ECN-W--07-009

Feasibility of Distributed Electricity Storage

F.D.J. Nieuwenhout, M.P.F. Hommelberg, G.J. Schaeffer, J.C.P. Kester, K. Visscher

Published in the International Journal of Distributed Energy Resources – Volume 2, Number 4, October – December 2006, ISSI

January 2007

Keywords: battery; distributed generation; electricity storage; LV-grid;

ABSTRACT

Four different business cases have been analysed for generating benefits from small-scale electricity storage systems. Benefits differ substantially from case to case. The imbalance market appears to be financially most attractive. This case has been worked out in more detail, in which a distinction has been made between active and passive contribution. It can be concluded that grid-connected electricity storage in small, distributed storage systems appears to be financially attractive, provided that battery costs fall significantly below €500 per kWh.

INTRODUCTION

Environmental policies have led to a rapid increase in the application of renewables over the last decade. This has contributed to a reduction of CO_2 emissions and reduced dependency on imported fossil fuels, but it also has its effect on the electricity market. There is a EU target to achieve 25% of electricity generation from renewables in 2020 [1]. The total share of intermittent sources will be substantially larger. This can lead to problems with the stability of the electricity supply. In such a situation electricity storage might become an appropriate solution.

One of the characteristics of distributed energy resources and renewable energy sources (DER and RES) is their variability. Variable energy sources produce fluctuating and (partly) unpredictable amounts of electricity over time.

Electricity storage is a possible technical solution for temporary mismatches between supply and demand of electricity due to these variable energy sources. Until now however, grid-connected electricity storage technologies are seldom economically efficient. This might change over time, as technology costs come down and market niches with higher value emerge.

This paper will look at possible markets for small-scale, grid-connected electricity storage in a liberalised market setting. In this paper the benefits of distributed electricity storage systems are compared for a number of different cases in which there is easy access to electricity price data, allowing straightforward quantification of benefits. Aim is to come up with a ranking of the most favourable markets for application of small-scale storage systems. Under certain circumstances, application of a storage system can lead to postponing investments in transmission or distribution infrastructure. But the extent of these benefits depends very much on the specific local circumstances. To make a ranking possible, we have omitted benefits from these grid services and instead limited ourselves to traded electricity only.

Approach

To evaluate the benefits of electricity storage, four business cases are analysed. In two cases there is no consumption of electricity, and all electricity that is bought is sold at a later time (except for storage losses). These cases we call the 'arbitrage' cases. Time series of electricity prices are used from a power exchange and an imbalance market. In the two other cases, where the storage system is located at the house of a domestic final consumer, consumption of electricity is assumed. In one case there is only consumption and no generation, and in another there is a combination of (micro-)generation and consumption. These four cases are described in more detail in the following sections. Electricity prices for these cases come from examples from the Netherlands. A similar analysis with market prices from other countries will give different numerical outcomes, but the main conclusions regarding the relative merits of the different markets for electricity storage are expected to be the same when similar markets exist.

For each case, first an estimate is made of the maximum theoretical benefits under ideal circumstances: no electricity losses in the storage system and existence of 'perfect foresight', i.e. all future prices are supposed to be known beforehand. To calculate the maximum theoretical benefits, it is also assumed that the storage system can be completely charged or discharged within the shortest period of time for which price information is available (15 minutes in our example). This is followed by an analysis with more realistic storage system characteristics. The cases that are financially most attractive are analysed further in more detail, by relaxing the assumption of 'perfect foresight'.

1 MARKETS FOR ELECTRICITY STORAGE

In liberalised electricity markets, most of the electricity is usually traded in the form of bilateral forward contracts. Since these are not publicly known, and differ from case to case, they are not suitable for the purpose of ranking different business cases for small-scale storage systems. The largest price volatility can be expected on markets with short-term contracts such as a day-ahead power exchange and the imbalance market. On a day-ahead market, electricity is traded for delivery the following day. Since the largest consumers of base-load electricity usually have long-term contracts, consumers having variable demand throughout the day and throughout the year dominate the day-ahead market. This results in substantial price fluctuations from hour to hour that can render operation of a storage system financially attractive.

To maintain a continuous balance between electricity supply and demand, regulating and reserve power are required. On the imbalance market, operators of suitable electricity generators can submit bids. Since the required amount of regulating power varies rapidly in the short term, the resulting imbalance prices show a high volatility.

Most of the smaller electricity consumers and suppliers rely on contracts with fixed prices that can depend on the time of the day. As soon as annual production or consumption is known, total costs or revenues are determined. With a single tariff there can be no benefits from storage. Whenever a peak (day) and off-peak (night) tariff is applied, an electricity consumer can potentially save money by charging the storage system during off-peak hours, followed by discharging the battery during peak hours. This market for electricity storage is called 'load-shifting'.

Another potential market for electricity storage is co-generation of electricity and heat, which becomes increasingly popular. At times when production is higher than demand, the surplus is usually fed into the grid. But the feed-in tariff for selling electricity is much lower than the price for buying. Storage of surplus electricity for own use at a later time can be financially attractive. This market is called 'avoided feed-in'.

1.1 Arbitrage on a day-ahead power exchange

When there is no local generation or consumption of electricity, the benefits of a storage system arise purely from arbitrage through buying at low and selling at higher prices. One of the possible markets for arbitrage is the day-ahead power exchange. In this analysis, prices of the Amsterdam Power Exchange APX have been used. Bidding curves are published on the company's website [2]. Historical time series of APX prices over the period 2000-2004 have been used to calculate the theoretical maximum revenues of a storage system. In the calculation of the theoretical maximum revenues, future prices are assumed to be known beforehand ('perfect foresight') and energy losses are assumed to be absent. In the calculations, the following control strategy is used to achieve the maximum revenues: Whenever the trend in the electricity price changes from increasing to decreasing, the storage system is completely discharged in the period with the highest price. When the trend changes from decreasing to increasing, the storage system is completely charged within the period with the lowest price.

Figure 1 shows the maximum theoretical revenues in € per year per kWh of storage capacity for the years 2000 to 2004. It shows large year-to-year variations up to a factor of more than 2. Average revenues amount to €44 per year per kWh of storage capacity.

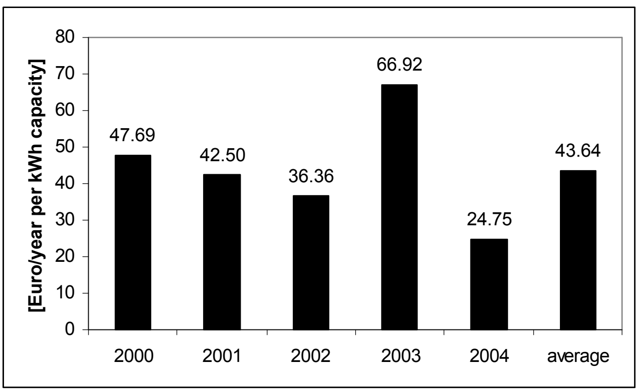

Figure 1: *Theoretical maximum revenues from arbitrage on the Amsterdam Power Exchange APX in €/year per kWh of installed storage capacity, with perfect foresight and no energy losses.*

Part of the theoretical benefits shown in figure 1 come from a large number of cycles with very small price differences between buying and selling. In real storage systems, battery life is limited to a certain number of cycles (typically in the order of 1000 in case of good deep-cycle lead-acid batteries, and 1500 in case of good lithium-ion). To recover the battery replacement costs, the revenues per cycle should be at least the investment cost in the batteries divided by the cycle life, accounting also for energy losses. Cycles that do not meet this criterion have been omitted in all cases except in the calculation of the theoretical maximum.

Figure 2 shows calculated annual revenues from arbitrage on the APX using a storage system with very favourable conditions that might be realised in 2010 (cycle life of 5000 cycles and cycle efficiency of 90%). Year-to-year variations have almost doubled to a factor of four. Average benefits are halved compared with the theoretical maximum to a level of only €22 per year per kWh. The simple pay-back period for the replacement cost of the batteries, assuming a battery system costs of €200/kWh storage capacity, is already about 10 years. This implies that arbitrage on the APX is not financially viable with the current levels of price volatility. The differences in prices should at least increase by a factor 2 compared to the most volatile year (2003), for battery systems to become financially viable.

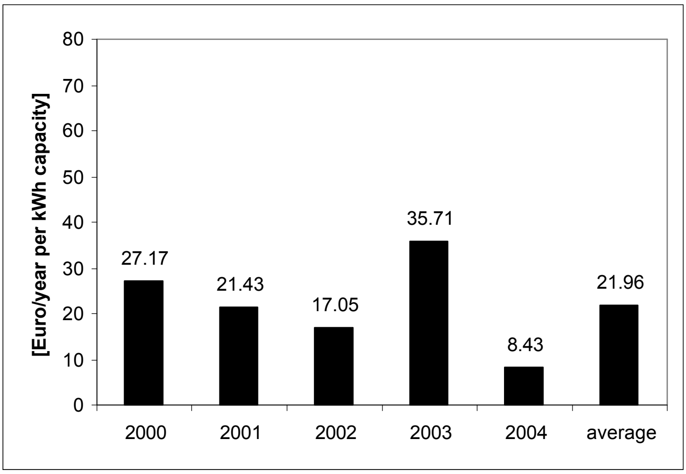

Figure 2: *Annual electricity storage revenues from arbitrage on the APX in €/year per kWh of installed storage capacity. Characteristics of a future lithium ion storage system. Required minimum benefits per cycle are €0.04/kWh. Cycle efficiency of the storage system is 90%.*

1.2 Arbitrage on an imbalance market

In the Netherlands, the imbalance market is organised by the Dutch Transmission System Operator TenneT. TenneT obtains bids from commercial parties to supply reserve and regulation power at short notice to achieve an instantaneous system balance. A more detailed description of the operation of this market, and time series of imbalance prices can be found on the TenneT website [3]. In the current market rules a minimum size of 5 MW is required. Small scale distributed storage systems can only be operated on the imbalance market if large amounts of these systems would be combined in the form of so-called 'virtual power plants'.

Three cases have been analysed with a storage system on the imbalance market: a) a storage system with characteristics of current lead-acid technology, b) a future storage system based on lithium ion, and c) the theoretical maximum using an ideal storage system without losses. Current lithium ion battery prices are in the order of €500 per kWh, but they are assumed to decrease to a level of €200 per kWh in 2010 (see table 1). The cycle efficiency is the average efficiency over a cycle due to losses in the three components: the charger, the battery and the inverter for generating the AC current. In practice, the cycle efficiency is not a fixed number, but depends on the charge rate and the charging- and discharging profiles. The battery costs per cycle provides a threshold that is used to prevent occurrence of those cycles for which the benefits per cycle are not sufficient to make up for the marginal cost due to battery depreciation. The costs of the electronics for a storage system are in the order of €150 per kW, but they are not supposed to affect the marginal cost of storage. Figure 3 shows the results of the analysis, assuming perfect foresight for all three cases, and transport costs of €33.1 per MWh for purchased electricity for the two cases with realistic storage systems.

Table 1: Characteristics of storage technologies used for analysing storage revenues on the imbalance market

	Current technology (lead-acid)	Future technology (lithium ion with estimated 2010 characteristics)
Battery costs:	€200/kWh	€200/kWh
Charging efficiency:	95%	97.5%
Battery efficiency:	78%	95%
Inverter efficiency:	95%	97.5%
Total cycle efficiency:	70%	90%
Cycle life:	1000 cycles	5000 cycles

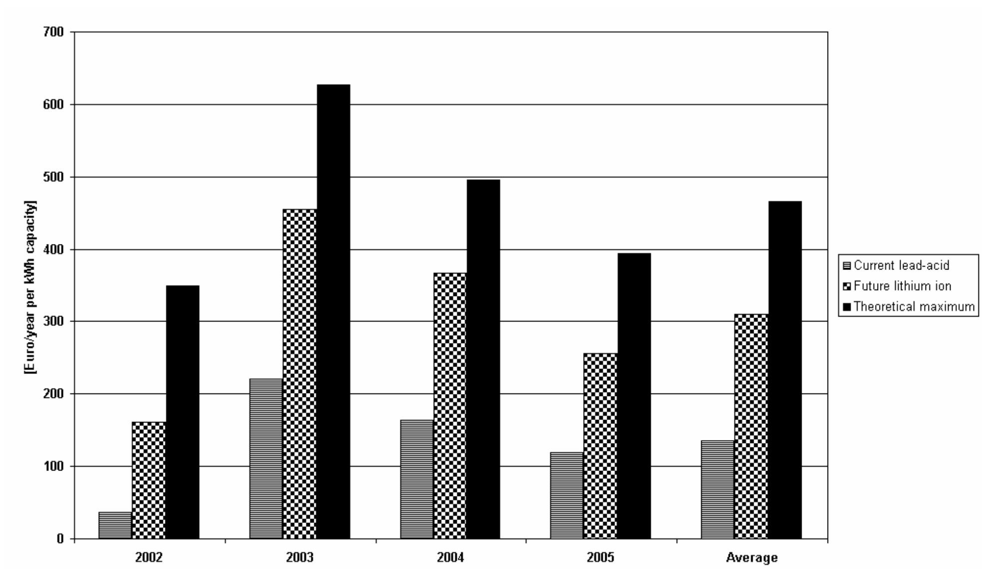

Figure 3: *Annual revenues on the Dutch imbalance market in €/year per kWh of installed capacity for three cases: a) current lead-acid storage system characteristics, b) future storage system based on Lithium ion, c) theoretical maximum. All three cases assume perfect foresight and no transport costs (2005: up to October 19th).*

Revenues from arbitrage on the power exchange as shown in figure 2 can be compared with the revenues on the imbalance market of case b) in figure 3. Year-to-year variations in annual revenues of arbitrage on the imbalance market are somewhat smaller than the variations on the day-ahead market. But the average revenues of arbitrage on the imbalance market are more than a factor ten higher then the annual revenues on the day-ahead market. This means that if the price dynamics of the imbalance market does not change too much and the costs and technical characteristics of lithium-ion battery systems will reach the projected levels by 2010, these systems will be economic in the imbalance market. Of course, introduction of storage systems in the imbalance market will have a dampening effect on the price volatility, limiting the size of this market for battery systems.

1.3 Load-shifting

An electricity consumer with a dual tariff meter can save money by shifting demand from the peak hours to off-peak hours. As an example we take the electricity price (including all grid charges) in 2005 of a domestic customer in the Netherlands of NUON, one of the large Dutch utilities: €0.203/kWh during peak hours and €0.137/kWh during off-peak hours (see figure 4). From this tariff difference, theoretical maximum revenues of a storage system from load-shifting can be calculated of €24.09 per year per kWh of installed storage capacity.

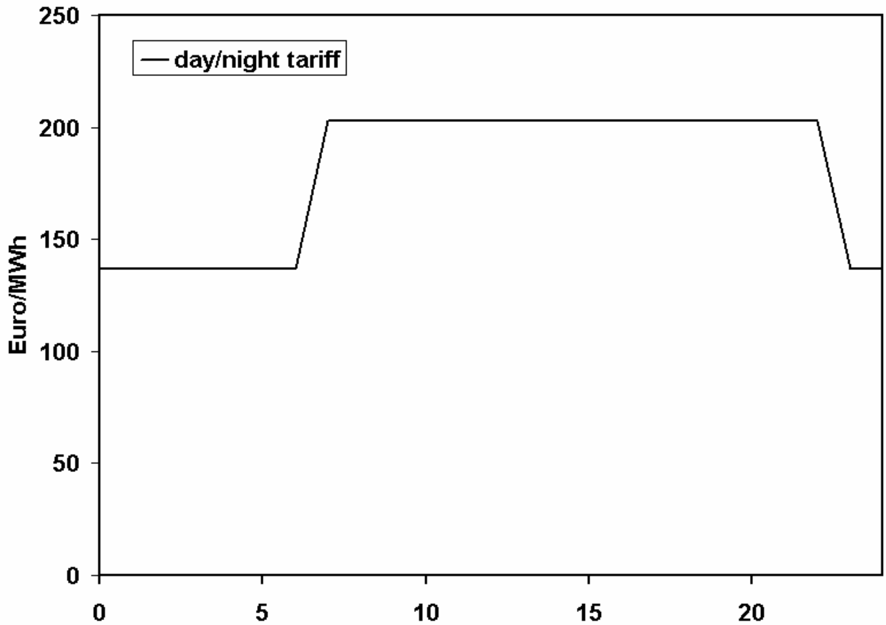

Figure 4: *Residential day/night tariff in the Netherlands in 2005 which was used to calculate benefits from load shifting.*

An hourly simulation model of household electricity demand with a realistic demand pattern and a storage system with a cycle efficiency of 70% showed net costs of €1.17 per year per installed kWh of storage capacity instead of benefits. This is caused by the relatively high storage losses [4]. With larger differences between peak and off-peak tariff, and with a higher efficiency of the storage system, the benefits are expected to be positive and higher. In the absence of substantial increases in the difference between peak and off peak tariffs, load shifting is expected to remain a financially unattractive means to create revenues with a storage system.

1.4 Avoiding feed-in

When an electricity consumer also generates electricity (for instance by micro-CHP or PV-solar cells), a storage system can be used to reduce the amount of electricity that is fed into the grid at times when domestic supply is larger than demand. Electricity feed-in tariffs are usually much lower than the tariffs for buying electricity. For the analysis the following feed-in tariff was assumed (see figure 5): a peak tariff for feed-in of €0.078 /kWh and an off-peak tariff for feed in of €0.03/kWh (this is a theoretical assumption, because currently, no feed-in tariff for small-scale cogeneration exists in the Netherlands). For a household with consumption of 4000 kWh/year, having a tariff as mentioned in the previous section 1.3, the maximum theoretical benefits with this feed in tariff would be €115.33 per year.

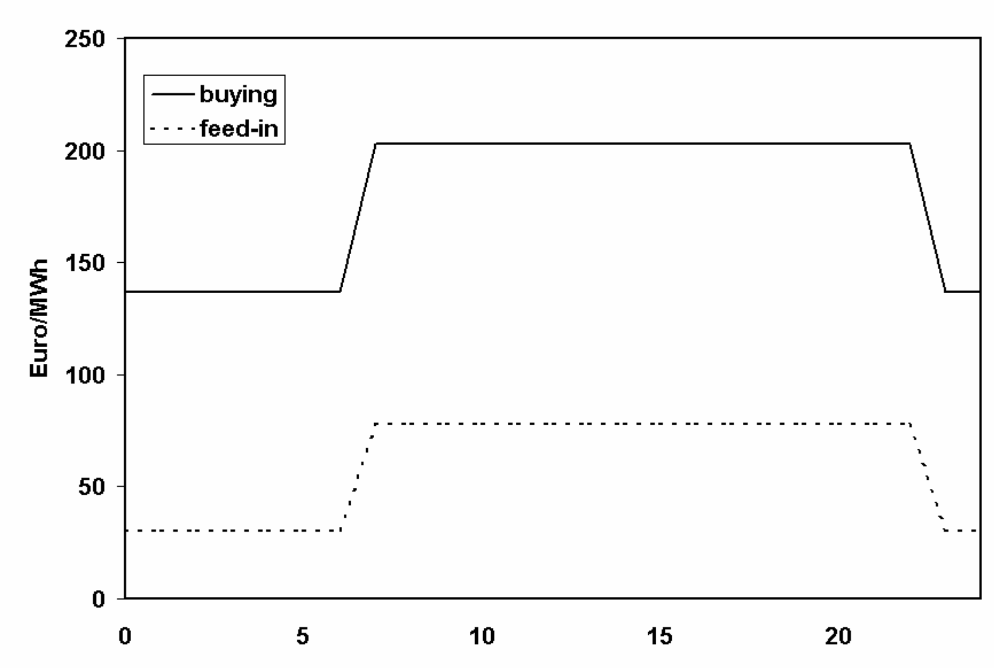

Figure 5: *Residential tariffs for buying and selling electricity in 2005 used to calculate benefits from avoiding feed in. The feed-in tariff is not an actual tariff, but is calculated from average APX prices during these periods of the day with an additional transport fee.*

The actual benefits when avoiding feed-in depends on both the load profile and the profile of the electricity generation. To obtain a first idea about the spread in benefits, a simulation was done with the same load profile as in section 1.3, and with three different generation options: a photovoltaic system and two types of cogeneration units. A 4.5 kWp solar PV system can generate almost 4000 kWh per year in the Netherlands. But compared to the household load profile, there will be a surplus during the day and in the summer and a shortage at night and in winter. Assuming a cycle efficiency of 70%, the simulation run showed annual revenues of €12.61.

With cogeneration units, electricity is generated at times when there is a heat demand for space heating or hot water. Two simulation runs were made. One with a small 1 kWe Stirling cogeneration unit, and another with a large, 15 kWe PEMFC fuel cell system (for the operation of a storage system, the type of cogeneration unit does not matter). The latter system is unrealistically large for a household with an annual consumption of 4000 kWh. It was deliberately oversized to calculate the maximum revenues from avoiding feed-in. With a similar simulation run as used in the previous section on 'load-shifting', and using the same 70% average cycle efficiency, annual revenues of the storage system with the 1 kWe cogeneration unit amounted to only €3.97 per kWh of storage capacity, while the annual revenues with the 15kWe unit were €26.46 per kWh of storage capacity [4].

These results show that the business case of 'avoiding feed-in' can be financially more attractive than the business case of 'load-shifting'. However, the revenues depend very much on the profiles of electricity generation and loads, the power of the electricity generator, the cycle efficiency of the battery system and the feed-in tariffs.

1.5 Comparison of different markets

1.5.1 Theoretical maximum

For the four business cases with electricity storage systems as described above, the results of the calculation of the theoretical maximum are summarised in table 2. Since the characteristics of an ideal storage system have been assumed, i.e. there are no storage losses, and there is perfect foresight regarding future electricity prices, annual revenues when using a real storage system will be substantially lower then the theoretical maximum values. Potentially, the benefits of arbitrage on the imbalance market appears to be about ten times higher than the revenues on the day-ahead market. This is mainly due to the much larger number of possible cycles per year, which is roughly an order of magnitude larger in case of the imbalance market. Table 2 also shows the effect of including a transport charge of €33.10/MWh for the two 'arbitrage cases' (for the other two cases it is included in the tariff). Inclusion of a transport charge results in a substantial drop in annual benefits. When the cases with load shifting and avoided feed-in are compared, avoided feed-in is potentially much more attractive than load shifting.

Table 2: Theoretical maximum revenues of an ideal storage system, with and without a transport charge.

	Excluding transport costs		Including transport costs	
	Cycles	Annual revenues	Cycles	Annual revenues
	[#/year]	[Euro/year/kWhCap]	[#/year]	[Euro/year/kWhCap]
Arbitrage on day-ahead market (2000-2004)	1113	43.64	263	27
Arbitrage on imbalance market (2002-2005)	7742	466.30	3433	297
Load shifting (peak, off-peak tariff)			365	24
Avoided feed-in (peak, off-peak tariff)			365	63

In the following two sections, the assumed ideal storage system is replaced with the characteristics of real storage systems. Firstly, characteristics are used that are representative for currently available technology with respect to prices and lifetime. Secondly, possible prices and technical characteristics are used that may be realised in the near future (approximately in 2010).

1.5.2 Current storage technology

Leaving the idealised case of an ideal storage system has two main consequences. First is that more electricity needs to enter the storage system than can be retrieved due to losses in the electronics and in the battery. For a storage system based on lead-acid batteries, a typical cycle efficiency is 70%. This means that 1.43 kWh has to be fed into the battery, to be able to recover 1 kWh.

Secondly, a battery has a limited lifetime in years and in the number of full (or nominal) cycles. Good quality deep-cycle lead-acid battery can have a lifetime of 1,000 cycles. With battery costs of €200 per kWh of capacity, in order to maximise lifetime benefits, battery use should be restricted to cycles that provide revenues that are higher than €0.20 per kWh. Since the revenues per cycle of the two cases with own consumption are always below €0.20 per kWh, they do not provide positive revenues over the lifetime. Therefore, only the two cases with arbitrage are compared in table 3. Both cases include transport costs of €33.1/MWh, use a cycle efficiency of 70% and assume perfect foresight. Furthermore, it is assumed that the batteries can be charged and discharged within a time period of 15 minutes.

Table 3: Average revenues of a current storage system on the Dutch imbalance market (2002-2005) and day-ahead market (2000-2004) assuming perfect foresight

	Cycles	Annual revenues	Revenue per cycle
	[#/year]	[Euro/year/kWhCap]	[Euro/cycle/kWhCap]
Arbitrage on day-ahead market (2000-2004)	34	11.18	0.33
Arbitrage on imbalance market (2002-2005)	373	135.11	0.36

1.5.3 Future storage technology

Lead acid batteries are only marginally suitable for grid connected storage systems, because of the short lifetime and resulting requirement of high minimum revenues per cycle. One of the new storage technologies, lithium ion, potentially has a much longer lifetime and higher efficiency than lead acid. Prices of lithium ion batteries are still decreasing. For the analysis we assume that future prices will reach a level of €200 per kWh, and lithium ion cycle life will reach a level of 5,000 cycles, with a cycle efficiency of 90%. With these storage system characteristics, average annual revenues for the two arbitrage cases are shown in table 4. Annual revenues on the imbalance market are found to be much higher than on the day-ahead market. This is mainly due to the larger number of suitable cycles per year.

Table 4: Average revenues of a future storage system on the Dutch imbalance market (2002-2005) and day-ahead market (2000-2004) assuming perfect foresight

	Cycles	Annual revenues	Revenue per cycle
	[#/year]	[Euro/year/kWhCap]	[Euro/cycle/kWhCap]
Arbitrage on day-ahead market (2000-2004)	196	29.70	0.15
Arbitrage on imbalance market (2002-2005)	1572	309.79	0.20

1.5.4 Conclusions

For each of the three storage systems analysed (ideal storage systems with no losses; current lead acid; future lithium ion), one business case turns out to be much more favourable than the other three. Arbitrage on the imbalance market provides at least five times more revenues per year and per kWh than the next best business case of using a storage system for avoiding feed-in of own generated electricity. The imbalance market turns out to be by far the most relevant market for small-scale distributed storage systems. Larger storage systems, such as pumped hydro, have costs per kWh that are much lower than the cost of batteries. For these larger systems other markets than the imbalance market can also be relevant. But the analysis in the previous sections shows that for small, distributed electricity storage systems, the imbalance market is the most relevant. Therefore this market is analysed in more detail in the following section.

2 IMBALANCE MARKET

2.1 Control strategies for storage systems

One of the possible control strategies of a storage system is the so-called 'active trade'. An active trader on a power exchange or imbalance market submits bids for buying or selling a certain amount of electricity for a certain price. A transaction only takes place when the price limit is met. Beforehand it is known that, whenever there is a transaction, costs per kWh are below a certain maximum or benefits will be higher than a certain minimum level. Whether a transaction takes place depends on market circumstances. With active trading, an operator of a storage system has guaranteed minimum revenues per storage cycle (charging followed by discharging). However, the number of storage cycles is not known beforehand. It can vary from year to year depending on market circumstances.

An alternative control strategy of a storage system is based on 'passive trading'. In this strategy the electricity of a storage system is lumped together in a portfolio with other sources and loads. A storage system can contribute in reducing the difference between planned or forecasted output and realised output in case there are variable sources or loads. The revenues come from a combination of decreasing imbalance costs and increasing imbalance income for the whole portfolio. Since in this case with passive trading, the electricity from the storage system is not traded directly, the operator has more freedom in deciding how to operate the system. Restrictions, such as a minimum bid size do not apply in this case. In the following two sections the revenues on the imbalance market are calculated for the two control strategies of 'active' and 'passive' trading.

2.2 Active contribution to the imbalance market

Assuming the characteristics of a future storage system with battery costs of 200€/kWh, battery lifetime of 5000 cycles, and a cycle efficiency of 90% results in marginal costs of the batteries of 40 €/MWh. Furthermore transport costs of €33.1/MWh have been included. For each year in the period 2002-2005, the optimum level of charging and discharging limits has been calculated that resulted in the highest annual revenues (minus depreciation of the battery calculated by multiplying the annual number of cycles with the marginal cost per cycle). The resulting charging and discharging limit prices, and the annual revenues are shown in table 5. The annual revenues in table 5 do not include depreciation of the battery. Annual revenues compared with the theoretical maximum are shown in figure 6.

Table 5: Optimal charging and discharging limits and maximum revenues with an active contribution on the Dutch imbalance market using future storage system characteristics

	Optimal limit prices per year (highest revenues minus battery depreciation of €40 per MWh)				*Fixed limit prices: charging 50 €/MWh, discharging 127€/MWh*	
Year	Limit price for charging €/MWh	Limit price for discharg-ing €/MWh	Cycles/ year	Revenues €/year per kWh capac-ity	Cycles/ year	Revenues €/year per kWh capacity
2002	41	118	574	113	533	109
2003	46	123	1404	303	1378	301
2004	43	120	1222	275	1188	272
2005 *)	75	152	624	152	701	156
Average			956	211	950	210

*) Up to October 19th 2005

Annual revenues and the number of beneficial cycles per year as shown in table 5 are not very sensitive to the level of the charging and discharging limits. When choosing fixed levels of 50€/MWh as charging limit and 127€/MWh as discharging limit for all the years 2002-2005, the annual revenues are all within 4% from the values with the optimal limit prices.

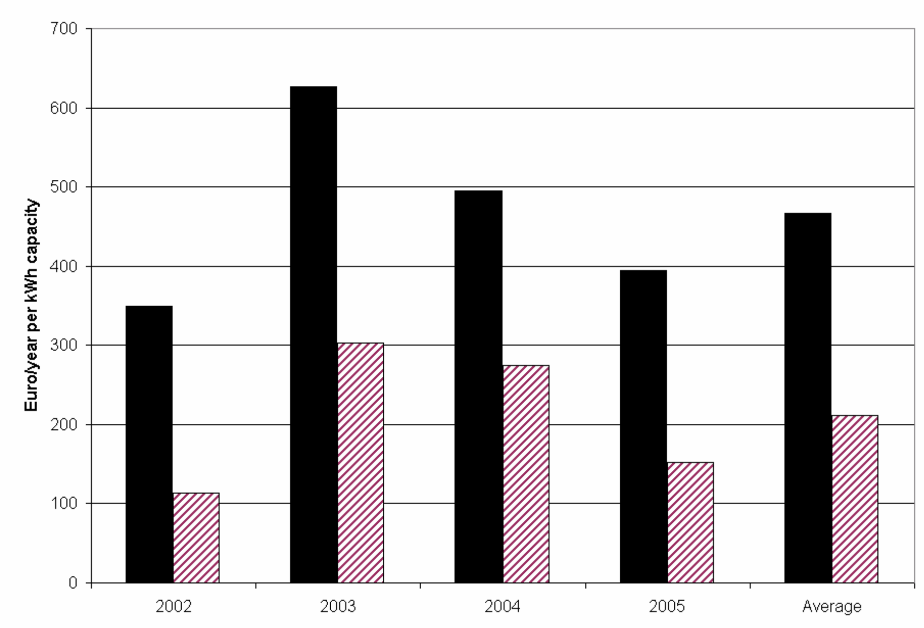

Figure 6: *Annual revenues with active contribution on the Dutch imbalance market with future lithium-ion storage technology (shaded) compared with theoretical maximum values (full).*

The average theoretical maximum revenues on the Dutch imbalance market over the period 2002-2005 was €466 per year per kWh of storage capacity. Assuming perfect foresight and the characteristics of a future Li-ion storage system (see table 1), the annual average revenues reduce to €310 per kWh. With the same storage system characteristics, and with active trade on the imbalance market, applying fixed limits of €50/MWh for charging and €127/MWh for discharging, average annual revenues become €210 per kWh of storage capacity. The €100 difference is a measure of the potential benefits from successfully forecasting imbalance prices, or more precisely, forecasting expected revenues for each cycle.

A sensitivity analysis has been conducted to evaluate how the revenues depend on the characteristics of the storage technology, especially the investment cost of the batteries. To be able to compare the different cases, the financial internal rate of return is calculated. This is the percentage with which the future costs and benefits have to be discounted to make discounted costs equal to discounted benefits. The higher the discount rate the more profitable the venture.

The analysis in the previous sections focused mainly on determining the revenues from an electricity storage system. To assess financial viability of storage activities, also the costs have to be taken into account. This has not been done to the same level of detail as the determination of the revenues. There are some promising developments with new technologies such as lithium ion, but there is still considerable uncertainty on the cost of small, distributed grid connected storage systems. A rough analysis has been conducted to obtain a first insight into the financial viability of electricity storage, using estimates of future costs.

A medium sized storage unit has been assumed with a capacity of 1 MWh that can be charged or discharged within 15 minutes, requiring a power rating of 4 MW. Batteries have to be replaced when they reach end of life after 1000 cycles in case of lead acid and 5000 cycles in case of lithium ion. In a sensitivity analysis, different battery prices in the range of €200 to €500 per kWh have been assumed. Investment costs in the electronics are estimated at €150 per kW, and for the housing and the grid connection €100,000 is assumed, resulting in a total investment cost (excluding batteries) of €700,000. Operation and maintenance costs are estimated to be €10,000 per year. With transport costs of €33.1/MWh the financial internal rate of return is shown in table 6 for different price levels of the Lithium ion batteries. From these figures it can be concluded that to make arbitrage on the imbalance market financially viable, lithium ion prices have to decrease to a level of €300 or lower.

Table 6: Financial viability (Internal Rate of Return) of an active contribution to the imbalance market for different storage technologies with fixed limit prices (€50/MWh for charging, €127/MWh for discharging)

	Internal Rate of Return [%]
Case: storage technology, cycle efficiency and battery costs	
Current storage technology: **Li-ion, 90%, 500 €/kWh**	-
Future storage technology: **Li-ion, 90%, 400 €/kWh**	5%
Future storage technology: **Li-ion, 90%, 300 €/kWh**	12%
Future storage technology: **Li-ion, 90%, 200 €/kWh**	19%

2.3 Passive contribution to the imbalance market

When a storage system is part of a large portfolio of electricity generating and consuming units, the storage system operator has more freedom compared with the situation of an active contribution. But due to lack of information on the imbalance price, the operator now needs a sort of forecasting algorithm for the imbalance prices to be able to decide on the optimal times to charge and discharge the storage system. The efficiency of the imbalance price forecasting algorithm is defined as the actual benefits divided by the maximum theoretical benefits given perfect foresight. For a number of forecasting efficiencies the internal rate of return of a storage system is presented in table 7, using the same cost figures as in the previous paragraph.

Table 7: Financial viability (Internal Rate of Return in %) of a passive contribution to the imbalance market for different storage technologies as a function of the efficiency of the forecasting algorithm for the imbalance price

Efficiency of forecasting algorithm ===>	**50%**	**70%**	**90%**	**100%**
Case: storage technology, cycle efficiency and battery costs				
Current storage technology: **Lead-acid, 70%, 200 €/kWh**	-	-	-	2%
Current storage technology: **Li-ion, 90%, 500 €/kWh**	-	-	11%	15%
Future storage technology: **Li-ion, 90%, 400 €/kWh**	-	6%	17%	21%
Future storage technology: **Li-ion, 90%, 300 €/kWh**	1%	13%	23%	28%
Future storage technology: **Li-ion, 90%, 200 €/kWh**	9%	20%	31%	37%

From this table 7 it can be concluded that application of lead acid technology (or other technologies with similar characteristics and costs) is not financially viable. At the current price level of approximately €500 per kWh, lithium ion is just financially viable if a forecasting efficiency of 90% can be achieved.

3 DISCUSSION

Liberalisation of the electricity sector has resulted in establishment of imbalance markets that has provided improved transparency regarding imbalance costs. Comparing the different possible markets providing revenues for operation of an electricity storage system, the analysis shows that the imbalance market provides by far the highest revenues. Active trading on the imbalance market in the Netherlands requires a minimum power of 5 MW. The calculated average benefits of active trade on the imbalance market amount to €210 per year per kWh of storage capacity constitute a maximum value because not all bids will be accepted. An alternative to active trading is to contribute to reducing the imbalance of a portfolio of sources of a so-called 'programme responsible party'. But since the imbalance prices are only published days later, one has to rely on a forecasting algorithm in deciding when to charge or discharge the storage system. With an efficient forecasting algorithm the benefits can be potentially higher than with active trade using fixed price limits. But there is more risk involved because of forecasting errors. In the short term the entrance barriers are likely to be lowest in case of passive trade through contribution to the portfolio of a programme responsible party. In both cases, bundling large numbers of storage systems into virtual power plants would be beneficial from an operational point of view.

4 CONCLUSIONS

The main findings from the previous sections can be summarised as follows:

- Arbitrage on the imbalance market is financially by far the most interesting market mechanism to generate revenues from an electricity storage system.
- Optimising the benefits from a storage system requires forecasting of either electricity loads and generation or electricity prices. The efficiency of the forecasting algorithms directly influences the annual benefits.
- Forecasting imbalance revenues for the upcoming cycle is inherently more difficult than forecasting revenues on a power exchange. This is due to the stochastic character of the imbalance market, compared to more regular, daily patterns on the day-ahead market.
- With the current stage of storage technology, passive arbitrage on the imbalance market is only financially viable when the efficiency of the imbalance price forecasts is better than 90%.
- When the cost of Lithium-ion batteries decreases from the current level of about €500 per kWh to €200 per kWh, electricity storage systems become financially viable in case the forecasting efficiency is better than about 50%. For technologies with similarly long cycle lifetimes and high energy efficiencies, similar conclusions are valid.

Electricity storage in small, distributed storage systems appear financially attractive provided lithium ion, or similar battery technology, show further price declines to a level significantly below €500 per kWh. When this cost reduction materialises, distributed storage can complement large-scale storage systems in maintaining system balance. All revenue figures that are mentioned here, refer to the current situation in the Netherlands. Different market structures in other countries are expected to lead to a different level of revenues.

5 ACKNOWLEDGEMENTS

Part of this work was funded by the Netherlands energy agency SenterNovem.

6 REFERENCES

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