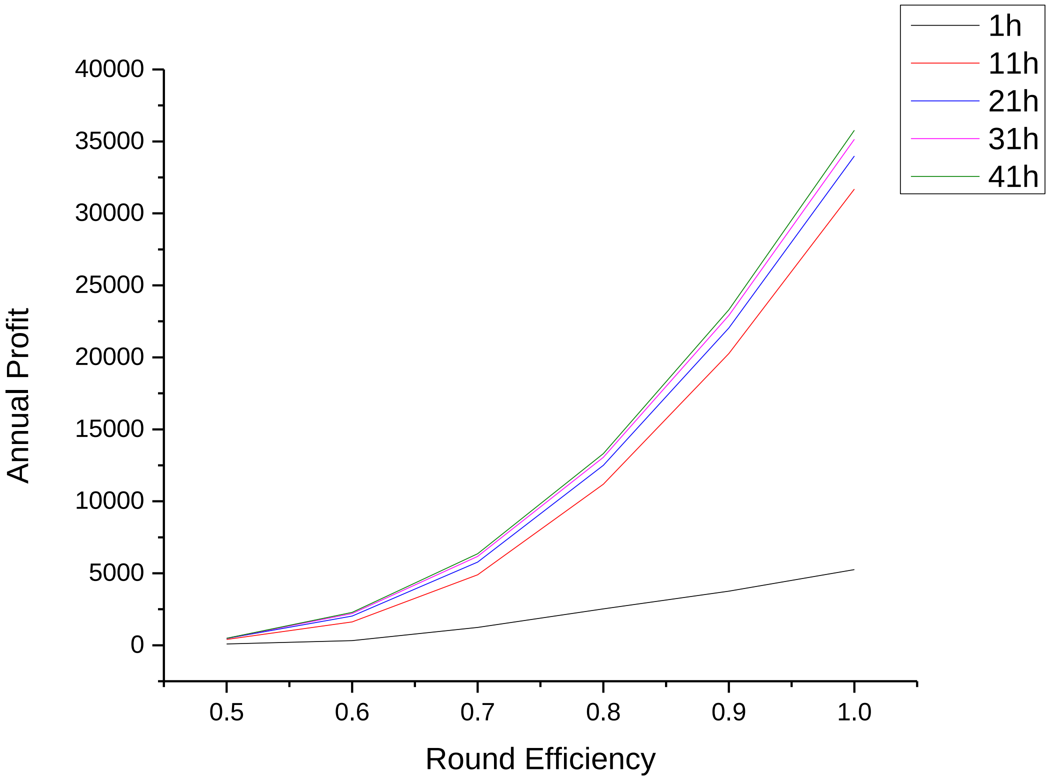
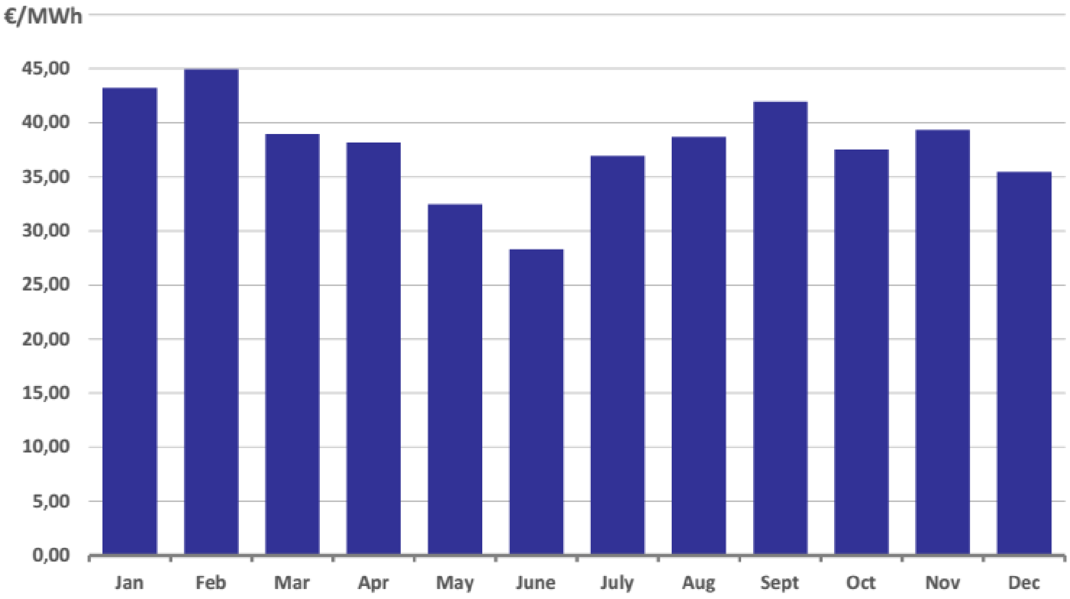


Figure 2. The relationship between round efficiency and annual profit with different storage capacity in German electrical market.

Additionally, Figure 2 summarizes the relationship between profit and the round efficiency. It clearly shows that the profit vs efficiency is a convex curve. Moreover, in also indicates that the marginal profit would be much less when the volume is larger than 11h. This factor should be taken into consideration when designing the flow battery tank in PJM.

Electricity Storage Arbitrage Potential in Germany

For studying a region with relatively high renewable energy contribution to the electricity and thus higher volatility, Germany is a very good candidate. Germany has achieved a 24% of renewable sources for electricity production in 2013. Around 17% of the total electricity is provided by solar and wind.



Firgure 3, Monthly average of day ahead price in 2013 in Germany(Mayer).

The average monthly electricity price in Germany has been shown in Figure 3. It clearly shows two peaks at February and September. The reason for these two peaks might because of the heating for the winter and air-conditioning for the summer.

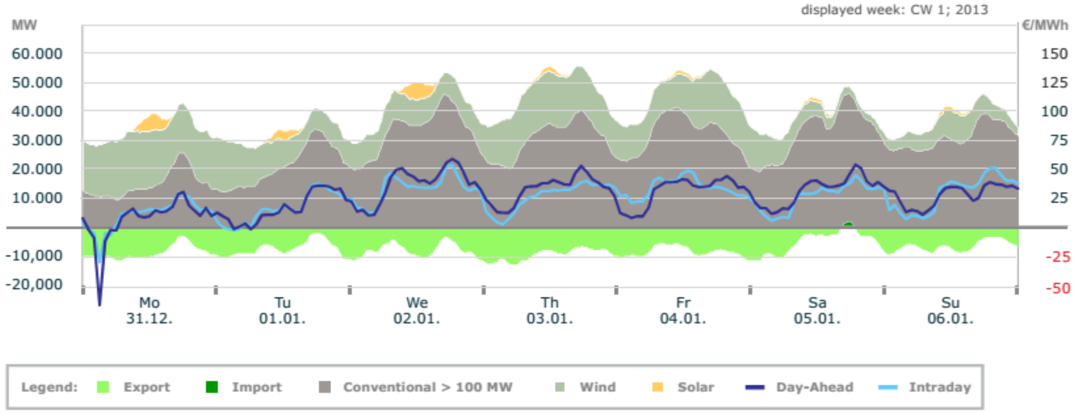


Figure 4, German electricity price fluctuation during a week in January 2013(Mayer).

In Figure 4, the upper figure clearly shows that the relationship between the volatile supply of wind and solar is an important driven power of the fluctuation of electricity price. In most of the days throughout the week, the price would should a single peak around noon. However, on Wednesday noon, the usual peak position was replaced with a valley surrounded by two peaks. This price valley is overlapped with the solar production peak very well, which is a good indication that the solar production is the cause of this fluctuation of price.

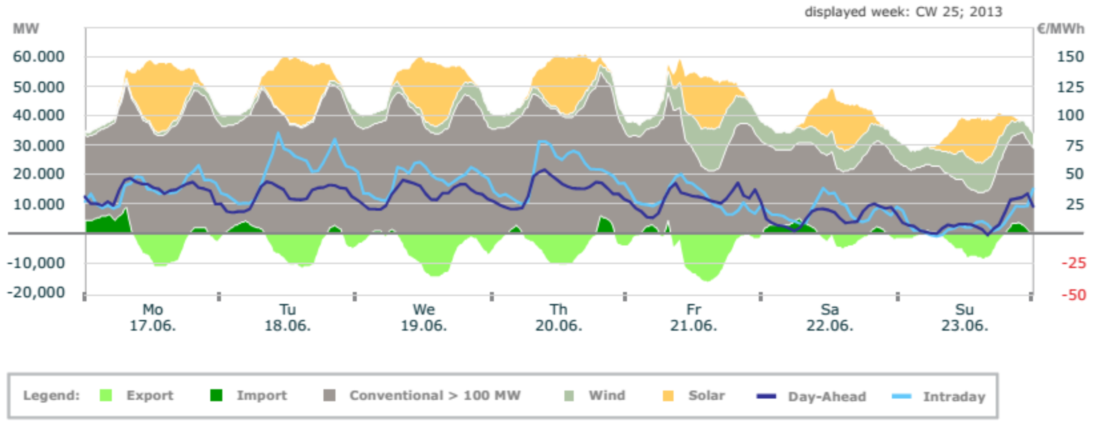


Figure 5, German electricity price fluctuation during a week in June 2013(Mayer).

In Figure 5, the average electricity price significantly cheaper than the winter. One of the most important reason is that the solar input during the day time is large enough to compensate the day time demand peak. But this is highly dependent on the weather condition. Moreover, the wind energy input at this time of the year is significantly less than winter.

The Germen hourly day ahead price data of 2013 was acquired from European Power Exchange(EUEXSPOT) official website. The data was in the unit of EUR/MWh. An average exchange rate of USD/EUR=0.75 in 2013 is employed in order to compare the modeling result with the PJM data. The weighted average electricity price of 2013 in Germany is 37.77 EUR/MWh, and the standard deviation is 16.48EUR. The relative standard deviation is 43.63%. The price of Germen electricity equals to $50.39/MWh, and the relative standard deviation is significantly larger than the PJM price. This is accord with the analysis of the volatility from solar and wind.

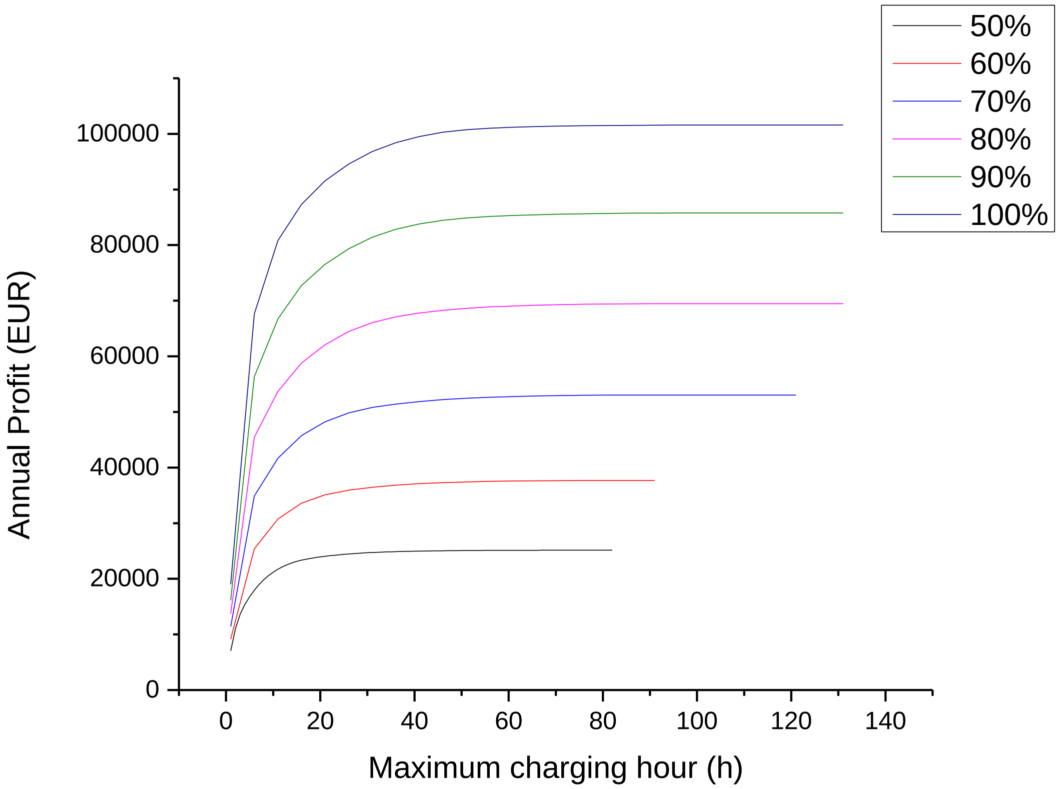


Figure 6. The maximum annual profit of flow battery with different round efficiency and maximum charging hour in Germen electrical market.

Figure 6 shows that the profit of flow battery would increase fast when the maximum charging hour is increase from 1h to 10h, but would increase less significantly afterwards. The profitability would be saturated with a capacity of more than 40h charging time for all frequencies. In designing the size of the flow battery tank, this marginal profitability of volume must be taken into account. A volume of 10-20 hours charging time should be the most economic range. Moreover, the general trend of the profit vs round efficiency seems to has a linear relationship.

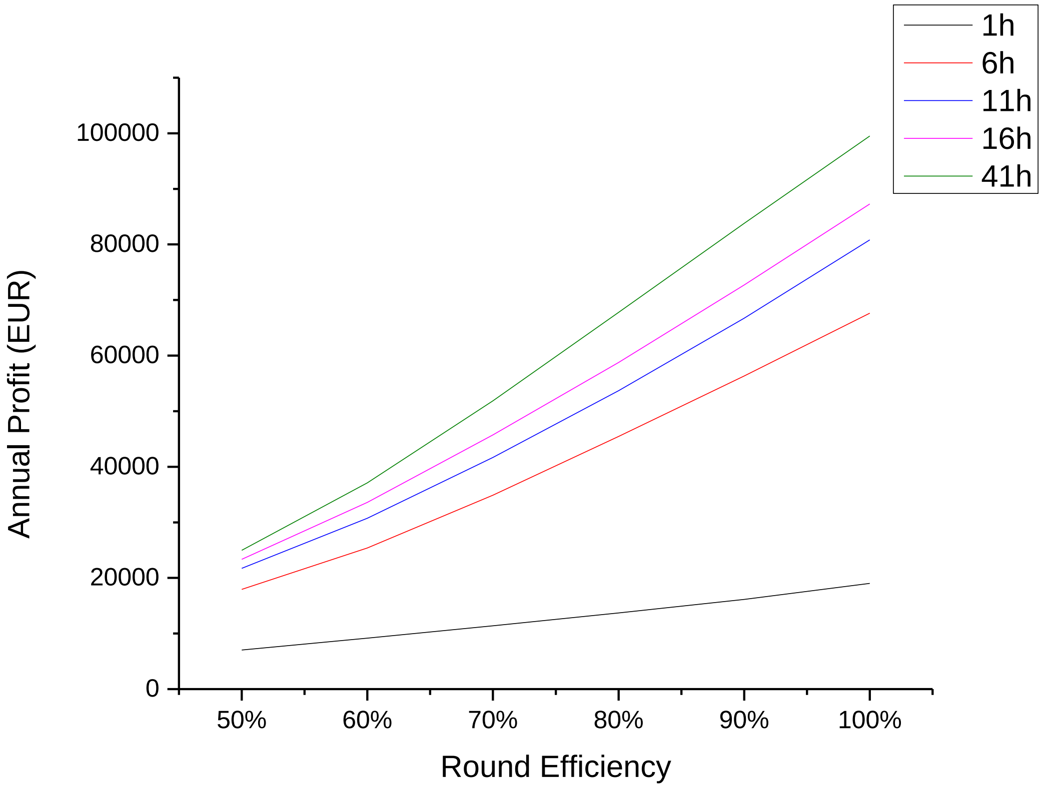


Figure 7. The relationship between round efficiency and annual profit with different storage capacity in German electrical market.

In Figure 7, the relationship between round efficiency and the profitability was plotted. Again, the curve has shown that the profitability increases faster when the volumes was small and the marginal profitability would decrease when the volume increases. Moreover, it indicates that the profitability increases almost linearly with the efficiency. Typically, a flow battery cannot exceed 80% round efficiency under current technology, but pushing the efficiency to 100% provides 50% more profit. This would be a very interesting factor to consider when designing the flow battery.

Flow Battery Arbitrage Potential Comparison between PJM and Germany

As discussed before, all the data acquired from Germany will be converted into USD at an average exchange rate of USD/EUR=0.75. In Table 2, some of the important characteristics of PJM and Germany electricity market has been summarized. Except the average price in Germany is higher than PJM, the higher renewable w/o hydro ratio in Germany is also significantly larger than PJM. As analyzed before, this might be the primary cause of the higher relative standard deviation of the price in Germany than in PJM.

	PJM	Germany
Average price $/MWh	30.89	50.39
Standard dev $/MWh	6.23	21.97
Relative standard dev	20.16%	43.63%
Renewable ratio	5.26%	24%
Renewable w/o hydro	2.92%	17%

Table 2. Selected characteristics of PJM and Germany electricity markets.

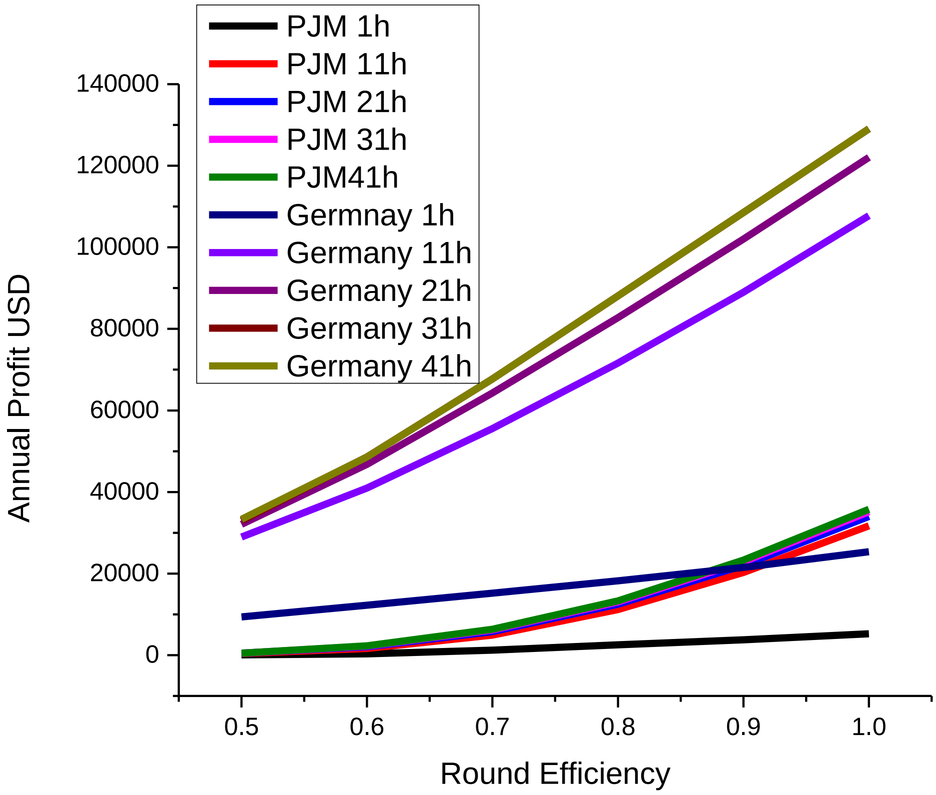


Figure 8. Comparison between Germany and PJM profitability regarding different round efficiency.

Figure 8 has plotted the difference between Germany and PJM flow battery arbitrage profit regarding with different efficiency and storage volume. The general trends of the two markets are the same: more efficient battery would generate more profit, the marginal profit would decrease with increasing volume. However, the volatility difference between the two markets leads to a large difference in the profitability. In general, the same flow battery would generate five times profit in Germen market than in PJM market. Moreover, the profit in PJM is much more sensitive to the storage volume compared with in Germany.

Conclusion

Based on the analysis in flow battery profitability in both Germany and PJM markets, it clearly shows that the flow battery has a better arbitrage potential in Germany than in PJM. The primary reason for such difference is the larger price volatility in Germany which due to the higher ratio of renewable energy. The sensitivity analysis of the profitability also indicates that a flow battery with 10-20 hours maximum charging time would be a reasonable volume range for arbitrage purpose in both PJM and Germany market. The profit would be more sensitive to the round efficiency when the volatility of the electricity price is lower.

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