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ANALYSIS IN THE FRAMEWORK OF THE INVESTIRE NETWORK

Economic performance of storage technologies

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Preface

This project has been performed in the framework of the project Investigation on Storage Technologies for Intermittent Renewable Energies (INVESTIRE), managed by the Renewable Energies Group of the Establishment of Cadarache (GENEC), located in France. This ECN contribution to the project is the deliverable of Work package 4 of the EU funded project (EU contract number ENK5-CT2000-20336). At ECN, this work is referred to under project number 77408. The main author of this report, Mr Luuk Beurskens, can be contacted by e-mail: ps@ecn.nl

Abstract

For evaluating energy storage technologies, economical parameters are of considerable importance. A qualitative assessment is given of storage technologies in general, contributing to success or failure of their use.

Based on data of nine storage technologies that are defined in the INVESTIRE Network, results of a quantitative cost analysis are presented, based on device-specific key parameters. The costs have been defined as additional costs, effected by the required investments and operation and maintenance expenditures, the efficiency of a device and its lifetime.

In order to compare the technologies properly, categories of typical use have been defined, ranging from stand-alone small applications (typical storage capacity of 0.1 kWh) to levelling of power production (approximately 1 MWh).

The outcome is presented in such a way that for each category of typical use, the best technological options are identified, based on a cost analysis. This has been done for both current state of the art technologies as for future technologies.

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1. INTRODUCTION

1.1 Assessment method

In work package 4 (WP4) of the INVESTIRE project, the objective is to evaluate for the nine storage technologies defined in the project the present costs of electricity storage, as well as the short-term development of these costs. Reference years are 2000, 2005 and 2010. This report presents the assessment of the economic performance of storage technologies. To this end, an analysis tool has been developed that, following the methodology presented in this report, calculates the cost of discharged electricity.

The evaluation is based on data delivered by partners in the INVESTIRE project, more specifically by the Storage Technology Work package Leaders (WPST), as delivered to and documented by WP3 (Jossen, Protogeropoulos 2003).

In the current report, no further consistency checks with other literature sources have been performed: data have been taken as such. As technology stakeholders have collected the data, it should be noticed that values possibly are biased, and that consistency between the technology data tables is not always 100%.

The main deliverable of WP4 is an economic assessment of the documented technologies, resulting in an overview of the additional costs of a kWh electricity output from a storage device, based on a number of parameters. These are:

- Cost of device and system integration costs,
- O&M costs,
- Lifetime of device,
- Number of equivalent cycles per day,
- Storage efficiency.

The current report elaborates on the calculation method and on the outcome of the analysis using that method. Below, the storage technologies (ST) that have been assessed are listed:
ST1: Lead acid batteries
ST2: Lithium batteries
ST3: Supercapacitors
ST4: Nickel batteries
ST5: Electrolyser, Hydrogen storage and fuel cells
ST6: Flywheels
ST7: Redox flow batteries
ST8: Pneumatic storage
ST9: Metal air batteries

Using a well-defined categorisation, technologies become comparable: the energy that needs to be stored is defined[1] as well as the power of the device. The categories are explained in Chapter 3. Based on the results from WP3, the total costs of a device is known by using the price parameter, and the lifetime by using either float life or the maximum number of equivalent cycles. Assuming system integration costs zero, and applying a conversion factor for expressing the qualitative operation and maintenance costs to quantitative numbers, an annual cost can be calculated. To this end, discounting at a rate of 10% has been applied. This number has been defined on mutual agreement in the INVESTIRE project.

[1] By defining an average power during an average time of autonomy.

1.2 Limitations of the method

The methodology presented in the current report only takes into account the *additional* costs of storing and releasing electricity in a device. This implicitly assumes the purchase price of the electricity to be equal to zero. This is only a part of the story, however, as illustrated by the example in the next paragraph.

In an imaginary case, a storage device fed by an unidentified electricity source is analysed. Assuming a positive purchase price of electricity, when a certain amount of electricity is to be stored its actual costs will increase according to two mechanisms. Firstly, the storage device will have a certain amount of energy losses, which makes that the total purchase amount will be borne by a smaller amount of energy output: the selling price will be higher per unit of electricity output. A second mechanism influencing the minimum selling price is because of the additional expenses for the storage device: this causes additional costs per unit of released electricity. Thus, the total costs of the discharged electricity increase due to both energy losses and additional costs of released electricity. This process is illustrated in Figure 1.1.

1.3 Outline

To begin, in Chapter 2 a qualitative overview of typical issues for electricity storage is given. Chapter 3 elaborates on the categories of typical use as defined in the project. Using the efficiency and the number of cycles for each category, the annual amount of stored energy can be calculated. Knowing the annual costs, the cost of the discharged electricity, based on the respective category can be calculated. The methodology for the calculation scheme is explained in Chapter 4. The outcome of the analysis is presented in Chapter 5. Finally, Chapter 6 summarises the conclusions.

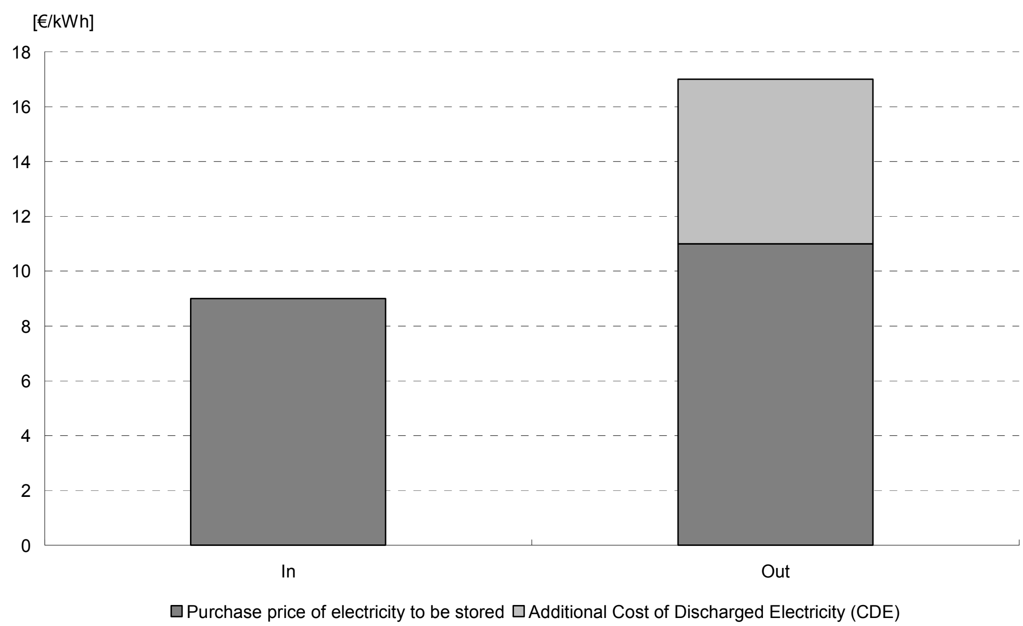

Figure 1.1 *Schematic picture illustrating that energy losses during the storage process and additional expenses for storing electricity make that the total costs of the discharged electricity are always higher than only the purchase price of electricity input*

2. STORAGE OF ELECTRIC ENERGY

2.1 Introduction

Intermittent sources of renewable electricity generation such as photovoltaic or wind power do not have a controllable output contrary to, for example, gas fired power plants. Storage of electricity could increase the market value of these intermittent sources by improving the controllability of the output.

The marginal cost (*MC*) function of the storage activity could be defined as:

$$MC = PP + EL + OC$$

Where the *MC* of storage devices depend on the purchase price (*PP*) of electricity, the electricity losses (*EL*) caused by operating the device and the operational costs (*OC*) raised. It should be stressed that the selling of electricity during high price periods is only one of the services, managers of storage devices can get involved with. The technology has potential to provide many other services, among others ancillary services and power quality increase.

This section qualitatively describes the economics behind the electricity storage activity. It first analyses the possible values power storage can generate in both on-grid and off-grid electricity systems. Then, as a way to illustrate the importance of the regulatory framework and market design implemented on the economics of electricity storage, the market opportunities of this technology in the Dutch electricity market are outlined.

No integral analysis is done due to the complexity of the issue. Particularly, opportunities for storage highly depend on the available types of storage devices. Besides that, there are significant differences per country, such as the available sources of renewable electricity generation, the consumer types (such as industry, service sector, etc), the diversity in conventional production facilities (nuclear, coal, gas) and finally the national electricity market regulations and design. Due to these topics an analysis of the market opportunities across Europe is very complex and beyond the scope of this project.

2.2 Values of electricity storage

Electricity storage systems can provide services that generate additional value in different ways. An obvious value is the inter-temporal arbitrage - also considered as peak shaving - where the storage device buys power during low price periods (off-peak) and sells it during high price periods (peak). In case the marginal costs of production are lower than the price differential between the two periods then it is profitable to use the storage facilities.

Nonetheless energy storage systems can provide other services to the electricity system. It should be stressed that under the current Dutch regulation many of these services are not correctly valued - this is described in the next section. Table 2.1 outlines other additional values storage facilities can generate in a system, discriminating between on-grid and off-grid systems.

It is important to note that all this values do not have to be positive. In many cases it is case specific. Furthermore, it is crucial to differentiate between short-term and long-term benefits. For example, although currently marginal, due to the expected increase in the share of wind energy in the EU, power quality management for wind farms can become an important market niche for storage facilities.

Table 2.1 *Added value of electricity storage in the case of on-grid and off-grid usage*

	On-grid	Off-grid
Inter-temporal arbitrage	×	
Balancing of the system	×	
Grid losses avoidance	×	
Grid investment avoidance	×	
Reserve capacity–emergency supply	×	×
Voltage/frequency support	×	
Black start	×	×
Seasonal/day-night renewable (DG) energy storage	×	×
Uninterruptible power supply (UPS)	×	×
Power quality management	×	

2.3 Market opportunities

As described, the profitability of energy storage systems depends not only on the costs of the device but also on the market opportunities, i.e. the income that the systems can generate. Storage facilities can provide a number of services, from which they should be rewarded when provided efficiently. The regulation and market design of the electricity system, as a result, has a strong impact on the economics of storage equipment. One illustrative example is given in the paragraph below, regarding avoidance of grid investments. Other mechanisms providing additional value as indicated in Table 2.1 can also yield an important market opportunity, such as emergency supply. In the latter case the avoided costs in case of a grid outage can be extremely important, thus justifying the use of storage technologies.

Under the current Dutch electricity grid regulation no location signals are provided. In other words, no price or payment incentives are given to producers who locate their generation capacity in places where it is most convenient to the distribution company or network operator. For instance, when a distribution firm has to upgrade the grid because of congestion, it always has the option to increase supply and thus by-pass the congestion in order to meet peak demand. Assuming that the implementation of a storage device reducing peak demand and thus avoiding grid upgrading costs is the most efficient of the options, the current regulatory system does not provide the instruments for stimulating such projects.

2.4 Conclusions

This section qualitatively describes the economics of electricity storage systems. Main conclusions are:

- Electricity storage systems can profit not only from the selling of electricity during high price periods but also have potential to provide many other services, among others ancillary services and increase in quality.
- Regulation and the market design have to provide the correct framework in order to value all services storage facilities can efficiently provide.

3. CATEGORIES

In the INVESTIRE Work package 2 (WP2) report (Sauer 2002) a categorisation of storage technologies has been proposed. The categorisation consists of several parameters, varying as a function of the category of typical use. These different uses have been displayed in Table 3.1.

Table 3.1 *Categories as defined in WP2*

Category 1	Small application
Category 2	Village power supply (Solar home system and hybrid system)
Category 3	Levelling of power production
Category 4	Power quality

Using a well-defined categorisation, technologies become comparable: all demand parameters within a category remaining equal, the specific cost of a device and the typical operational expenses will result in costs of discharged electricity only depending on the device, and not on the application.

Two parameters of importance for the categorisation are the *typical number of equivalent full cycles* and the *typical depth of discharge (DOD) per cycle*. The number of equivalent full cycles incorporates the typical DOD per cycle and the number of cycles per day, yielding a figure representing one year of operation. This number is used for calculating the annual amount of discharged electricity.

Category 1: Batteries with 480 hours (20 days) of autonomy, and a size of 0.1 kWh. Typical number of equivalent full cycles is almost 20 per year, the DOD per cycle is 5%. All systems are PV powered and a high power supply guarantee is required by the applications (for example sensors, telecommunication and data loggers).

Category 2: Batteries with 20 to 100 hours (1 to 4 days) of autonomy, ranging in size from 1 kWh for solar home systems (SHS) to 480 kWh for a hybrid system for a village power supply. These two sub-categories have a typical number of equivalent full cycles of around 75 and can be identified at a DOD per cycle of 20%.

Category 3: Batteries with 2 hours of autonomy and a size of 1000 kWh. The number of full cycles per year amounts to 1000 per year at DOD of 50% per cycle. The applications are mainly load levelling application to level out power generation with high fluctuation (wind, PV) and load. Proper matching between power supply from generator with intermittent power production (wind, PV) and battery systems can avoid problems with power quality in weak grids and it gives better opportunities for energy trading[2].

Category 4: Batteries with 30 seconds of autonomy for power applications of approximately 42 kWh. The typical number of equivalent full cycles is assumed 10000 per year at DOD per cycle of 80%. This category is used for power quality units in grids.
An overview of all assumptions is presented in Table 3.2.

[2] A more predictable power output makes that the operator can claim better terms for his power supply.

Table 3.2 *Definitions of technical parameters for storage categories*

Category number		1	2a	2b	3	4
Application		Small application	Solar home systems (SHS)	Hybrid system village power supply	Levelling of power production	Power quality
Average power	[kW]	$0.2 \cdot 10^{-3}$	0.01	20	500	5000
Autonomy	[h]	480	100	24	2	0.0083
Number of equivalent full cycles per year	[cycle/year]	18.25	73	80	1,000	10,000
DOD/cycle	[%]	5	20	20	50	80
Restituted energy	[kWh/cycle]	0.1	1	480	1,000	41.5
Annually discharged	[kWh/year]	1.8	73	38,400	1,000,000	415,000

Based on the typical amounts of restituted electricity per cycle, a storage system can be designed using the device-specific parameters, to yield thus the cost of the discharged electricity. This will be done in the following chapters.

Multiplying the amount of hours of autonomy with the number of equivalent full cycles per year yields an indication of the degree of capacity utilisation of a category. The more this indicator approaches the total amount of hours in a year (namely 8760), the more continuously it is used. Evaluating this indicator for the categories yields the picture as indicated in Table 3.3.

Table 3.3 *Degree of capacity utilisation*

Category number	1	2a	2b	3	4
Capacity utilisation (hrs)	8760	7300	1920	2000	83
Degree of capacity utilisation	100%	83%	22%	23%	1%

It can be stated that the *time period* in which income is generated is shorter for the categories of higher numbers. There are two options to manipulate the income when fixing the amount of hours:

1. Storing large amounts of electricity in a limited timeframe.
2. Making sure that the added value of the stored electricity is very high: when prices per kWh are high, the income, although generated in a short period, can be quite of importance.

The smaller the degree of capacity utilisation, the higher the amount of income per kWh-discharged electricity should be per period of autonomy. This concept can be borne in mind when evaluating the costs of discharged electricity in Chapter 5. However, no position will be taken regarding absolute amounts of income required for profitable operation. This is outside the scope of the current analysis.

4. METHODOLOGY

4.1 Assessment method

Being aware of the restrictions when only using an economical evaluation tool, the additional cost of the discharged electricity (CDE) still is an important parameter for defining the success of a technology. To this end, the following approach is used:

1. Determine the energy to be stored during one cycle of autonomy.
2. Determine the annual amount of energy stored.
3. Determine the annual costs.
4. Determine the additional costs of the discharged electricity.

These steps will be illustrated consecutively below.

Step 1: Calculation of stored energy E_{sto} [kWh]
In this step, the efficiency and the self-discharge of the storage device is considered. By this is meant that the energy required for a discharged amount of energy E_{dis} has been fixed for a certain category according to Table 3.3, and that the actual energy that needs to be fed into the device is larger than E_{dis} itself. Having the storage efficiency η_{tot} and the self-discharge *SD* available form WP3, the total efficiency is:

$$\eta_{tot} = (\eta_{sto} \times (1 - SD))$$

Making the value of E_{sto} to be calculated as follows:

$$E_{sto} = E_{dis} / \eta_{tot}$$

Note, that the above expression is rather an over-estimate, due to the share of self-discharge which is possibly too large. This is because the relative importance of *SD* diminishes as the state of charge varies over time.

Step 2: Determine the annual amount of energy stored E_{ann}
Per year, the amount of energy stored is obtained by multiplying E_{sto} with the number of equivalent full cycles (*EFC*) per year, obtained from WP2

$$E_{ann} = E_{sto} \times EFC$$

Step 3: Determine the investment and O&M costs

The investment costs of the storage device can be expressed in two ways:

1. Using specific costs in €/kWh (per kWh storage size)
2. Using specific costs in €/kW (per unit of output power)

In order to determine the device cost based on specific cost, it is required to know the leading parameter for each category, i.e. whether the design is to be based on energy content (kWh) or power (kW). In case both types of specific costs were available, the most expensive design has been chosen. The choices for each technology are given in Section 5.1.

From the input data, the storage device specific 'price' *P* (for each storage technology defined as a yield per €, expressed in both capacity units (W/€) and energy units (Wh/€) [3]) is available,

[3] The price is expressed at 'E_{100}', indicating the amount of energy available at a constant discharge in 100 hours.

gathered from the WP3 questionnaire. This price is supposed to be a customer price (excluding taxes and customs).

In case the price parameter for energy storage is leading, the total investment costs of the storage device I_{device} [€] are determined using price P [kWh/€] and E_{sto} [kWh]:

$$I_{device} = E_{sto} / P$$

In case the price for the power of the storage device is leading, the total investment costs of the storage device I_{device} [€] are determined using price P [kW/€] and the capacity that has been defined for the catagory at stake C_{cat} [kW], also considering the same efficiency η_{tot}. The efficiency accounted for here is supposed to correct for losses due to power modes that are not optimal for a device and overdimensioning of the system: in the categories average powers have been defined, indicating that occasionally, both lower and higher powers are possible. This yields the following expression for determining the device cost for these cases:

$$I_{device} = (C_{cat} / \eta_{tot}) / P$$

For the operation and maintenance costs a conversion is required, as the data table only defines a qualitative scaling (from 1 to 5 for 'very high' to 'very low'). For the economic evaluation a translation step needs to be made. A proposal is indicated in Table 4.1, in which each qualitative label is defined as a certain percentage of the investment costs I_{device}.

$$O\&M = S_{O\&M} \times I_{device}$$

Table 4.1 *Translating qualitative maintenance to quantitative O&M by assumptions*

	Qualitative label	Annual share $S_{O\&M}$ of investment costs
Maintenance = 1	very high	10%
Maintenance = 2	high	8%
Maintenance = 3	fair	6%
Maintenance = 4	low	4%
Maintenance = 5	very low	2%

Step 4: Determine the annual costs
In order to know the annual costs, it is required to know the lifetime of a device. This parameter can be obtained in two ways: firstly, directly from the WP3 inventory, in which the expected float life[4] FL at 20°C has been specified. It can be argued whether the float life is the correct parameter for estimating the expected lifetime in an application. In the parameter tables supplied by WP3, no other information about lifetime has been provided.

Secondly, the inventory specifies the cycle life at 20°C in equivalent cycles, based on 10% DOD. Combined with a category typical number of equivalent full cycles (*NEC*) per year, this yields a calculated lifetime. Of these two parameters, the minimum amount of years is taken as the lifetime L of a device:

$$L = \min(FL , (CL / NEC))$$

In order to calculate the annual costs, the annuity factor $a = function(L, r)$ with r the interest rate is used[5]:

[4] The float life is defined under conditions as appropriate for the specific technology, but at least at a state of charge (SOC) > 90%.
[5] The annuity factor a is defined as $(r\times(1+r)^L) / ((1+r)^L-1)$, in which the interest rate r=10%.

$$AC = a \times (I_{device} + IC) + O\&M$$

The investment costs I_{device} and O&M are known from step 2. The device integration costs IC are initially assumed to be zero, as the parameter tables do not specify this parameter:

$$IC = 0$$

Step 5: Defining the costs of discharged electricity
Finally, the cost of the discharged electricity *CDE* can be calculated by dividing the annual costs *AC* by the annually discharged electricity E_{dis}:

$$CDE = AC/ E_{dis} \text{ [€/kWh]}$$

4.2 Indicators of performance

The above calculated cost of the discharged electricity *CDE* is of importance for the evaluation of the storage technology, but is does not take into account the purchase price of the electricity that is fed into the device, as already mentioned in Section 1.2. In order to complete the picture, it is also important to know the losses of the device. The losses E_{loss} can be determined for the efficiency:

$$E_{loss} = E_{dis} / (1- \eta_{tot})$$

Assuming that the cost of the electricity fed into the device is not equal to zero and is positive, the higher the losses of electricity are, the higher also the financial losses.

For the evaluation of the results, the two parameters *CDE* and $(1-\eta_{tot})$ are presented to assess the storage technologies.

5. RESULTS OF THE ECONOMIC ASSESSMENT

5.1 Input

As input for the technologies, the WP3 dataset is used. As technology stakeholders have collected the data, it should be noticed that the data possibly are biased, and that the technology data tables are possibly not always fully consistent. The following tables present the input data for the further assessment. In Table 5.6 the data provenance per technology has been indicated.

Category 1
For category 1 (small applications), the following technologies are applicable: Lead-acid batteries, Li-Ion batteries, Supercaps[6], NiCd batteries and Zinc/air batteries. The parameters have been displayed in Table 5.1. For all technologies, the price of the storage device has been based on energy (Wh/€).

Category 2a
For category 2a (solar home system, SHS), the following storage technologies apply: Lead-acid batteries, Li-Ion batteries, Supercaps, NiCd batteries, Electrolyser and hydrogen storage, Compressed air and Zinc/air batteries. The parameters have been displayed in Table 5.2. For all technologies, the price of the storage device has been based on energy (Wh/€).

Category 2b
For category 2b (hybrid system for village) the following technologies have been considered: Lead-acid batteries, Li-Ion batteries, Supercaps, NiCd batteries, Electrolyser and hydrogen storage, Compressed air and Zinc/air batteries. The parameters have been displayed in Table 5.2. For all technologies, the price of the storage device has been based on energy (Wh/€). As the same base input parameters have been taken as for category 2a, possible changes in the outcome have only been effected by differences resulting from the categorisation.

Category 3
For category 3 (levelling of power production), Lead-acid batteries, Li-Ion batteries, Supercaps, NiCd batteries, Flywheel, Vanadium redox battery, Compressed air and Zinc/air batteries. The parameters have been displayed in Table 5.4. For the first five technologies in Table 5.4 the determination of the investment cost of the storage device has been based on energy (Wh/€), while for latter technologies this has been based on power (W/€).

Category 4
For category 4 (power quality), Lead-acid batteries, Li-Ion batteries, Supercaps, NiCd batteries, Flywheel, Vanadium redox battery and Zinc/air batteries. The parameters have been displayed in Table 5.5. For most of the storage technologies the price of the device has been based on power (W/€); only for supercaps and vanadium redox battery the energy content was leading.

[6] Note, that the important self-discharge for this technology makes that it is not very suited for this category. In order to design a working system, the self-discharge is assumed to be less than it will be in reality, according the parameter tables.

Table 5.1 *Input parameters assumed for category 1*

			Lead-acid	Li-Ion	Supercaps	NiCd	Zinc/air
Efficiency	[η_{sto}]	-	0.80-0.90	0.98-1.00	0.84-0.99	0.60	0.50-0.60
Self discharge	[SD]	per period	0.02-0.03	0.01-0.02	0.40-0.75	0.13-0.20	0.01
Price	[P]	Wh/€ [E_{100}]	10 - 20	0.70-1.00	0.01-0.02	0.60-3.30	10
O&M		1…5	3-4	5	5	3-4	3
Lifetime	[L]	year	5-15	5-15	10	15-20	0
Lifetime*	[L]	year	55-164	2740-4384	5479-27,397	66-88	2-3

* Based on the number of equivalent cycles as applies to category 1.

Table 5.2 *Input parameters assumed for category 2a*

			Lead-acid	Li-Ion	Supercaps	NiCd	Electrolyser, H_2, PEMFC	Compressed air	Zinc/air
Efficiency	[η_{sto}]	-	0.80-0.90	0.97-0.99	0.84-0.99	0.60	0.25-0.45	0.55-0.72	0.50-0.60
Self discharge	[SD]	per period	0.00-0.01	0.00	0.08-0.42	0.03-0.04	0.02-0.08	0.35	0.00
Price	[P]	Wh/€ [E_{100}]	10-20	0.70-1.00	0.01-0.02	0.60-3.30	0.05-0.10	0.58-9.86	10
O&M		1…5	3-4	5	5	3-4	3-4	3.4	3
Lifetime	[L]	year	5-15	5-15	10	15-20	2	20	0
Lifetime*	[L]	year	14-41	685-1096	1370-6849	16-22	1-2	0	0-1

* Based on the number of equivalent cycles as applies to category 2a.

Table 5.3 *Input parameters assumed for category 2b*

			Lead-acid	Li-Ion	Supercaps	NiCd	Electrolyser, H_2, PEMFC	Compressed air	Zinc/air
Efficiency	[η_{sto}]	-	0.80-0.90	0.97-0.99	0.84-0.99	0.60	0.25-0.45	0.55-0.72	0.50-0.60
Self discharge	[SD]	per period	0.00	0.00	0.02-0.10	0.01	0.01-0.02	0.08	0.00
Price	[P]	Wh/€ [E_{100}]	10-20	0.70-1.00	0.01-0.02	0.60-3.30	0.05-0.10	0.58-9.86	10
O&M		1…5	3-4	5	5	3-4	3-4	3-4	3
Lifetime	[L]	year	5-15	5-15	10	15-20	2	20	0
Lifetime*	[L]	year	13-38	625-1000	1250-6250	15-20	1-2	0	0-1

* Based on the number of equivalent cycles as applies to category 2b.

Table 5.4 *Input parameters assumed for category 3*

			Lead-acid	Li-Ion	Supercaps	NiCd	Flywheel	Vanadium Redox	Compressed air	Zinc/air
Efficiency	[η_{sto}]	-	0.80-0.90	0.95-0.98	0.84-0.99	0.60	0.80-0.92	0.70-0.80	0.55-0.72	0.50-0.60
Self discharge	[SD]	per period	0.00	0.00	0.00-0.01	0.00	0.04	0.00	0.01	0.00
Price	[P]	Wh/€ [E_{100}]	5.0-8.0	0.50-0.80	0.01-0.02	0.60-3.30	0.10-0.50			
Price	[P]	W/€ [E_{100}]						0.34-0.91	4.59	5.00
O&M	[L]	1…5	3-4	5	5	3-4	5	4	3-4	3
Lifetime	[L]	year	8-10	5-15	10	15-20	20	5-15	20	0
Lifetime*		year	1	50-80	100-500	1-2	50-100	12	0	0

* Based on the number of equivalent cycles as applies to category 3.

Table 5.5 *Input parameters assumed for category 4*

			Lead-acid	Li-Ion	Supercaps	NiCd	Flywheel	Vanadium Redox	Zinc/air
Efficiency	[η_{sto}]	-	0.85-0.90	0.95-0.98	0.84-0.99	0.60	0.80-0.92	0.55-0.72	0.50-0.60
Self discharge	[SD]	per period	0.00	0.00	0.00-0.01	0.00	0.04	0.01	0.00
Price	[P]	Wh/€ [E_{100}]	5.0-8.0	0.50-0.80	0.01-0.02	0.60-3.30	0.10-0.50	4.59	5.00
O&M	[P]	1…5	3-4	5	5	3-4	5	3-4	3
Lifetime	[L]	year	8-10	5-15	10	15-20	20	20	0
Lifetime*	[L]	year	1	50-80	100-500	1-2	50-100	0	0

* Based on the number of equivalent cycles as applies to category 4.

Table 5.6 *Overview of INVESTIRE partners responsible for input data*

Storage technology	Data delivered by	Contact person
ST1: Lead acid batteries	Tudor-Exide	Ms María Luisa Soria soriaml@tudor.es
ST2: Lithium batteries	ZSW	Dr Andreas Jossen andreas.jossen@zsw-bw.de
ST3: Supercapacitors	ISET	Mr Bernd Willer bwiller@iset.uni-kassel.de
ST4: Nickel batteries	Catella Generics	Magnus Dahlen magnus.dahlen@genericsgroup.com
ST5: Electrolyser, Hydrogen storage and fuel cells	CEA-GENEC	Ms Marion Perrin Marion.perrin@cea.fr
ST6: Flywheels	CCLRC Rutherford Appleton Laboratory	Dr. Alan Ruddell alan.ruddell@rl.ac.uk
ST7: Redox flow batteries	SORAPEC (data from Sumitomo Electric)	Ms Noëlle Tassin, SORAPEC
ST8: Pneumatic storage	Alternativas CMR	Mr Iván Cyphelly, cyphelly@ran.es
ST9: Metal air batteries	ZOXY Energy Systems AG	Mr Guenter Semrau semrau@zoxy.net

5.2 Results

The steps explained in Section 4 will be performed, and the results will be presented in this part of the report. The results will be presented per category, for the state of the art technology. Also for future technologies an economical assessment has been performed. The outcomes of these exercises are displayed in appendices.

In the tables presenting the results, care has been taken to indicate, to the extent possible, the ranges within which the parameters can vary[7]. For the graphical presentation, however, all ranges have been condensed to a single value, using large bullets in order not to suggest accuracy. This has been done in order to make the graphs easier to interpret. Still a lot of information is neglected in doing so. That is why the reader is referred to the tables including the ranges, rather than focusing mainly on the pictures.

5.2.1 Results for category 1: small application

Storage technologies in this category have been designed to deliver an average power of 0.2 W during an autonomy period of 480 hours (20 days). The total storage capacity is 0.1 kWh, annually equalling a value for E_{dis} of 1.8 kWh. Typical applications (for example sensors, telecommunication and data loggers) are often remotely installed, with no grid connection available. The cost of the storage device in most cases is no bottleneck for the realisation of such installations. Because of the small storage sizes, the resulting additional costs of discharged electricity are rather high. Although supercaps were mentioned as suitable for this category, the price of seems to indicate the contrary.

[7] The ranges for *CDE* follow from the ranges in input parameters, as defined by the INVESTIRE partners. For some technologies, no ranges have been defined.

As the energy supply off-grid is mainly from renewable energy options, notably photovoltaics, the minimisation of losses (η_{tot}) is an important design parameter, whereas, for applications in industrialised countries possibly the additional costs of discharged electricity have less importance: lifetime could be, next to losses, more important. Therefore, Zinc/air and NiCd batteries are less advantageous, although the level of additional costs may be acceptable. The Li-Ion battery is rather expensive, but due to lower losses and higher lifetime could be more attractive that the cheapest option, the lead-acid battery.

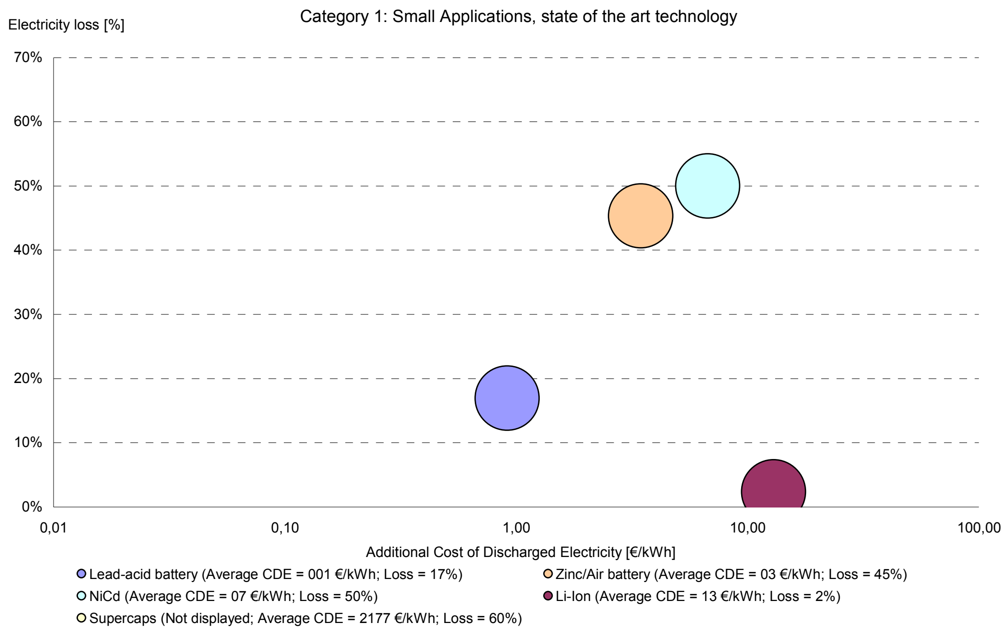

Figure 5.1 *Graphical presentation of the results for storage technologies in category 1 applications (year 2000). Note, that the values for the additional cost of discharged electricity (CDE) have been averaged. For a more accurate overview, refer to Table 5.7*

5.2.2 Results for category 2a: solar home system

For this category of village power supply, solar home systems (SHS), a storage technology for 100 hours (4 days) of autonomy with a capacity of 1 kWh is required, with a number of full cycles per year of 73, totalling to a value for E_{dis} of 73 kWh per year. In this category, electricity losses are extremely undesired, for the purchase price of electricity from photovoltaic is very high, and the income for the target group of SHS is expected to be rather low. Lead-acid batteries are the cheapest option, whereas the losses are much less for the Li-ion battery.

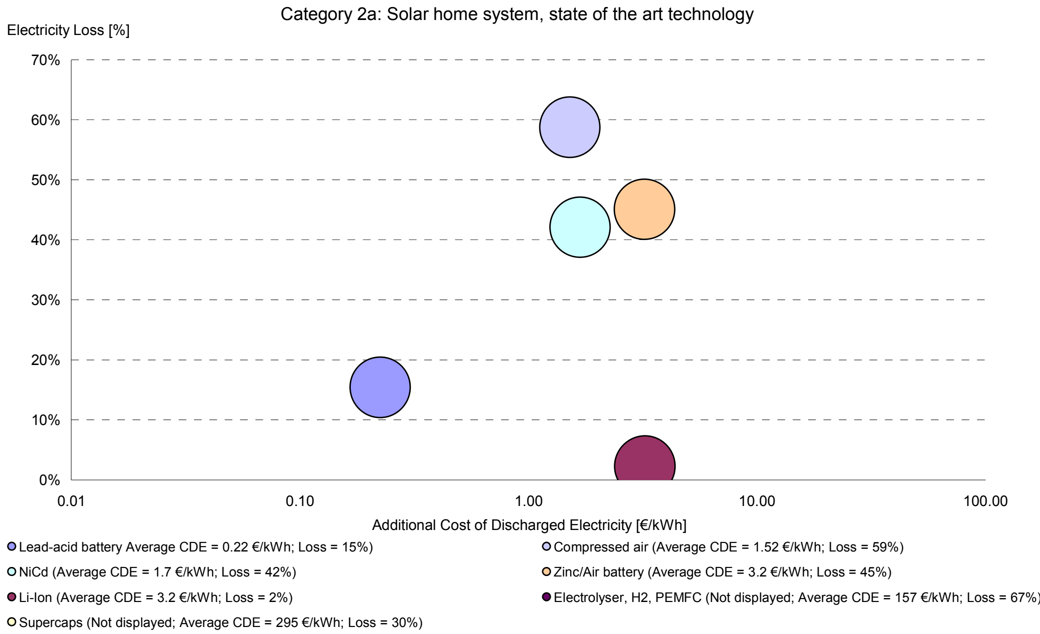

Figure 5.2 *Graphical presentation of the results for storage technologies in category 2a applications (year 2000) (note, that the electrolyser and the supercaps are not indicated in the graph)*

5.2.3 Results for category 2b: hybrid system for village power supply

For this category of village power supply, hybrid power systems, a storage technology for 24 hours (1 day) of autonomy and a capacity of 480 kWh is required. The number of full cycles per year amounts to 80, totalling to a value for E_{dis} of 38400 kWh per year. As the input parameters differ not very much from category 2a, resulting prices are roughly the same. However, as electricity input is not only from PV power, higher losses could be acceptable; lead-acid remains the best option for this category, from an economic point of view.

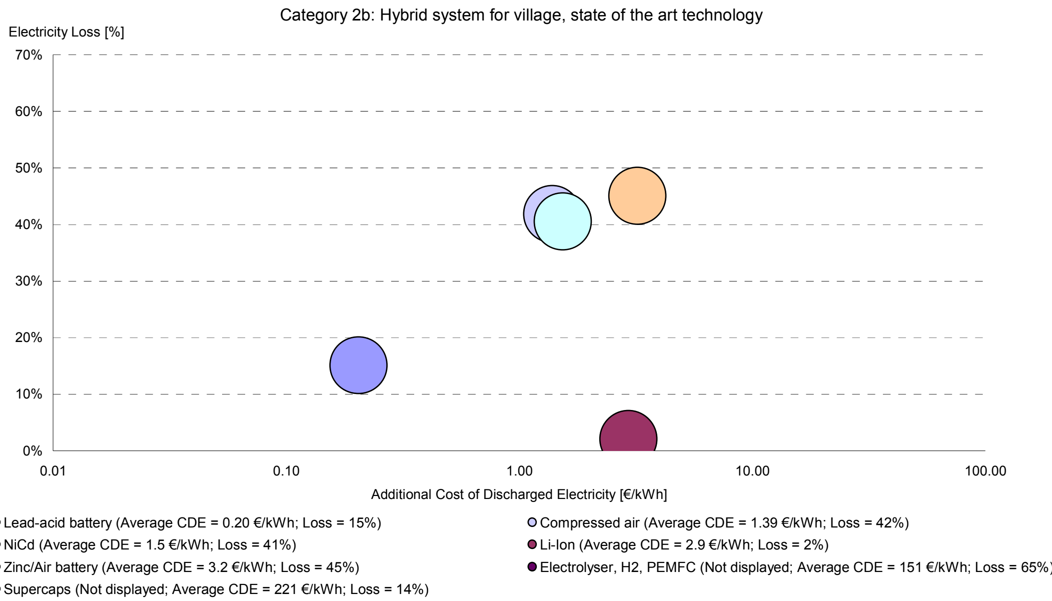

Figure 5.3 *Graphical presentation of the results for storage technologies in category 2b applications (year 2000) (note, that the electrolyser and the supercaps are not indicated in the graph)*

5.2.4 Results for category 3: Levelling of power production

To characterise a typical power levelling application, a storage system with 2 hours of autonomy and a size of 1000 kWh has been defined. The number of full cycles per year amounts to 1000, resulting a value for E_{dis} of 1 GWh per year. In order to assess what price level may be acceptable for this category, more information is required on the regulatory framework: the penalty for not delivering power as predicted will help to estimate what additional costs of discharged electricity combined with a certain loss of electricity may be acceptable. The aim is that the use of a storage device increases the overall value of the operation of an intermittent power source. In a first estimate, it could be concluded that all storage technologies with a higher additional cost level of 0.1 €/kWh will not meet this requirement, leaving only the compressed air as an option. Still, the electricity losses of this device are very important. An integral assessment, including the regulatory framework and electricity prices is required.

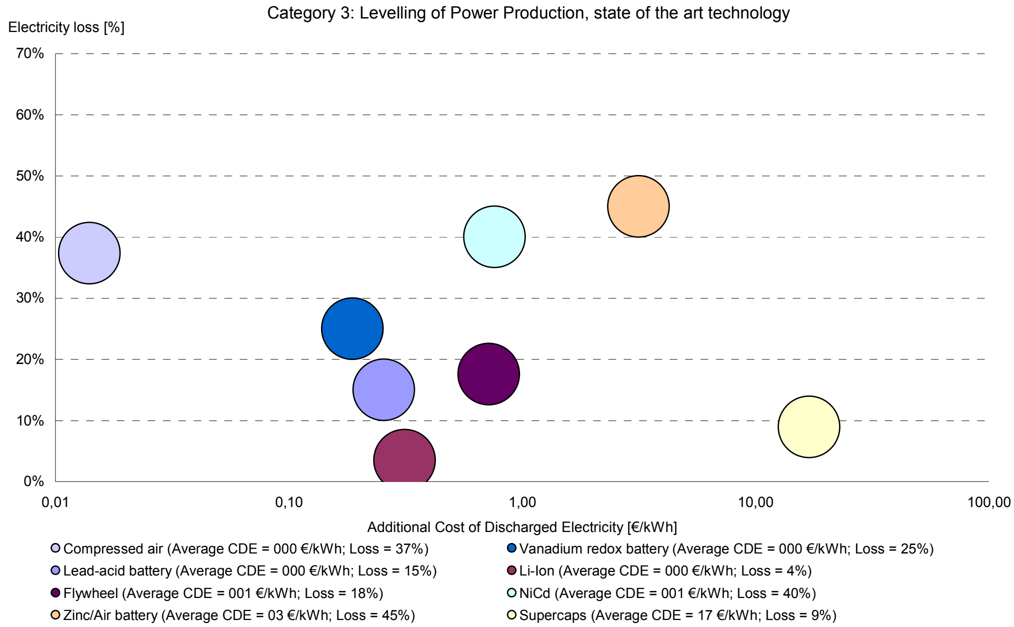

Figure 5.4 *Graphical presentation of the results for storage technologies in category 3 applications (year 2000)*

5.2.5 Results for category 4: Power Quality

For power quality devices an average of 5 MW is assumed, with a period of autonomy of 30 seconds and a storage capacity of 41.5 kWh. The typical number of equivalent full cycles is assumed 10000, resulting in a total amount of discharged electricity of 415 MWh per year. In this category, the financial impact of a disruption is very high. However, the use of a storage device adds high costs to the power system. In order to estimate the importance of the additional costs, it is important to know the total amount of electricity to which these costs can be charged. As also is the case for category 3, more information is required on the framework and the setting the storage technology is used in. As such an analysis is beyond the scope if this project, the resulting costs can only be regarded as a first guideline.

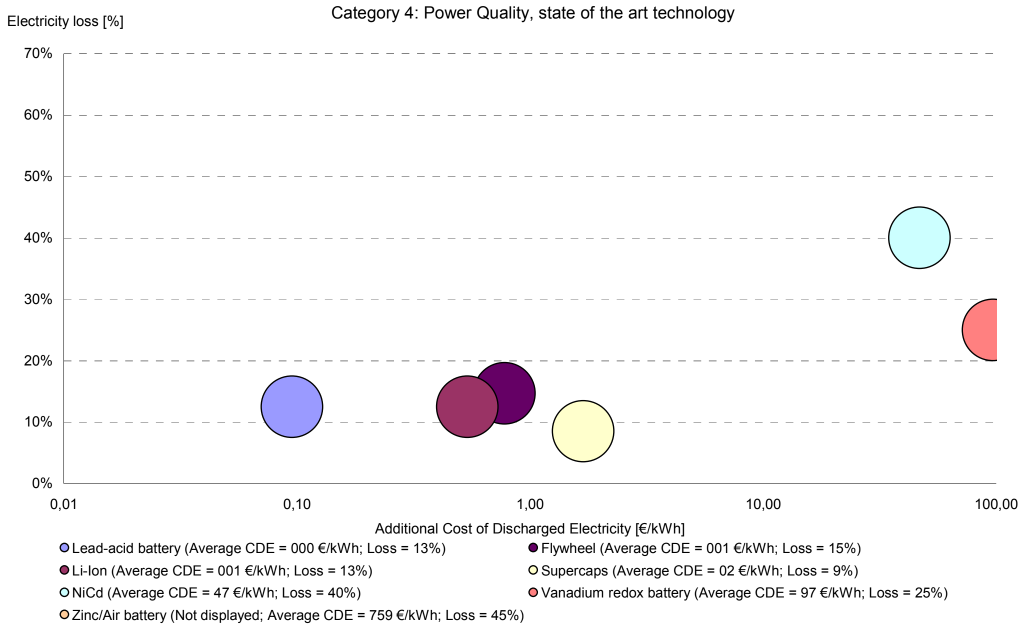

Figure 5.5 *Graphical presentation of the results for storage technologies in category 4 applications (year 2000)*

Table 5.7 *Results for technologies in category 1 applications*

			Lead-acid	Li-Ion	Supercaps	NiCd	Zinc/air
Total Efficiency	[η_{tot}]	-	0.78-0.88	0.96-0.99	0.21-0.59	0.48-0.52	0.50-0.60
Amount of stored electricity per cycle	[E_{sto}]	[kWh]	0	0	0	0	0
Annual amount of stored electricity	[E_{ann}]	[kWh/year]	2	2	3-9	4	3-4
Device costs	[I_{device}]	[€]	6-11	104-144	23,810-24,050	63-321	20-17
Annual O&M	[$S_{O\&M} \times I_{device}$]	[€/year]	0	2-3	476-481	4-13	1
Lifetime of annuity	[L]	[year]	5-15	5-15	10	15-20	1.6-2.7
Annuity factor	[a]	-	0.26-0.13	0.26-0.13	0.16	0.13-0.12	0.69-0.44
Annual costs	[AC]	[€/yr]	2-2	19-28	3952-3992	9-39	8-15
Cost of discharged electricity	[CDE]	[€/kWh]	0.85-0.98	10.58-15.35	2166-2188	2.31-11.16	2.10-4.81

Table 5.8 *Results for technologies in category 2a applications*

			Lead-acid	Li-Ion	Supercaps	NiCd	Electrolyser, H_2, PEMFC	Compressed air	Zinc/ air
Total efficiency	[η_{tot}]	-	0.80-0.90	0.97-0.99	0.49-0.91	0.58	0.23-0.44	0.36-0.47	0.50-0.60
Amount of stored electricity per cycle	[E_{sto}]	[kWh]	1	1	1-2	2	2-4	2-3	2
Annual amount of stored electricity	[E_{ann}]	[kWh/year]	81-92	74-76	80	125-127	166-319	156-204	122-146
Device costs	[I_{device}]	[€]	63-112	1,035-1,445	102,041-157,418	527-2,857	43,636-45,390	284-3659	200-167
Annual O&M	[$S_{O\&M} \times I_{device}$]	[€/year]	4	21-29	2,041-3,148	32-114	2,618-1,816	17-146	12-10
Lifetime for annuity	[L]	[year]	5-15	5-15	10	15-20	1.4-2.0	20	0.4-0.7
Annuity factor	[a]	-	0.26-0.13	0.26-0.13	0.16	0.13-0.12	0.82-0.58	0.12	2.60-1.58
Annual costs	[AC]	[€/year]	15-18	194-279	16,393-16,131	17-349	27,199-37,790	35-447	280-553
Cost of discharged electricity	[CDE]	[€/kWh]	0.21-0.24	2.65-3.82	232-358	0.58-2.79	85-228	0.17-2.86	1.91-4.54

Table 5.9 *Results for technologies in category 2b applications*

			Lead-acid	Li-Ion	Supercaps	NiCd	Electrolyser, H_2, PEMFC	Compressed air	Zinc/air
Total efficiency	[η_{tot}]	-	0.80-0.90	0.97-0.99	0.76-0.97	0.59-0.60	0.25-0.45	0.50-0.66	0.50-0.60
Amount of stored electricity per cycle	[E_{sto}]	[kWh]	534-601	485-495	495-635	805-808	1,072-1,959	728-953	800-960
Annual amount of stored electricity	[E_{ann}]	[MWh/year]	42.7-48.1	38.8-39.6	39.6-50.8	64.4-64.6	85.8-156.7	58.2-76.2	64.0-76.8
Device costs	[I_{device}]	[k€]	30-53	495-693	31,756-70,678	245-1,342	19,592-21,440	97-1,246	96-80
Annual O&M	[$S_{O\&M} \times I_{device}$]	[€/year]	1,802-2,135	9,907- 13,857	634,921- 1,413,552	14,692- 53,691	1,175,510- 857,621	5,800- 49,542	5,762-4,801
Lifetime for annuity	[L]	[year]	5-15	5-15	10	15-20	1.3-1.9	20	0.4-0.6
Annuity factor	[a]	-	0.26-0.13	0.26-0.13	0.16	0.13-0.12	0.89-0.61	0.12	2.85-1.73
Annual costs	[AC]	[€/year]	7,300-8,399	92,916- 13,283	5,269,851- 11,732,507	34,126- 163,970	13,625,621- 1,849,0358	12,036- 152,214	146,675- 289,927
Cost of discharged electricity	[CDE]	[€/kWh]	0.19-0.22	2.42-3.47	137-306	0.53-2.54	87-216	0.16-2.61	1.91-4.53

Table 5.10 *Results for technologies in category 3 applications*

			Lead-acid	Li-Ion	Supercaps	NiCd	Flywheel	Vanadium redox battery	Compressed air	Zinc/air
Total efficiency	[η_{tot}]	-	0.80 - 0.90	0.95 - 0.98	0.83 - 0.99	0.60 - 0.60	0.77 - 0.88	0.70 - 0.80	0.54 - 0.71	0.50 - 0.60
Amount of stored electricity per cycle	[E_{sto}]	[kWh]	1,111 - 1,250	1,020 - 1,053	1,012 - 1,200	1,668 - 1,668	1,134 - 1,304	1,250 - 1,429	1,408 - 1,844	1,667 - 2,000
Annual amount of stored electricity	[E_{ann}]	[GWh/year]	1.1 - 1.3	1.0	1.0 - 1.2	1.7	1.1 - 1.3	1.3 - 1.4	1.4 - 1.8	1.7 - 2.0
Device costs	[I_{device}]	[k€]	156 - 222	1,316 - 2,041	60,024 - 144,541	505 - 2,779	2,609 - 11,342	785 - 1,838	201 - 154	200 - 167
Annual O&M	[$S_{O\&M} \times I_{device}$]	[€/year]	9,376 - 8,889	26,318 - 40,817	1,200,480 - 2,890,821	30,328 - 111,173	52174 - 226843	31,400 - 73,536	12,058 - 6,141	12,000 - 10,000
Lifetime for annuity	[L]	[year]	0.7 - 1.0	5 - 15	10	1.2 - 1.6	20	5 - 12	20	0.0 - 0.1
Annuity factor	[a]	-	1.55 - 1.10	0.26 - 0.13	0.16	0.93 - 0.71	0.12	0.26 - 0.15	0.12	35.02 - 21.03
Annual costs	[AC]	[€/year]	254,229 - 256,637	2,736,88 - 354,073	9,964,004 - 23,993,857	495,771 - 2,043,649	312,545 - 1,358,890	215,363 - 280,600	18,754 - 25,023	3,716,112 - 7,425,199
Cost of discharged electricity	[CDE]	[€/kWh]	0.25 - 0.26	0.27 - 0.35	10.0 – 24.0	0.30 - 1.23	0.24 - 1.20	0.15 - 0.22	0.01 - 0.02	1.86 - 4.46

Table 5.11 *Results for technologies in category 4 applications*

			Lead-acid	Li-Ion	Supercaps	NiCd	Flywheel	Vanadium Redox	Zinc/air
Total efficiency	[η_{tot}]	-	0.85 - 0.90	0.85 - 0.90	0.84 - 0.99	0.60 - 0.60	0.79 - 0.92	0.70 - 0.80	0.50 - 0.60
Amount of stored electricity per cycle	[E_{sto}]	[kWh]	46 - 49	46 - 49	42 - 49	69 - 69	45 - 53	52 - 59	69 - 83
Annual amount of stored electricity	[E_{ann}]	[MWh/year]	461 - 488	461 - 488	419 - 494	692	451 - 528	519 - 593	692 - 830
Device costs	[I_{device}]	[k€]	49 - 69	980 - 1,111	2,470 - 5,988	833 - 8,334	489 - 5,436	59,286 - 51,875	2,000 - 1,66 7
Annual O&M	[$S_{O\&M} \times I_{device}$]	[€/year]	1,961 - 1,389	19,608 - 22,222	49,406 - 119,770	50,005 - 333,351	9,785 - 108,714	2,371,429 - 2,075,001	120,000 - 100,000
Lifetime for annuity	[L]	[year]	1.5 - 2.0	5 - 10	10	0.1 - 0.2	20	1.2	0.0
Annuity factor	[a]	-	0.75 - 0.58	0.26 - 0.16	0.16	8.79 - 6.61	0.12	0.93	34,979 - 20,989
Annual costs	[AC]	[€/year]	38,269 - 40,813	184,445 - 263,798	410,074 - 994,092	7,768,386 - 57,269,375	58,614 - 651,247	49,919,473 - 570,50,826	370,807,779 - 741,544,904
Cost of discharged electricity	[CDE]	[€/kWh]	0.09 - 0.10	0.44 - 0.64	0.99 - 2.40	11.2 - 83	0.11 - 1.44	84 - 110	447 - 1,072

5.3 Future prospects

The data tables as provided by the experts also provided future estimates, based on reference years 2005 and 2010. Indicatively, these improvements have been indicated in Table 5.12. The resulting costs of discharged electricity, based on the improved input data, are listed in Section 5.3.2.

Table 5.12 *Overview of changing parameters for future technologies, based on expert judgements*

Storage technology	Improvement price and O&M	Improvement efficiency
ST1: lead acid batteries	Not for categories 1 and 2, for category 3 and 4 between 10% and 30%	Generally not, only little for category 4 in 2010
ST2: Lithium batteries	Important improvements expected	Small improvement expected
ST3: Super capacitors	Important improvements expected for 2010	No improvement expected
ST4: Nickel batteries	Improvement expected from 15% for 2005 to 35% for 2010	No improvement expected, data for improved self-discharge in 2010 are not validated
ST5: Electrolyser, H_2-storage and fuel cells	No future data available	No future data available
ST6: Flywheels	Important improvements for prices expected	Important improvements for self discharge expected
ST7: Redox flow batteries	No future data available	No future data available
ST8: Pneumatic storage	No data on price improvement.	Efficiency improvement from 10% for 2005 to 25% for 2010, relative to state of the art.
ST9: Metal air batteries	Important improvements expected, no difference between 2005 and 2010 values	Important improvements expected, no difference between 2005 and 2010 values

5.3.1 Results for the year 2005

The results of the analysis of the nine storage technologies for the year 2005 have been displayed in tables as well as graphically below.

Category 1 (2005)			Lead-acid	Li-Ion	Supercaps	NiCd	Zinc/air
Total efficiency	$[\eta_{tot}]$	-	0.78 - 0.88	0.97 - 0.99	0.21 - 0.59	0.48 - 0.52	0.60 - 0.70
Amount of stored electricity per cycle	$[E_{sto}]$	[kWh]	0	0	0	0	0
Annual amount of stored electricity	$[E_{ann}]$	[kWh/year]	2	2	3 - 9	4	3
Device costs	$[I_{device}]$	[€]	6 - 11	23 - 34	23810 - 24050	54 - 276	2 - 1
Annual O&M	$[S_{O\&M} \times I_{device}]$	[€/year]	0	0 - 1	476 - 481	3 - 11	0
Lifetime for annuity	[L]	[year]	5 - 15	5 - 15	10	15 - 20	2.7 - 3.3
Annuity factor	[a]	-	0.26 - 0.13	0.26 - 0.13	0.16	0.13 - 0.12	0.44 - 0.37
Annual costs	[AC]	[€/yr]	2	5 - 6	3952 - 3992	8 - 34	1
Cost of discharged electricity	[CDE]	[€/kWh]	0.83 - 0.96	2.47 - 3.38	2166 - 2188	2.0 - 9.6	0.18 - 0.29

Category 2a (2005)			Lead-acid	Li-Ion	Supercaps	NiCd	Electrolyser, H_2, PEMFC	Compressed air	Zinc/air
Total efficiency	$[\eta_{tot}]$	-	0.80 - 0.90	0.97 - 0.99	0.49 - 0.91	0.58 - 0.58	0.23 - 0.44	0.53 - 0.66	0.60 - 0.70
Amount of stored electricity per cycle	$[E_{sto}]$	[kWh]	1	1	1 - 2	2	2 - 4	2	1 - 2
Annual amount of stored electricity	$[E_{ann}]$	[kWh/year]	81 - 92	74 - 75	80 - 149	125 - 127	166 - 319	111 - 137	104 - 122
Device costs	$[I_{device}]$	[€]	63 - 112	230 - 337	102041 - 157418	455 - 2465	43636 - 45390	190 - 2595	17 - 14
Annual O&M	$[S_{O\&M} \times I_{device}]$	[€/year]	3 - 2	5 - 7	2041 - 3148	27 - 99	2618 - 1816	11 - 104	1
Lifetime for annuity	[L]	[year]	5 - 15	5 - 15	10	15 - 20	1.4 - 2.0	20	0.7 - 0.8
Annuity factor	[a]	-	0.26 - 0.13	0.26 - 0.13	0.16	0.13 - 0.12	0.82 - 0.58	0.12	1.58 - 1.33
Annual costs	[AC]	[€/year]	15 - 17	45 - 62	16939 - 26131	63 - 301	27199 - 37790	24 - 317	20 - 27
Cost of discharged electricity	[CDE]	[€/kWh]	0.20 - 0.24	0.62 - 0.85	232 - 358	0.50 - 2.41	85 - 228	0.17 - 2.86	0.16 - 0.26

Category 2b (2005)			Lead-acid	Li-Ion	Supercaps	NiCd	Electrolyser, H_2, PEMFC	Compressed air	Zinc/air
Total efficiency	[η_{tot}]	-	0.80 - 0.90	0.97 - 0.99	0.76 - 0.97	0.59 - 0.60	0.25 - 0.45	0.61 - 0.75	0.60 - 0.70
Amount of stored electricity per cycle	[E_{sto}]	[kWh]	534 - 601	485 - 495	495 - 635	805 - 808	1,072 - 1,959	639 - 791	686 - 800
Annual amount of stored electricity	[E_{ann}]	[MWh/year]	42.7 - 48.0	38.8 - 39.6	39.6 - 50.8	64.4 - 64.6	85.8 - 156.7	51.1 - 63.3	54.9 - 64.0
Device costs	[I_{device}]	[k€]	30 - 53	110 - 162	31,746 - 70,678	211 - 1,158	1,9592 - 21,441	80 - 1,094	8 - 7
Annual O&M	[$S_{O\&M} \times I_{device}$]	[€/year]	1,202 - 1,068	2,200 - 3,233	634,921 - 1,413,552	12,674 - 46,315	1,175,510 - 85,7621	48,16 - 43,762	320 - 274
Lifetime for annuity	[L]	[year]	5 - 15	5 - 15	10.0	15 – 20	1.3 - 1.9	20	0.6 - 0.8
Annuity factor	[a]	-	0.26 - 0.13	0.26 - 0.13	0.16	0.13 - 0.12	0.89 - 0.61	0.12	1.73 - 1.45
Annual costs	[AC]	[€/year]	7,159 - 8,241	21,680 - 29,604	5,269,851 - 11,732,507	29,437 - 141,442	13,625,621 - 18,490,358	9,995 - 133,648	10,339 - 14,390
Cost of discharged electricity	[CDE]	[€/kWh]	0.19 - 0.21	0.56 - 0.77	137 - 306	0.46 - 2.20	87 - 216	0.16 - 2.61	0.16 - 0.26

Category 3 (2005)			Lead-acid	Li-Ion	Supercaps	NiCd	Flywheel	Vanadium redox battery	Compressed air	Zinc/air
Total efficiency	[η_{tot}]	-	0.80 - 0.90	0.95 - 0.98	0.83 - 0.99	0.60 - 0.60	0.83 - 0.92	0.70 - 0.80	0.63 - 0.78	0.60 - 0.70
Amount of stored electricity per cycle	[E_{sto}]	[MWh]	1.1 - 1.3	1.0	1.0 - 1.2	1.7	1.1 - 1.2	1.3 - 1.4	1.3 - 1.6	1.4 - 1.7
Annual amount of stored electricity	[E_{ann}]	[GWh/year]	1.1 - 1.3	1.0	1.0 - 1.2	1.7	1.1 - 1.2	1.3 - 1.4	1.3 - 1.6	1.4 - 1.7
Device costs	[I_{device}]	[k€]	156 - 185	263 - 340	60,024 - 144,541	436 - 2,397	1,210 - 1,083	785 - 1,838	174 - 141	42 - 36
Annual O&M	[$S_{O\&M} \times I_{device}$]	[€/year]	6,250 - 3,704	5,263 - 6,803	1,200,480 - 2,890,821	26,161 - 95,899	24,202 - 21,654	31,400 - 73,536	10,443 - 5,623	1,667 - 1,429
Lifetime for annuity	[L]	[year]	0.8 - 1.5	5 - 15	10	1.2 - 1.6	20	5 - 12	20	0.1
Annuity factor	[a]	-	1.36 - 0.75	0.26 - 0.13	0.16	0.93 - 0.71	0.12	0.26 - 0.15	0.12	21.0 - 17.5
Annual costs	[AC]	[€/year]	141,796 - 221,360	45,615 - 70,812	9,964,004 - 23,993,857	427,656 - 1,762,870	129,718 - 144,979	215,363 - 280,600	17,173 - 21,671	651,375 - 911,493
Cost of discharged electricity	[CDE]	[€/kWh]	0.14 - 0.22	0.05 - 0.07	10.0 – 24.0	0.26 - 1.06	0.11 - 0.13	0.15 - 0.22	0.01 - 0.02	0.39 - 0.64

Category 4 (2005)			Lead-acid	Li-Ion	Supercaps	NiCd	Flywheel	Vanadium Redox	Zinc/air
Total efficiency	[η_{tot}]	-	0.85 - 0.90	0.85 - 0.92	0.84 - 0.99	0.60	0.85 - 0.95	0.70 - 0.80	0.60 - 0.70
Amount of stored electricity per cycle	[E_{sto}]	[kWh]	46 - 49	45 - 49	42 - 49	69	44 - 49	52 - 59	59 - 69
Annual amount of stored electricity	[E_{ann}]	[MWh/year]	461 - 488	451 - 488	419 - 494	692	437 - 488	519 - 593	593 - 692
Device costs	[I_{device}]	[k€]	49 - 56	147 - 181	618 - 5,988	833 - 8,334	294 - 263	59,286 - 51,875	417 - 357
Annual O&M	[$S_{O\&M} \times I_{device}$]	[€/yr]	1,961 - 1,111	2,941 - 3,623	12,352 - 119,770	50,005 - 333,351	5,883 - 5,264	2,371,429 - 2,075,001	16,667 - 14,286
Lifetime for annuity	[L]	[year]	1.8 - 2.2	5 - 15	10	0.1 - 0.2	20	1.2	0.0
Annuity factor	[a]	-	0.63 - 0.53	0.26 - 0.13	0.16	8.8 - 6.6	0.12	0.93	210 - 175
Annual costs	[AC]	[€/year]	29,957 - 32,338	24,294 - 39,570	102,519 - 994,092	7,768,386 - 57,269,375	31,532 - 35,242	49,919,473 - 57,050,826	64,969,416 - 90,952,849
Cost of discharged electricity	[CDE]	[€/kWh]	0.07 - 0.08	0.06 - 0.10	0.25 - 2.40	11.2 - 83	0.06 - 0.08	84 - 110	94 - 153

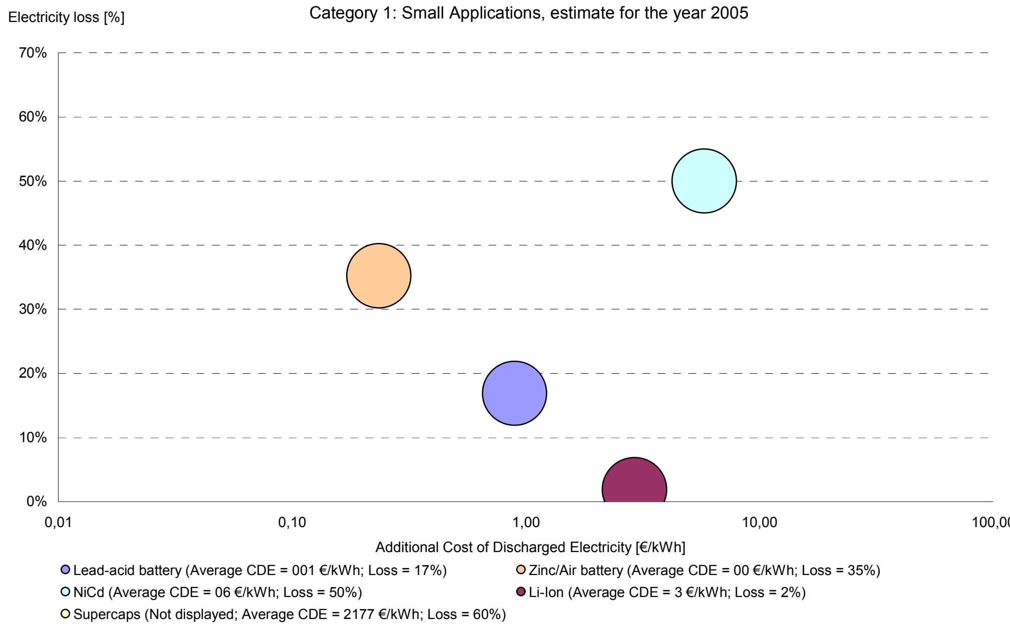

Figure 5.6 *Results for storage technologies in category 1, year 2005*

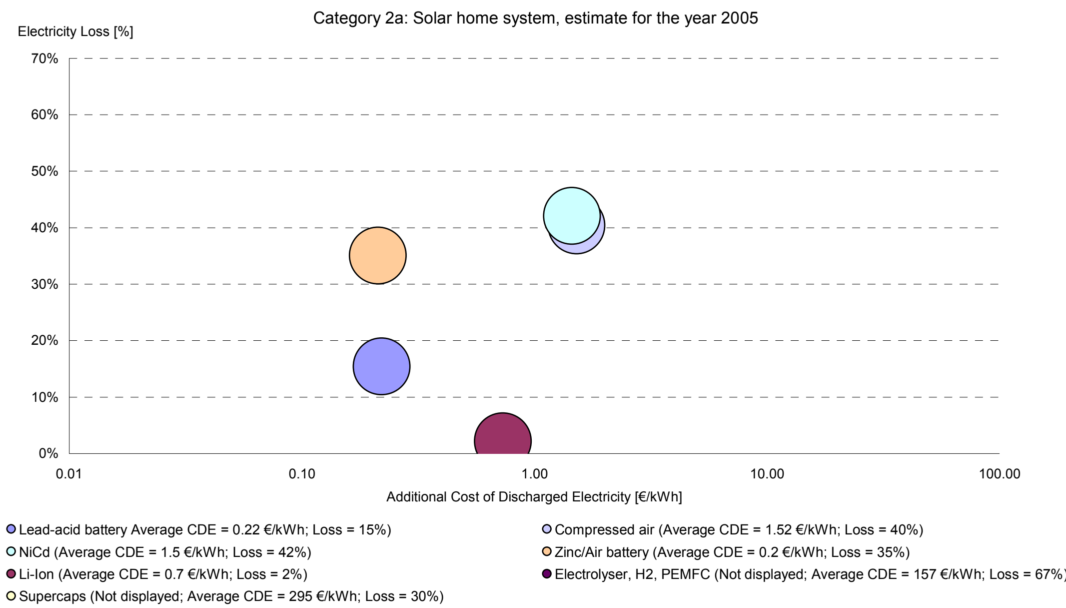

Figure 5.7 *Results for storage technologies in category 2a, year 2005*

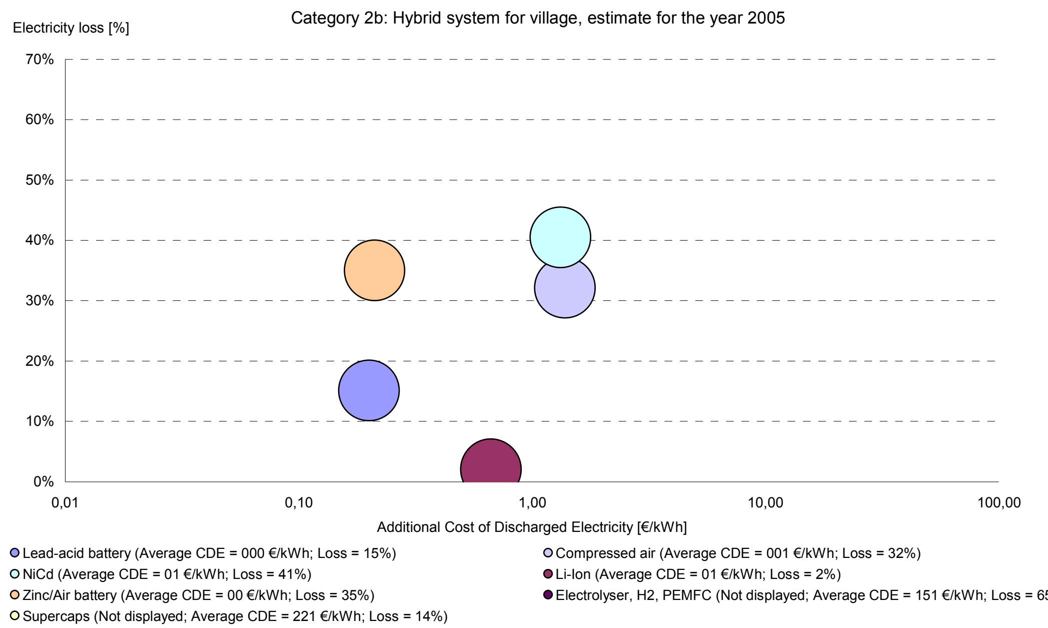

Figure 5.8 *Results for storage technologies in category 2b, year 2005*

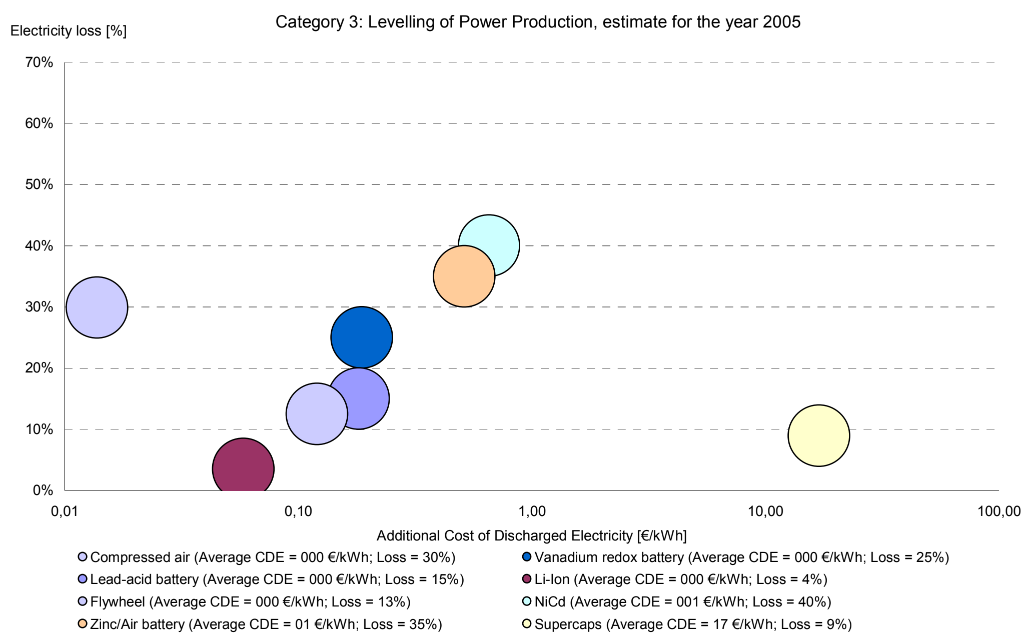

Figure 5.9 *Results for storage technologies in category 3, year 2005*

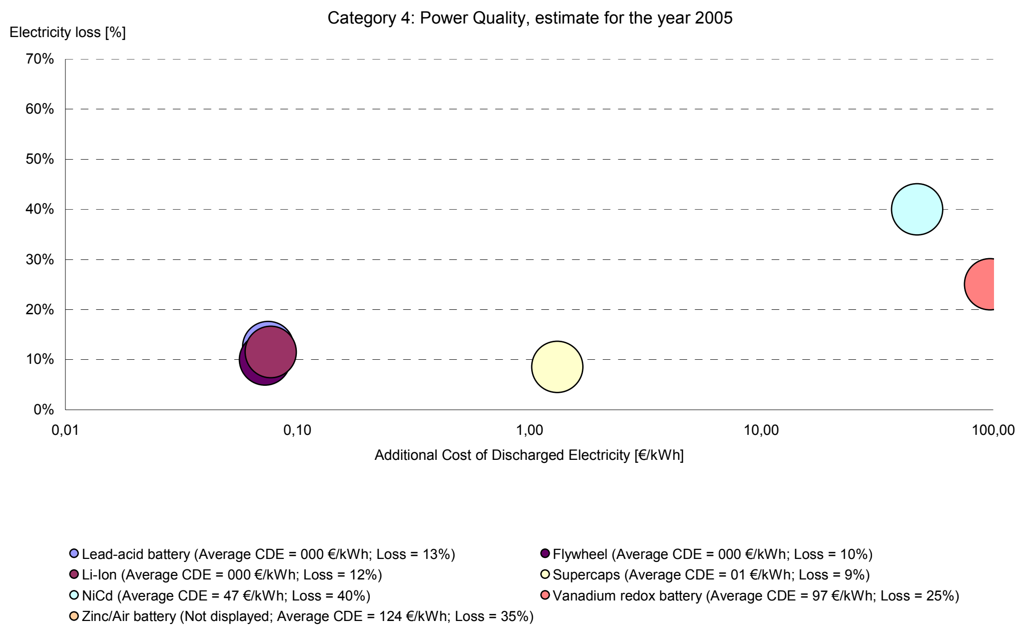

Figure 5.10 *Results for storage technologies in category 4, year 2005*

5.3.2 Results for the year 2010

The results of the analysis of the nine storage technologies for the year 2010 have been displayed in tables as well as graphically below.

Category 1 (2010)			Lead-acid	Li-Ion	Supercaps	NiCd			Zinc/air
Total efficiency	[η_{tot}]	-	0.78 - 0.88	0.97 - 0.99	0.21 - 0.59	0.48 - 0.52			0.70 - 0.80
Amount of stored electricity per cycle	[E_{sto}]	[kWh]	0	0	0	0			0
Annual amount of stored electricity	[E_{ann}]	[kWh/year]	2	2	3 - 9	4			2 - 3
Device costs	[I_{device}]	[€]	6 - 11	15 - 22	23,810 - 24,050	47 - 238			1
Annual O&M	[$S_{O\&M} \times I_{device}$]	[€/year]	0	0	476 - 481	3 - 10			0
Lifetime for annuity	[L]	[year]	5.0 - 15.0	5.0 - 20.0	10.0	65.8 - 87.7			3.8 - 4.4
Annuity factor	[a]	-	0.26 - 0.13	0.26 - 0.12	0.16	0.10 - 0.10			0.33 - 0.29
Annual costs	[AC]	[€/yr]	2	3 - 4	3,952 - 3,992	5 - 25			0
Cost of discharged electricity	[CDE]	[€/kWh]	0.83 - 0.96	1.47 - 2.27	2,166 – 2,188	1.31 - 7.07			0.15 - 0.21

Category 2a (2010)			Lead-acid	Li-Ion	Supercaps	NiCd	Electrolyser, H_2, PEMFC	Compressed air	Zinc/air
Total efficiency	[η_{tot}]	-	0.80 - 0.90	0.97 - 0.99	0.49 - 0.91	0.58 - 0.58	0.23 - 0.44	0.65 - 0.79	0.70 - 0.80
Amount of stored electricity per cycle	[E_{sto}]	[kWh]	1	1	1 - 2	2	2 - 4	1 - 2	1
Annual amount of stored electricity	[E_{ann}]	[kWh/year]	81 - 92	74 - 75	80 - 149	125 - 127	166 - 319	92 - 113	91 - 104
Device costs	[I_{device}]	[€]	63 - 112	154 - 225	102,041 - 157,418	392 - 2,126	43,636 - 45,390	157 - 2,166	14 - 13
Annual O&M	[$S_{O\&M} \times I_{device}$]	[€/year]	3 - 2	3 - 4	2,041 - 3,148	24 - 85	2618 - 1816	9 - 87	1
Lifetime for annuity	[L]	[year]	5.0 - 15.0	5.0 - 20.0	10.0	16.4 - 21.9	1.4 - 2.0	20.0	1.0 - 1.1
Annuity factor	[a]	-	0.26 - 0.13	0.26 - 0.12	0.16	0.13 - 0.11	0.82 - 0.58	0.12	1.14 - 1.01
Annual costs	[AC]	[€/yr]	15 - 17	27 - 41	16,939 - 26,131	53 - 252	27,199 - 37,790	20 - 265	13 - 17
Cost of discharged electricity	[CDE]	[€/kWh]	0.20 - 0.24	0.37 - 0.57	232 – 358	0.41 - 2.02	85 - 228	0.17 - 2.86	0.13 - 0.19

Category 2b (2010)			Lead-acid	Li-Ion	Supercaps	NiCd	Electrolyser, H_2, PEMFC	Compressed air	Zinc/air
Total efficiency	[η_{tot}]	-	0.80 - 0.90	0.97 - 0.99	0.76 - 0.97	0.59 - 0.60	0.25 - 0.45	0.70 - 0.86	0.70 - 0.80
Amount of stored electricity per cycle	[E_{sto}]	[kWh]	534 - 601	485 - 495	495 - 635	805 - 808	1,072 - 1,959	559 - 683	600 - 686
Annual amount of stored electricity	[E_{ann}]	[MWh/year]	42.7 - 48.0	38.8 - 39.6	39.6 - 50.8	64.4 - 64.6	85.8 - 156.7	44.7 - 54.7	48.0 - 54.9
Device costs	[I_{device}]	[k€]	30 - 53	74 - 108	31,746 - 70,678	182 - 999	19,592 - 21,441	69 - 957	7 - 6
Annual O&M	[$S_{O\&M} \times I_{device}$]	[€/year]	1,202 - 1,068	1,478 - 2,156	634,921 - 1,413,552	10,933 - 39,951	1,175,510 - 857,621	4,160 - 38,287	274 - 240
Lifetime for annuity	[L]	[year]	5.0 - 15.0	5.0 - 20.0	10.0	15.0 - 20.0	1.3 - 1.9	20.0	0.9 - 1.0
Annuity factor	[a]	-	0.26 - 0.13	0.26 - 0.12	0.16	0.13 - 0.12	0.89 - 0.61	0.12	1.25 - 1.10
Annual costs	[AC]	[€/year]	7,159 - 8,241	12,913 - 19,883	5,269,851 - 11,732,507	25,393 - 122,009	13,625,621 - 18,490,358	8,632 - 116,925	6,865 - 8,914
Cost of discharged electricity	[CDE]	[€/kWh]	0.19 - 0.21	0.34 - 0.52	137 – 306	0.39 - 1.89	87 - 216	0.16 - 2.61	0.13 - 0.19

Category 3 (2010)			Lead-acid	Li-Ion	Supercaps	NiCd	Flywheel	Vanadium redox battery	Compressed air	Zinc/air
Total efficiency	[η_{tot}]	-	0.80 - 0.90	0.95 - 0.98	0.83 - 0.99	0.60 - 0.60	0.85 - 0.95	0.70 - 0.80	0.72 - 0.88	0.70 - 0.80
Amount of stored electricity per cycle	[E_{sto}]	[kWh]	1,111 - 1,250	1,020 - 1,053	1,012 - 1,200	1,668 - 1,668	1,054 - 1,180	1,250 - 1,429	1,141 - 1,395	1,250 - 1,429
Annual amount of stored electricity	[E_{ann}]	[GWh/year]	1.1 - 1.2	1.0	1.0 - 1.2	1.7	1.0 - 1.2	1.3 - 1.4	1.1 - 1.4	1.3 - 1.4
Device costs	[I_{device}]	[k€]	125 - 159	175 - 255	60,024 - 144,541	376 - 2,068	1,180 - 1,054	785 - 1,838	152 - 124	36 - 31
Annual O&M	[$S_{O\&M} \times I_{device}$]	[€/year]	5,000 - 3,175	3,509 - 5,102	1,200,480 - 2,890,821	22,567 - 82,723	23,595 - 21,082	31,400 - 73,536	9,121 - 4,975	1,429 - 1,250
Lifetime for annuity	[L]	[year]	1.0 - 2.0	5.0 - 20.0	10.0	1.2 - 1.6	20.0	5.0 - 12.0	20.0	0.1 - 0.1
Annuity factor	[a]	-	1.10 - 0.58	0.26 - 0.12	0.16	0.93 - 0.71	0.12	0.26 - 0.15	0.12	15.04 - 13.17
Annual costs	[AC]	[€/year]	93,291 - 143,008	30,564 - 47,208	9,964,004 - 23,993,857	368,900 - 1,,520,667	126,290 - 141,344	215,363 - 280,600	15,194 - 18,928	427,871 - 558,587
Cost of discharged electricity	[CDE]	[€/kWh]	0.09 - 0.14	0.03 - 0.05	10.0 – 24.0	0.22 - 0.91	0.11 - 0.13	0.15 - 0.22	0.01 - 0.02	0.30 - 0.45

Category 4 (2010)			Lead-acid	Li-Ion	Supercaps	NiCd	Flywheel	Vanadium Redox	Zinc/air
Total efficiency	[η_{tot}]	-	0.87 - 0.92	0.85 - 0.95	0.84 - 0.99	0.60 - 0.60	0.85 - 0.95	0.70 - 0.80	0.70 - 0.80
Amount of stored electricity per cycle	[E_{sto}]	[kWh]	45 - 48	44 - 49	42 - 49	69 - 69	44 - 49	52 - 59	52 - 59
Annual amount of stored electricity	[E_{ann}]	[MWh/year]	451 - 477	437 - 488	419 - 494	692	437 - 488	519 - 593	519 - 593
Device costs	[I_{device}]	[k€]	41 - 54	84 - 88	309 - 5,988	833 - 8,333	294 - 263	59,286 - 51,875	357 - 313
Annual O&M	[$S_{O\&M} \times I_{device}$]	[€/year]	1,642 - 1,087	1,681 - 1,754	6,176 - 119,770	50,000 - 333,333	5,882 - 5,263	2,371,429 - 2,075,001	14,286 - 12,500
Lifetime for annuity	[L]	[year]	2.0 - 2.5	5.0 - 20.0	10.0	0.1 - 0.2	20.0	1.2	0.0 - 0.0
Annuity factor	[a]	-	0.58 - 0.47	0.26 - 0.12	0.16	8.79 - 6.61	0.12	0.93	149,94 - 131,20
Annual costs	[AC]	[€/year]	24,599 - 26,147	10,510 - 22,611	51,259 - 994,092	7,767,585 - 57,266,433	31,529 - 35,238	49,919,473 - 57,050,826	42,640,242 - 55,690,724
Cost of discharged electricity	[CDE]	[€/kWh]	0.06	0.03 - 0.05	0.12 - 2.40	11.2 - 83	0.06 - 0.08	84 – 110	72 - 107

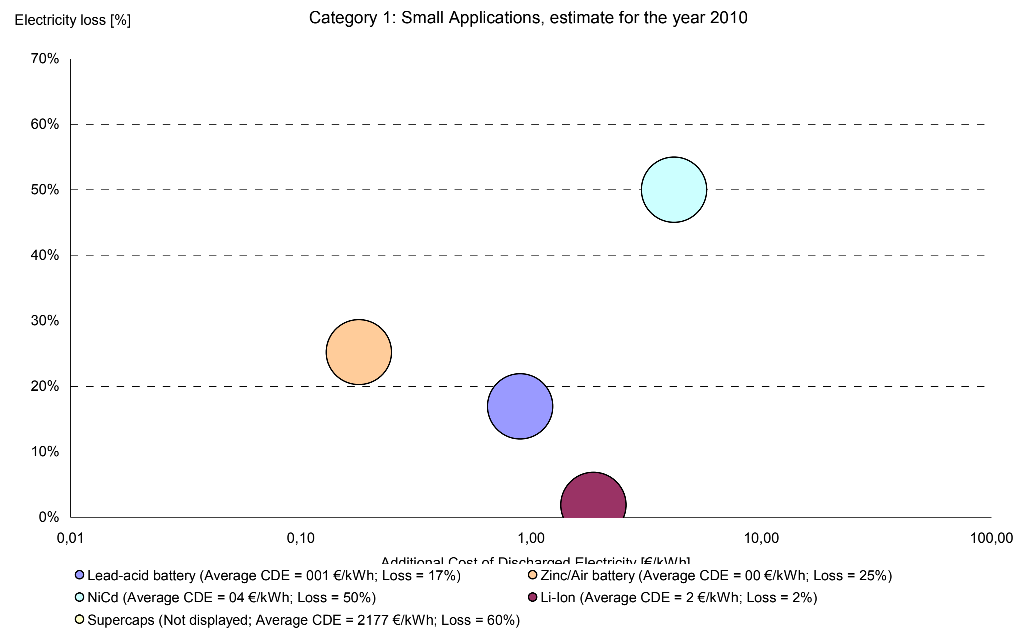

Figure 5.11 *Results for storage technologies in category 1, year 2010*

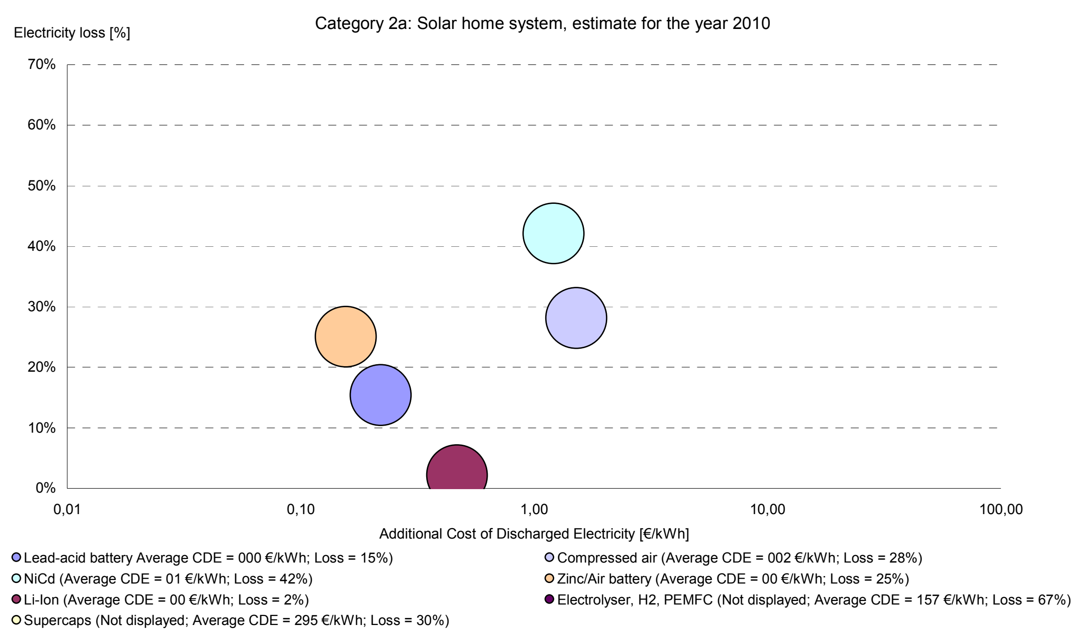

Figure 5.12 *Results for storage technologies in category 2a, year 2010*

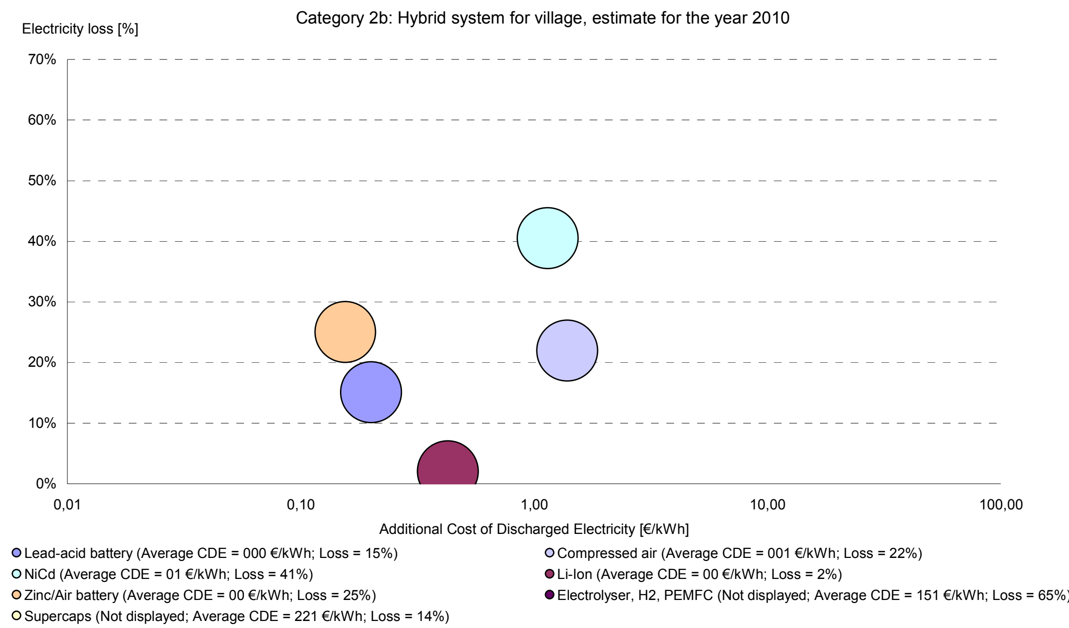

Figure 5.13 *Results for storage technologies in category 2b, year 2010*

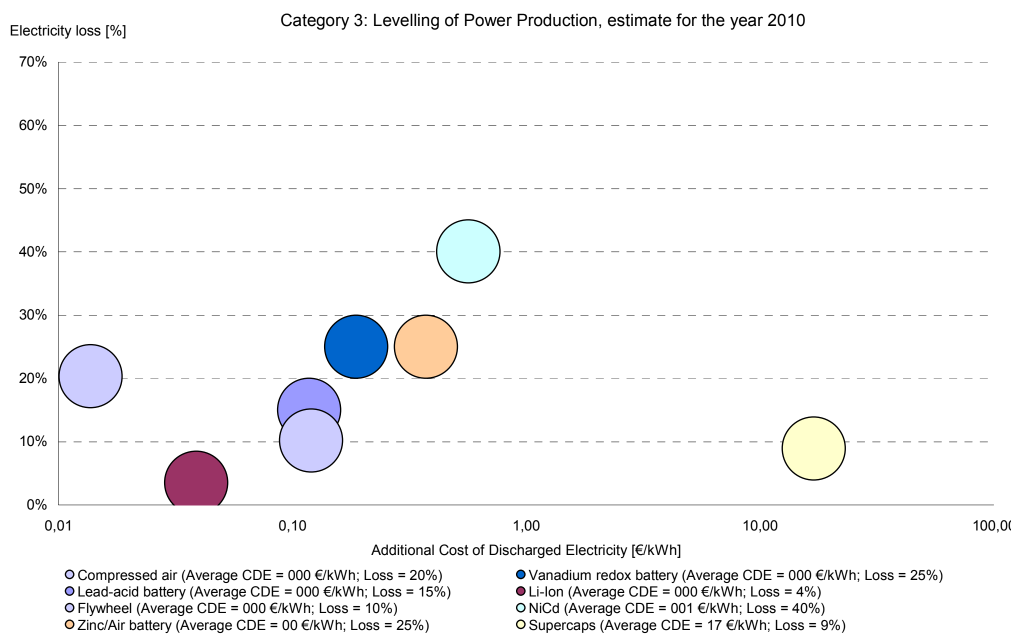

Figure 5.14 *Results for storage technologies in category 3, year 2010*

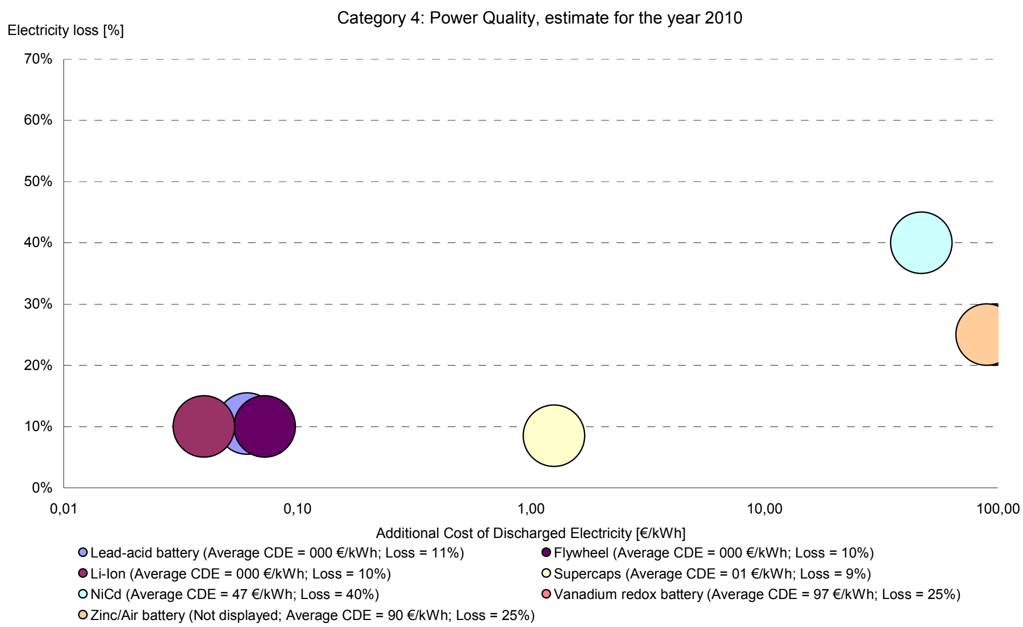

Figure 5.15 *Results for storage technologies in category 4, year 2010*

6. CONCLUSIONS

The conclusions of WP4 have been split in three: firstly, conclusions regarding storage in general and the assessment method are presented, secondly best options for each category are defined, and finally short summaries per storage technologies are listed.

The summary of the storage technologies focuses mainly on the state-of-the-art. From the graphs depicting the expectations for future additional costs it can be concluded, that important improvements are expected. However, as at least for some technologies these expectations could be interpreted rather as estimates instead of projections, it is not advisable to draw strong conclusions from the future data presented in this report.

Purchase prices of electricity may have a strong impact on the profitability of storage systems, through the induced costs by energy losses. Thus, when assessing the viability of a storage system, purchase costs of electricity should be taken into account in the annualised costs. When doing so, it is important to realise that the purchase cost of electricity differ, depending on the system one is considering, as for example on-grid costs for electricity may be much lower than off-grid costs of electricity. Thus, the impact of the purchase price will also differ, depending on the application of the storage device. As explained before, such an analysis has not been performed in the current study.

6.1 General conclusions

- The additional value of electricity storage can be of several origins, where it should be noted that a fundamental difference occurs between on-grid applications and off-grid applications.
- For on-grid applications, added values can be found in inter-temporal arbitrage (peak-shaving), balancing of the system, grid losses avoidance, grid investment avoidance, reserve capacity and emergency supply, voltage and frequency support, black start, seasonal or day-night renewable (distributed generation) energy storage, Uninterruptible Power Supply (UPS), and Power Quality Management.
- For off-grid applications, added values can be found in reserve capacity and emergency supply, black start, seasonal or day-night renewable (distributed generation) energy storage and UPS.
- Regulation and the market design have to provide the correct framework in order to value all services storage facilities can efficiently provide.
- In the current report, the methodology for assessing the storage devices, the focus has been only on the direct economical cost. Namely, the additional cost of the discharged electricity has been calculated, based on typical user patterns, defined in categories. However, as already mentioned in Chapter 2, benefits of different origin than only a financial perspective can be identified. This is a serious shortcoming of the current analysis. In addition, the purchase price of the electricity to be stored should be considered, in particular since it has an impact on the costs of a system through the financial consequences of the losses in the storage process. In order to evaluate the economical performance of storage systems more correctly, a total energy system should be considered.
- The prices on which the financial assessment has been based consist mainly on expert judgements, of which it is difficult to estimate the reliability. The data provenance for each technology is indicated in Table 5.6 on page 18.

6.2 Conclusions regarding the categories of typical use

- For category 1, small applications, minimisation of losses is an important design parameter, whereas, possibly the additional costs of discharged electricity have less importance: lifetime could be, next to losses, more important. Therefore, Zinc/air and NiCd batteries are less advantageous, although the level of additional costs may be acceptable. The Li-Ion battery is rather expensive, but due to lower losses could be more attractive that the cheapest option, the lead-acid battery.
- For category 2a, Solar home systems (SHS), electricity losses are extremely undesired, for the purchase price of electricity from photovoltaic is very high, and the income for the target group of SHS is expected to be rather low. Lead-acid batteries are the cheapest option, whereas the losses are much less for the Li-ion battery.
- For category 2b, hybrid power systems for village power supply, the results are roughly the same as for category 2a. However, as electricity input is not only from PV power, higher losses could be acceptable, although still undesirable.
- For category 3, power-levelling applications, additional costs can be perceived as the most important parameter, which is strongly related to the regulational setting of the system the device is integrated. This leaves mainly the compressed air storage system as an option, although the electricity losses of this device are quite important.
- For category 4, power quality, the financial impact of a disruption is very high, making higher values of the additional costs from storage more easily to accept. As also is the case for category 3, more information is required on the framework and the setting the storage technology is used in. The technologies of Lead-acid, Li-ion, flywheel and super caps result as options that are the least expensive.

6.3 Conclusions regarding the storage technologies

The evaluation of the storage technologies focuses on the state of the art results.

ST1: Lead acid batteries
Lead acid batteries are cheapest options for off-grid applications and power quality. Future improvements are not very likely, as lead-acid batteries are a well-developed technology, except for improvements for new applications that have not been addressed yet.

ST2: Lithium batteries
Li-Ion storage technology is characterised by high efficiency, which is very important for most categories in addition to a very good cycling stability. Future improvements in investment price are promising, resulting in lower costs of discharged electricity.

ST3: Supercapacitors
This technology is mainly of interest for levelling of power production and power quality. Relatively low losses occur, and for power quality the resulting additional cost could be acceptable in some markets.

ST4: Nickel batteries
According to the table of adequacy, Nickel Cadmium batteries perform best in levelling of power production. However, the losses and costs are relatively high.

ST5: Electrolyser, Hydrogen storage and fuel cells
This storage technology is only evaluated for use in village power supply. The additional costs are extremely high, and losses are substantial. A possible type of additional value at present time can be in seasonal storage.

ST6: Flywheels
Only adapted for power levelling and power quality, yields relatively low additional costs, which are expected to improve in future.

ST7: Redox flow batteries
The Vanadium redox battery is most adapted for levelling of power production and power quality. For the latter, it is very expensive, but for the first the additional costs are relatively low.

ST8: Pneumatic storage
Compressed air as a storage medium is, according to the evaluation based on the input data as provided by the expert, very well suited for levelling of power production. For village power supply it is rather expensive and not well suited because of its losses.

ST9: Metal air batteries
According to the table of adequacy, the outcome for Zinc/air batteries are rather similar for all categories, and the technology is not significantly well suited for either of the applications. For future use, the improvements are important, but the future estimates seem to be rather rough.

REFERENCES

Sauer D.U. (2002): *INVESTIRE WP 2 – Technical criteria and specifications*, December 2002.

Jossen A., Protogeropoulos C. (2003): *INVESTIRE WP 3 – Existing Data, Recommendations for the best matching of storage technologies for renewable applications,* October 2003.

APPENDIX A WP3 DATA TABLES

On the following pages, the data tables as delivered by WP3 partners mentioned in Table 5.6 on page 18.are displayed. For further information on the values, refer to (Jossen, Protogeropoulos 2003).

The next definitions are used in the Tables A.1 to .9.

Definitions	
	Energy available at a constant discharge in x (E_X) hours in
E_{100}	category 1
E_{10}	category 2
E_1	category 3
$E_{0.1}$	category 4
[1] *Rating*	1 - very poor, 2 - poor, 3 - fair, 4 - good, 5 - very good
[2] *Rating*	1 - very high, 2 - high, 3 - fair, 4 - low, 5 - very low
[3] *Rating*	Temperature increase of 10 K (with respect to 20°C) cause a reduction of lifetime by a factor of X: 1 - X = 4, 2 - X = 2, 3 - X = 1.5, 4 - X = 1.2, 5 - X = 1.0
[4] *Rating*	Time to get nominal power from the storage starting from an idle state (float charging or no charging and no discharging) 1 - more than 10 minutes, 2 - 1 to 10 minutes, 3 - 1 to 60 seconds, 4 - 20 to 1000 milliseconds, 5 - less than 20 milliseconds
[a] *Float life*	Conditions as appropriate for the specific technology, but at least @ SOC > 90%
[b] *Self discharge*	@ open circuit conditions, time until 1% capacity have been lost
[c] *Temp. Increase*	Temperature increase during a complete charging with the indicated relative current in the starting constant current charging period
[d] *Price*	Customers price (excluding taxes and customs) should be considered here
[e] *Power*	Power is defined as the maximum power [W] related to the size of the battery [Wh] for a one second discharge
[f] *Equiv. cycles*	Meany number of cylces x DOD
[g] *Greenhouse gas emissions*	These are greenhouse gas emissions released during the production process. This must not be evaluated by the partners. This will be done during the analysis within WP.
[h] *Energy efficiency*	Here an average value should be given for typical operation in this category. If no experience is available, the efficiency during a cycle with 10 hours discharge and charge current should be given here.

Table A.1 *ST1: lead acid batteries*

Parameter	Unit	Category 1						Category 2					
		today		in 5 years		future		today		in 5 years		future	
		min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.
Price[d] (energy)	Wh/€ [E_{100}]	10	20	10	20	10	20	10	20	10	20	10	20
Price[d] (power[e])	W/€ [E_{100}]	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Energy efficiency[h]	%	80	90	80	90	80	90	80	90	80	90	80	90
Self discharge[b] @ 20°C	days/%	8	10	8	10	8	10	8	10	8	10	8	10
Gravimetric Energy density	Wh/kg [E_{100}]	35	40	35	40	35	40	35	40	35	40	35	40
Volumetric energy density	Wh/l [E_{100}]	100	110	100	110	100	110	100	110	100	110	100	110
Specific power[e]	W/Wh [E_{100}]	n.a.	n.a.	n.a.	n.a.	n.a.	n.a..	n.a..	n.a.	n.a.	n.a.	n.a.	n.a.
Time to full power[4]	1 ... 5	4	5	4	5	4	5	4	5	4	5	4	5
Cycle life @ 20°C @ 100% DOD	cycles	500	1,800	600	1,800	800	2,000	500	1,800	600	1,800	800	2,000
Cycle life @ 20°C @ 10% DOD	equiv. cycles[f]	1,000	3,000	1,500	3,500	2,000	4,000	1,000	3,000	1,500	3,500	2,000	4,000
Float life[a] @ 20°C (SOC = 90%)	years	5	15	5	15	5	15	5	15	5	15	5	15
Shelf life[b] @ 20°C	month	0.27	0.33	0.27	0.33	0.27	0.33	0.27	0.33	0.27	0.33	0.27	0.33
Decrease in life-time with temp.	1 ... 5	2	3	2	3	2	3	2	3	2	3	2	3
Max. ambient charge temperature	°C	40	60	40	60	40	60	40	60	40	60	40	60
Min. ambient discharge temperature	°C	20	-30	-20	-30	-30	-40	20	-30	-20	-30	-30	-40
Temp. increase during charging[c]	K @ 0.1 x C_{10}	2	3	2	3	2	3						
	K @ 0.2 x C_{10}							2	3	2	3	2	3
Recycling capability	1 ... 5	4	5	4	5	5	5	4	5	4	5	5	5
Greenhouse gas emissions[g]	1 ... 5												
Health & safety	1 ... 5	3	4	3	4	3	4	3	4	3	4	3	4
Maintenance	1 ... 5	3	4	4	5	4	5	3	4	4	5	4	5
Efforts for SOC & SOH monitoring	1 ... 5	3	4	3	4	3	4	3	4	3	4	3	4
Electronic efforts (charger, safety)	1 ... 5	4	5	4	5	4	5	4	5	4	5	4	5

Parameter	Unit	Category 3						Category 4					
		today		in 5 years		future		today		in 5 years		future	
		min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.
Price[d] (energy)	Wh/€ [E_1]	5	8	6	8	7	10	4	6	5	6	5	7
Price[d] (power[e])	W/€ [E_1]	40	64	48	64	56	80	80	120	100	120	100	140
Energy efficiency[h]	%	80	90	80	90	80	90	85	90	85	90	87	92
Self discharge[b] @ 20°C	days/%	15	30	15	30	15	30	30	30	30	30	30	30
Gravimetric Energy density	Wh/kg [E_1]	25		27		30		15	18	15	20	17	20
Volumetric energy density	Wh/l [E_1]	75		80		90		35	40	35	40	35	40
Specific power[e]	W/Wh [E_1]	8		8		10		20	20	20	23	20	25
Time to full power[4]		5		5		5		5		5		5	
Cycle life @ 20°C @ 100% DOD	cycles	500	800	600	1,000	800	1,200	5,000	6,000	6,000	7,000	7,000	8,000
Cycle life @ 20°C @ 10% DOD	equiv. cycles[f]	700	1,000	800	1,500	1,000	2,000	15,000	20,000	18,000	22,000	20,000	25,000
Float life[a] @ 20°C (SOC = 90%)	years	8	10	8	10	10	12	8	10	8	10	10	12
Shelf life[b] @ 20°C	month	0.5	1	0.5	1	0.5	1	1	1	1	1	1	1
Decrease in life-time with temp.	1 ... 5	2	3	2	3	2	3	2	3	3	3	3	3
Max. ambient charge temperature	°C	40	60	40	60	40	60	40	50	40	50	40	60
Min. ambient discharge temperature	°C	-20	-30	-20	-30	-30	-40	-30	-40	-30	-40	-30	-40
Temp. increase during charging[c]	K @ 1.0 x C_{10}	5	10	5	10	5	10						
	K @ 100 x C_{10}							10	15	10	15	10	15
Recycling capability	1 ... 5	4	5	4	5	5	5	4	5	5	5	5	5
Greenhouse gas emissions[g]	1 ... 5												
Health & safety	1 ... 5	3	4	3	4	3	4	3	4	4	4	4	4
Maintenance	1 ... 5	3	4	4	5	4	5	4	5	4	5	4	5
Efforts for SOC & SOH monitoring	1 ... 5	3	4	3	4	3	4	3	4	3	4	4	4
Electronic efforts (charger, safety)	1 ... 5	4	5	4	5	4	5	4	5	4	5	4	5

Table A.2 *ST2: lithium batteries*

Parameter	Unit	Category 1						Category 2					
		today		in 5 years		future		today		in 5 years		future	
		min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.
Price[d] (energy)	Wh/€ [E_{100}]	0.7	1	3	4.5	4.5	6.7	0.7	1	3	4.5	4.5	6.7
Price[d] (power[e])	W/€ [E_{100}]	2	3	10	14	17	20	2	3	10	14	17	20
Energy efficiency[h]	%	98	99,9	98	99,9	98	99,9	97	99	97	99	97	99
Self discharge[b] @ 20°C	days/%	10	30	20	30	20	30	10	30	20	30	20	30
Gravimetric Energy density	Wh/kg [E_{100}]	140	180	140	200	140	210	140	180	140	200	140	210
Volumetric energy density	Wh/l [E_{100}]	280	400	280	420	280	450	280	400	280	420	280	450
Specific power[e]	W/Wh [E_{100}]	3	3	3	3	3	3	3	3	3	3	3	3
Time to full power[4]	1 ... 5	5	5	5	5	5	5	5	5	5	5	5	5
Cycle life @ 20°C @ 100% DOD	cycles	1,000	2,000	1,000	2,000	2,000	3,000	1,000	2,000	1,000	2,000	1,500	3,000
Cycle life @ 20°C @ 10% DOD	equiv. cycles[f]	50,000	80,000	80,000	100,000	100,000	150,000	50,000	80,000	80,000	100,000	100,000	150,000
Float life[a] @ 20°C (SOC = 90%)	years	5	15	5	15	5	20	5	15	5	15	5	20
Shelf life[b] @ 20°C	month	12	60	12	60	12	60	12	60	12	60	12	60
Decrease in life-time with temp.	1 ... 5	3	4	3	4	3	4	3	4	3	4	3	4
Max. ambient charge temperature	°C	50	70	50	70	50	70	50	70	50	70	50	70
Min. ambient discharge temperature	°C	-10	-20	-10	-20	-15	-20	-10	-20	-10	-20	-15	-20
Temp. increase during charging[c]	K @ 0.1 x C_{10}	0	0	0	0	0	0						
	K @ 0.2 x C_{10}							0	0	0	0	0	0
Recycling capability	1 ... 5	3	4	4	5	5	5	3	4	4	5	5	5
Greenhouse gas emissions[g]	1 ... 5												
Health & safety	1 ... 5	3	4	4	5	4	5	3	4	4	5	4	5
Maintenance	1 ... 5	5	5	5	5	5	5	5	5	5	5	5	5
Efforts for SOC & SOH monitoring	1 ... 5	4	4	4	5	5	5	4	4	4	5	5	5
Electronic efforts (charger, safety)	1 ... 5	4	4	4	5	5	5	4	4	4	5	5	5

Parameter	Unit	Category 3						Category 4					
		today		in 5 years		future		today		in 5 years		future	
		min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.
Price[d] (energy)	Wh/€ [E_1]	0.5	0.8	3	4	4	6	0.3	0.5	1.7	2	2.7	3.3
Price[d] (power[e])	W/€ [E_1]	3	5	16	22	27	31	5	6	30	40	60	70
Energy efficiency[h]	%	95	98	95	98	95	98	85	90	85	92	85	95
Self discharge[b] @ 20°C	days/%	10	30	20	30	20	30	10	30	20	30	20	30
Gravimetric Energy density	Wh/kg [E_1]	110	130	110	130	110	130	60	70	60	75	65	80
Volumetric energy density	Wh/l [E_1]	300	360	300	380	300	400	160	180	160	180	170	200
Specific power[e]	W/Wh [E_1]	6	6	6	6	6	6	15	15	15	15	15	15
Time to full power[4]		5	5	5	5	5	5	5	5	5	5	5	5
Cycle life @ 20°C @ 100% DOD	cycles	1,000	2,000	1,000	2,000	1,500	3,000	1,000	2,000	2,000	2,000	1,500	3,000
Cycle life @ 20°C @ 10% DOD	equiv. cycles[f]	50,000	80,000	80,000	100,000	100,000	150,000	70,000	100,000	100,000	200,000	200,000	300,000
Float life[a] @ 20°C (SOC = 90%)	years	5	15	5	15	5	20	5	15	5	15	5	20
Shelf life[b] @ 20°C	month	12	60	12	60	12	60	12	60	12	60	12	60
Decrease in life-time with temp.	1 ... 5	3	4	3	4	3	4	3	4	3	4	3	4
Max. ambient charge temperature	°C	50	70	50	70	50	70	50	70	50	70	50	70
Min. ambient discharge temperature	°C	-10	-20	-10	-20	-15	-20	-25	-20	-30	-20	-30	-20
Temp. increase during charging[c]	K @ 1.0 x C_{10}	1	1	1	1	1	1						
	K @ 100 x C_{10}												
Recycling capability	1 ... 5	3	4	4	5	5	5	3	4	4	5	5	5
Greenhouse gas emissions[g]	1 ... 5												
Health & safety	1 ... 5	3	4	4	5	4	5	3	4	4	5	4	5
Maintenance	1 ... 5	5	5	5	5	5	5	5	5	5	5	5	5
Efforts for SOC & SOH monitoring	1 ... 5	4	4	4	5	5	5	4	4	4	5	5	5
Electronic efforts (charger, safety)	1 ... 5	4	4	4	5	5	5	4	4	4	5	5	5

Table A.3 *ST3: Supercapacitors*

Parameter	Unit	Category 1						Category 2					
		today		in 5 years		future		today		in 5 years		future	
		min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.
Price[d] (energy)	Wh/€ [E_{100}]	0.007	0.02	0.007	0.02	0.007	0.02	0.007	0.02	0.007	0.02	0.007	0.02
Price[d] (power[e])	W/€ [E_{100}]	4	4	4	4	4	4	4	4	4	4	4	4
Energy efficiency[h]	%	84	99	84	99	84	99	84	99	84	99	84	99
Self discharge[b] @ 20°C	days/%	0.1	0.5	0.1	0.5	0.1	0.5	0.1	0.5	0.1	0.5	0.1	0.5
Gravimetric Energy density	Wh/kg [E_{100}]	0.5	5	0,5	10	0.5	10	0.5	5	0.5	10	0.5	10
Volumetric energy density	Wh/l [E_{100}]	6.5	6.5	6.5	6.5	6,5	6.5		6.5	6.5	6.5	6.5	6.5
Specific power[e]	W/Wh [E_{100}]	20	200	20	200	20	200	20	200	20	200	20	200
Time to full power[4]	1 ... 5	2	3	2	3	2	3	2	3	2	3	2	3
Cycle life @ 20°C @ 100% DOD	cycles	100,000	500,000	100,000	500,000	100,000	500,000	100,000	500,000	100,000	500,000	100,000	500,000
Cycle life @ 20°C @ 10% DOD	equiv. cycles[f]	100,000	500,000	100,000	500,000	100,000	500,000	100,000	500,000	100,000	500,000	100,000	500,000
Float life[a] @ 20°C (SOC = 90%)	years	10	10	10	10	10	10	10	10	10	10	10	10
Shelf life[b] @ 20°C	month												
Decrease in life-time with temp.	1 ... 5												
Max. ambient charge temperature	°C	70	70	70	70	70	70	70	70	70	70	70	70
Min. ambient discharge temperature	°C	-40	-40	-60	-40	-60	-40	-60	-40	-60	-40	-60	-40
Temp. increase during charging[c]	K @ $0.1 \times C_{10}$												
	K @ $0.2 \times C_{10}$												
Recycling capability	1 ... 5	4	5	4	5	4	5	4	5	4	5	4	5
Greenhouse gas emissions[g]	1 ... 5												
Health & safety	1 ... 5	4	5	4	5	4	5	4	5	4	5	4	5
Maintenance	1 ... 5	5	5	5	5	5	5	5	5	5	5	5	5
Efforts for SOC & SOH monitoring	1 ... 5	4	5	4	5	4	5	4	5	4	5	4	5
Electronic efforts (charger, safety)	1 ... 5	4	5	4	5	4	5	4	5	4	5	4	5

Parameter	Unit	Category 3						Category 4					
		today		in 5 years		future		today		in 5 years		future	
		min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.
Price[d] (energy)	Wh/€ [E_1]	0.007	0.02	0.007	0.02	0.007	0.02	0.007	0.02	0.007	0.08	0.007	0.16
Price[d] (power[e])	W/€ [E_1]	4	4	4	4	4	4	4	4	4	4	4	4
Energy efficiency[h]	%	84	99	84	99	84	99	84	99	84	99	84	99
Self discharge[b] @ 20°C	days/%	0.1	0.5	0.1	0.5	0.1	0,5	0.1	0.5	0.1	0.5	0.1	0.5
Gravimetric Energy density	Wh/kg [E_1]	0.5	5	0.5	10	0.5	10	0.5	5	0.5	10	0.5	10
Volumetric energy density	Wh/l [E_1]		6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
Specific power[e]	W/Wh [E_1]	20	200	20	200	20	200	20	20	20	20	20	20
Time to full power[4]		2		2	3	2	3	3	3	3	3	3	3
Cycle life @ 20°C @ 100% DOD	cycles	100,000	500,000	100,000	500,000	100,000	500,000						
Cycle life @ 20°C @ 10% DOD	equiv. cycles[f]	100,000	500,000	100,000	500,000	100,000	500,000	100,000	500,000	500,000	1,000,000	500,000	1,000,000
Float life[a] @ 20°C (SOC = 90%)	years	10	10	10	10	10	10	10	10	10	10	10	10
Shelf life[b] @ 20°C	month												
Decrease in life-time with temp.	1 ... 5												
Max. ambient charge temperature	°C	70	70	70	70	70	70	70	70	70	75	70	80
Min. ambient discharge temperature	°C	-60	-40	-60	-40	-60	-40	-60	-40	-60	-40	-60	-40
Temp. increase during charging[c]	K @ 1.0 x C_{10}												
	K @ 100 x C_{10}												
Recycling capability	1 ... 5	4	5	4	5	4	5	4	5	4	5	4	5
Greenhouse gas emissions[g]	1 ... 5												
Health & safety	1 ... 5	4	5	4	5	4	5	4	5	4	5	4	5
Maintenance	1 ... 5	5	5	5	5	5	5	5	5	5	5	5	5
Efforts for SOC & SOH monitoring	1 ... 5	4	5	4	5	4	5	4	5	4	5	4	5
Electronic efforts (charger, safety)	1 ... 5	4	5	4	5	4	5	4	5	4	5	4	5

Table A.4 *ST4: Nickel batteries*

Parameter	Unit	Category 1						Category 2					
		today		in 5 years		future		today		in 5 years		future	
		min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.
Price[d] (energy)	Wh/€ [E_{100}]	0.6	3.3	0.7	3.8	0.8	4.4	0.6	3.3	0.7	3.8	0.8	4.4
Price[d] (power[e])	W/€ [E_{100}]	1	10	1	10	1	10	1	10	1	10	1	10
Energy efficiency[h]	%	60	60	60	60	60	60	60	60	60	60	60	60
Self discharge[b] @ 20°C	days/%	1	1.5	1	1.5	1	1.5	1	1.5	1	1.5	1	1.5
Gravimetric Energy density	Wh/kg [E_{100}]	13	27	13	27	13	27	13	27	13	27	13	27
Volumetric energy density	Wh/l [E_{100}]	40	55	40	55	40	55	40	55	40	55	40	55
Specific power[e]	W/Wh [E_{100}]	2	14	2	14	2	14	2	14	2	14	2	14
Time to full power[4]	1 ... 5	4	4	4	4	4	4	4	4	4	4	4	4
Cycle life @ 20°C @ 100% DOD	cycles	800	1,200	800	1,200	800	1,200	800	1,200	800	1,200	800	1,200
Cycle life @ 20°C @ 10% DOD	equiv. cycles[f]	1,200	1,600	1,200	1,600	1,200	1,600	1,200	1,600	1,200	1,600	1,200	1,600
Float life[a] @ 20°C (SOC = 90%)	years	15	20	15	20			15	20	15	20		
Shelf life[b] @ 20°C	month	12	24	12	24	12	24	12	24	12	24	12	24
Decrease in life-time with temp.	1 ... 5	4	4	4	4	4	4	4	4	4	4	4	4
Max. ambient charge temperature	°C	45	60	45	60	45	60	45	60	45	60	45	60
Min. ambient discharge temperature	°C	-20	-40	-20	-40	-20	-40	-20	-40	-20	-40	-20	-40
Temp. increase during charging[c]	K @ 0.1 x C_{10}	1	3	1	3	1	3						
	K @ 0.2 x C_{10}							1	3	1	3	1	3
Recycling capability	1 ... 5	4	5	4	5	4	5	4	5	4	5	4	5
Greenhouse gas emissions[g]	1 ... 5												
Health & safety	1 ... 5	3	4	3	4	3	4	3	4	3	4	3	4
Maintenance	1 ... 5	3	4	3	4	3	4	3	4	3	4	3	4
Efforts for SOC & SOH monitoring	1 ... 5	3	4	3	4	3	4	3	4	3	4	3	4
Electronic efforts (charger, safety)	1 ... 5	3	4	3	4	3	4	3	4	3	4	3	4

Parameter	Unit	Category 3						Category 4					
		today		in 5 years		future		today		in 5 years		future	
		min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.
Price[d] (energy)	Wh/€ [E_1]	0.6	3.3	0.7	3.8	0.8	4.4	0.6	3.3	0.7	3.8	0.8	4.4
Price[d] (power[e])	W/€ [E_1]	1	10	1	10	1	10	1	10	1	10	1	10
Energy efficiency[h]	%	60	60	60	60	60	60	60	60	60	60	60	60
Self discharge[b] @ 20°C	days/%	1	1.5	1	1.5	1	1.5	0.03	0.067	0.03	0.067	2	14
Gravimetric Energy density	Wh/kg [E_1]	13	27	13	27	13	27	13	27	13	27	13	27
Volumetric energy density	Wh/l [E_1]	40	55	40	55	40	55	40	55	40	55	40	55
Specific power[e]	W/Wh [E_1]	2	14	2	14	2	14	2	14	2	14	2	14
Time to full power[4]													
Cycle life @ 20°C @ 100% DOD	cycles	800	1,200	800	1,200	800	1,200	800	1,200	800	1,200	800	1,200
Cycle life @ 20°C @ 10% DOD	equiv. cycles[f]	1,200	1,600	1,200	1,600	1,200	1,600	1,200	1,600	1,200	1,600	1,200	1,600
Float life[a] @ 20°C (SOC = 90%)	years	15	20	15	20			15	20	15	20		
Shelf life[b] @ 20°C	month	12	24	12	24	12	24	12	24	12	24	12	24
Decrease in life-time with temp.	1 ... 5	4	4	4	4	4	4	4	4	4	4	4	4
Max. ambient charge temperature	°C	45	60	45	60	45	60	45	60	45	60	45	60
Min. ambient discharge temperature	°C	-20	-40	-20	-40	-20	-40	-20	-40	-20	-40	-20	-40
Temp. increase during charging[c]	K @ 1.0 x C_{10}	1	3	1	3	1	3						
	K @ 100 x C_{10}							1	3	1	3	1	3
Recycling capability	1 ... 5	4	5	4	5	4	5	4	5	4	5	4	5
Greenhouse gas emissions[g]	1 ... 5												
Health & safety	1 ... 5	3	4	3	4	3	4	3	4	3	4	3	4
Maintenance	1 ... 5	3	4	3	4	3	4	3	4	3	4	3	4
Efforts for SOC & SOH monitoring	1 ... 5	3	4	3	4	3	4	3	4	3	4	3	4
Electronic efforts (charger, safety)	1 ... 5	3	4	3	4	3	4	3	4	3	4	3	4

Table A.5 *ST5: Electrolyser, Hydrogen storage and fuel cells*

Parameter	Unit	Category 1						Category 2					
		today		in 5 years		future		today		in 5 years		future	
		min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.
Price[d] (energy)	Wh/€ [E_{100}]							0.05	0.10	0.05	0.10	0.05	0.10
Price[d] (power[e])	W/€ [E_{100}]							0.10	0.17	0.10	0.17	0.10	0.17
Energy efficiency	%							25	45	25	45	25	45
Self discharge[b] @ 20°C	days/%							0.5	2	0.5	2	0.5	2
Gravimetric Energy density	Wh/kg [E_{100}]												
Volumetric energy density	Wh/l [E_{100}]												
Specific power[e]	W/Wh [E_{100}]												
specific power	W/kg												
Cycle life @ 20°C @ 100% DOD	cycles							100	150	100	150	100	150
Cycle life @ 20°C @ 10% DOD	equiv. cycles[f]							100	150	100	150	100	150
life time	years							2	2	2	2	2	2
Float life[a] @ 20°C	years							0,2	0,2	0,2	0,2	0,2	0,2
Shelf life[b] @ 20°C	month							1,000	1,000	1000	1,000	1,000	1,000
Decrease in life-time with temp.	1 ... 5							5		5		5	
Max. ambient charge temperature	°C							60		60		60	
Min. ambient discharge temperature	°C							0		0		0	
Temp. increase during charging[c]	K @ 0.1 x C_{10}												
	K @ 0.2 x C_{10}							0	10	0	10	0	10
Recycling capability	1 ... 5							4	5	4	5	4	5
Safety rating	1 ... 5							3	4	3	4	3	4
Maintenance	1 ... 5							3	4	3	4	3	4
Efforts for SOC & SOH monitoring	1 ... 5							4	4	4	4	4	4
Electronic efforts (charger, safety)	1 ... 5							3	4	3	4	3	4

Parameter	Unit	Category 3						Category 4					
		today		in 5 years		future		today		in 5 years		future	
		min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.
Price[d] (energy)	Wh/€ [E_1]												
Price[d] (power[e])	W/€ [E_1]												
Energy efficiency	%												
Self discharge[b] @ 20°C	days/%												
Gravimetric Energy density	Wh/kg [E_1]												
Volumetric energy density	Wh/l [E_1]												
Specific power[e]	W/Wh [E_1]												
specific power													
Cycle life @ 20°C @ 100% DOD	cycles												
Cycle life @ 20°C @ 10% DOD	equiv. cycles[f]												
life time	years												
Float life[a] @ 20°C	years												
Shelf life[b] @ 20°C	month												
Decrease in life-time with temp.	1 ... 5												
Max. ambient charge temperature	°C												
Min. ambient discharge temperature	°C												
Temp. increase during charging[c]	K @ 1.0 x C_{10}												
	K @ 100 x C_{10}												
Recycling capability	1 ... 5												
Safety rating	1 ... 5												
Maintenance	1 ... 5												
Efforts for SOC & SOH monitoring	1 ... 5												
Electronic efforts (charger, safety)	1 ... 5												

Table A.6 *ST6: Flywheels*

Parameter	Unit	Category 1						Category 2					
		today		in 5 years		future		today		in 5 years		future	
		min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.
Price[d] (energy)	Wh/€ [E_{100}]												
Price[d] (power[e])	W/€ [E_{100}]												
Energy efficiency[h]	%												
Self discharge[b] @ 20°C	days/%												
Gravimetric Energy density	Wh/kg [E_{100}]												
Volumetric energy density	Wh/l [E_{100}]												
Specific power[e]	W/Wh [E_{100}]												
Time to full power[4]	1 ... 5												
Cycle life @ 20°C @ 100% DOD	cycles												
Cycle life @ 20°C @ 10% DOD	equiv. cycles[f]												
Float life[a] @ 20°C (SOC = 90%)	years												
Shelf life[b] @ 20°C	month												
Decrease in life-time with temp.	1 ... 5												
Max. ambient charge temperature	°C												
Min. ambient discharge temperature	°C												
Temp. increase during charging[c]	K @ 0.1 x C_{10}												
	K @ 0.2 x C_{10}												
Recycling capability	1 ... 5												
Greenhouse gas emissions[g]	1 ... 5												
Health & safety	1 ... 5												
Maintenance	1 ... 5												
Efforts for SOC & SOH monitoring	1 ... 5												
Electronic efforts (charger, safety)	1 ... 5												

Parameter	Unit	Category 3						Category 4					
		today		in 5 years		future		today		in 5 years		future	
		min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.
Price[d] (energy)	Wh/€ $[E_1]$	0.1	0.5	1	1	1	1	0.02	0.05	0.1	0.1	0.1	0.1
Price[d] (power[e])	W/€ $[E_1]$	0,33	1	2	2	2	2	1	13	20	20	20	20
Energy efficiency[h]	%	80	92	85	95	85	95	80	92	85	95	85	95
Self discharge[b] @ 20°C	days/%	0.02	0.02	0.03	0.03	0.3	0.6	0.0002	0.02	0.03	0.03	0.3	0.6
Gravimetric Energy density	Wh/kg $[E_1]$	7.5	7.5	10	10	10	10	1.2	1.5	5	5	5	5
Volumetric energy density	Wh/l $[E_1]$	10	10	15	15	15	15	0,7	2	7,5	7,5	7,5	7,5
Specific power[e]	W/Wh $[E_1]$	0.33	0.33	0.1	0.33	0.05	2	10	200	10	1,000	10	1,000
Time to full power[4]	1 ... 5	5	5	5	5	5	5	5	5	5	5	5	5
Cycle life @ 20°C @ 100% DOD	cycles	50,000	100,000	100,000	1,000,000	1E+06	1E+06	500,000	1E+07	1,000,000	1E+07	1,000,000	1E+07
Cycle life @ 20°C @ 10% DOD	equiv. cycles[f]	50,000	100,000	100,000	100,0000	1E+06	1E+06	500,000	1E+07	1,000,000	1E+07	1,000,000	1E+07
Float life[a] @ 20°C (SOC = 90%)	years	20	20	20	20	20	20	20	20	20	20	20	20
Shelf life[b] @ 20°C	month	0.0007	0.0007	0.001	0.001	0.01	0.02	0.000007	0.0007	0.001	0.001	0.01	0.02
Decrease in life-time with temp.	1 ... 5	5	5	5	5	5	5	5	5	5	5	5	5
Max. ambient charge temperature	°C	40	40	40	40	40	40	40	40	40	40	40	40
Min. ambient discharge temperature	°C	-20	-20	-20	-20	-20	-20	-20	-20	-20	-20	-20	-20
Temp. increase during charging[c]	K @ 1.0 x C_{10}	1	1	1	1	1	1						
	K @ 100 x C_{10}							1	1	1	1	1	1
Recycling capability	1 ... 5	4	4	5	5	5	5	4	4	5	5	5	5
Greenhouse gas emissions[g]	1 ... 5												
Health & safety	1 ... 5	5	5	5	5	5	5	5	5	5	5	5	5
Maintenance	1 ... 5	5	5	5	5	5	5	5	5	5	5	5	5
Efforts for SOC & SOH monitoring	1 ... 5	5	5	5	5	5	5	5	5	5	5	5	5
Electronic efforts (charger, safety)	1 ... 5	4	4	5	5	5	5	4	4	5	5	5	5

Table A.7 *ST7: Redox flow batteries*

Parameter	Unit	Category 1						Category 2					
		today		in 5 years		future		today		in 5 years		future	
		min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.
Price[d] (energy)	Wh/€ [E_{100}]												
Price[d] (power[e])	W/€ [E_{100}]												
Energy efficiency[h]	%												
Self discharge[b] @ 20°C	days/%												
Gravimetric Energy density	Wh/kg [E_{100}]												
Volumetric energy density	Wh/l [E_{100}]												
Specific power[e]	W/Wh [E_{100}]												
Time to full power[4]	1 ... 5												
Cycle life @ 20°C @ 100% DOD	cycles												
Cycle life @ 20°C @ 10% DOD	equiv. cycles[f]												
Float life[a] @ 20°C (SOC = 90%)	years												
Shelf life[b] @ 20°C	month												
Decrease in life-time with temp.	1 ... 5												
Max. ambient charge temperature	°C												
Min. ambient discharge temperature	°C												
Temp. increase during charging[c]	K @ 0.1 x C_{10}												
	K @ 0.2 x C_{10}												
Recycling capability	1 ... 5												
Greenhouse gas emissions[g]	1 ... 5												
Health & safety	1 ... 5												
Maintenance	1 ... 5												
Efforts for SOC & SOH monitoring	1 ... 5												
Electronic efforts (charger, safety)	1 ... 5												

Parameter	Unit	Category 3						Category 4					
		today		in 5 years		future		today		in 5 years		future	
		min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.
Price[d] (energy)	Wh/€ [E_1]	1	2,8	1	2,8	1	2,8	0,001	0,001	0,001	0,001	0,001	0,001
Price[d] (power[e])	W/€ [E_1]	0.34	0.91	0.34	0.91	0.34	0.91	0.34	0.91	0.34	0.91	0.34	0.91
Energy efficiency[h]	%	70	80	70	80	70	80	70	80	70	80	70	80
Self discharge[b] @ 20°C	days/%	10	10	10	10	10	10	10	10	10	10	10	10
Gravimetric Energy density	Wh/kg [E_1]	17	35	17	35	17	35	17	35	17	35	17	35
Volumetric energy density	Wh/l [E_1]	15	28	15	28	15	28	15	28	15	28	15	28
Specific power[e]	W/Wh [E_1]	5.8824	5.88	5.8824	5.88	5.8824	5.88	5.8824	5.88	5.8824	5.88	5,8824	5.88
Time to full power[4]		3	5	3	5	3	5	3	5	3	5	3	5
Cycle life @ 20°C @ 100% DOD	cycles	12,000	12,000	12,000	12,000	12,000	12,000	12,000	12,000	12,000	12,000	12,000	12,000
Cycle life @ 20°C @ 10% DOD	equiv. cycles[f]	12,000	12,000	12,000	12,000	12,000	12,000	12,000	12,000	12,000	12,000	12,000	12,000
Float life[a] @ 20°C (SOC = 90%)	years	5	15	5	15	5	15	5	15	5	15	5	15
Shelf life[b] @ 20°C	month	24	24	24	24	24	24	24	24	24	24	24	24
Decrease in life-time with temp.	1 ... 5												
Max. ambient charge temperature	°C	45	45	45	45	45	45	45	45	45	45	45	45
Min. ambient discharge temperature	°C	5	5	5	5	5	5	5	5	5	5	5	5
Temp. increase during charging[c]	K @ 1.0 x C_{10}	0	0	0	0	0	0						
	K @ 100 x C_{10}							0	0	0	0	0	0
Recycling capability	1 ... 5	2	3	2	3	2	3	2	3	2	3	2	3
Greenhouse gas emissions[g]	1 ... 5												
Health & safety	1 ... 5	4	4	4	4	4	4	4	4	4	4	4	4
Maintenance	1 ... 5	4	4	4	4	4	4	4	4	4	4	4	4
Efforts for SOC & SOH monitoring	1 ... 5	4	4	4	4	4	4	4	4	4	4	4	4
Electronic efforts (charger, safety)	1 ... 5	4	5	4	5	4	5	4	5	4	5	4	5

Table A.8 *ST8: Pneumatic storage*

Parameter	Unit	Category 1						Category 2					
		today		in 5 years		future		today		in 5 years		future	
		min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.
Price[d] (energy)	Wh/€ [E_{100}]							0.58	9.86	0.58	9.86	0.58	9.86
Price[d] (power[e])	W/€ [E_{100}]							0.29	0.82	0.29	0.82	0.29	0.82
Energy efficiency	%							55	72	63	78	72	88
Self discharge[b] @ 20°C	days/%							0.119	0.119	0.27	0.27	0.41	0.41
Gravimetric Energy density	Wh/kg [E_{100}]							21	45	27	50	27	50
Volumetric energy density	Wh/l [E_{100}]							16	16	18	18	18	18
Specific power[e]	W/Wh [E_{100}]							0.1	0.1	0.1	0.1	0.1	0.1
Cycle life @ 20°C @ 100% DOD	cycles							15,000	99,000	15,000	99,000	15,000	99,000
Cycle life @ 20°C @ 10% DOD	equiv. cycles[f]												
Float life[a] @ 20°C	years							20	20	20	20	20	20
Shelf life[b] @ 20°C	month							99,999	99,999	99,999	99,999	99,999	99,999
Decrease in life-time with temp.	1 ... 5							5	5	5	5	5	5
Max. ambient charge temperature	°C							70	70	70	70	70	70
Min. ambient discharge temperature	°C							80	80	80	80	80	80
Temp. increase during charging[c]	K @ 0.1 x C_{10}												
	K @ 0.2 x C_{10}							18	25	18	25	18	25
Recycling capability	1 ... 5							5	4	5	4	5	4
Safety rating	1 ... 5							3	4	3	4	3	4
Maintenance	1 ... 5							3	4	3	4	3	4
Efforts for SOC & SOH monitoring	1 ... 5							5	5	5	5	5	5
Electronic efforts (charger, safety)	1 ... 5							5	5	5	5	5	5

Parameter	Unit	Category 3						Category 4					
		today		in 5 years		future		today		in 5 years		future	
		min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.
Price[d] (energy)	Wh/€ [E_{100}]	9,174	9,174	9,174	9,174	9,174							
Price[d] (power[e])	W/€ [E_{100}]	4,587	4,587	4,587	4,587	4,587							
Energy efficiency	%	55	72	63	78	72							
Self discharge[b] @ 20°C	days/%	0.06	0.06	0.14	0.14	0.2							
Gravimetric Energy density	Wh/kg [E_1]	19	42	25	47	25							
Volumetric energy density	Wh/l [E_1]	13	13	15	15	15							
Specific power[e]	W/Wh [E_1]	2	2	2	2	2							
Cycle life @ 20°C @ 100% DOD	cycles	15,000	99,000	15,000	99,000	15,000							
Cycle life @ 20°C @ 10% DOD	equiv. cycles[f]												
Float life[a] @ 20°C	years	20	20	20	20	20							
Shelf life[b] @ 20°C	month	99,999	99,999	99,999	99,999	99,999							
Decrease in life-time with temp.	1 ... 5	5	5	5	5	5							
Max. ambient charge temperature	°C	70	70	70	70	70							
Min. ambient discharge temperature	°C	80	80	80	80	80							
Temp. increase during charging[c]	K @ 1.0 x C_{10}	40	47	40	47	40							
	K @ 100 x C_{10}												
Recycling capability	1 ... 5	5	4	5	4	5							
Safety rating	1 ... 5	3	4	3	4	3							
Maintenance	1 ... 5	3	4	3	4	3							
Efforts for SOC & SOH monitoring	1 ... 5	5	5	5	5	5							
Electronic efforts (charger, safety)	1 ... 5	5	5	5	5	5							

Table A.9 *ST9: Metal air batteries*

Parameter	Unit	Category 1						Category 2					
		today		in 5 years		future		today		in 5 years		future	
		min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.
Price[d] (energy)	Wh/€ $[E_{100}]$	10	10	100	100	100	100	10	10	100	100	100	100
Price[d] (power[e])	W/€ $[E_{100}]$	5	5	20	20	20	20	5	5	20	20	20	20
Energy efficiency[h]	%	50	60	60	70	70	80	50	60	60	70	70	80
Self discharge[b] @ 20°C	days/%	30	40	60	70	70	80	30	40	60	70	70	80
Gravimetric Energy density	Wh/kg $[E_{100}]$	80	120	80	200	80	200	80	120	80	200	80	200
Volumetric energy density	Wh/l $[E_{100}]$	60	80	70	80	70	100	60	80	70	80	70	100
Specific power[e]	W/Wh $[E_{100}]$												
Time to full power[4]	1 ... 5												
Cycle life @ 20°C @ 100% DOD	cycles												
Cycle life @ 20°C @ 10% DOD	equiv. cycles[f]	30	50	50	60	70	80	30	50	50	60	70	80
Float life[a] @ 20°C (SOC = 90%)	years												
Shelf life[b] @ 20°C	month	100	100	100	100	100	100	100	100	100	100	100	100
Decrease in life-time with temp.	1 ... 5	4	4	5	5	5	5	4	4	5	5	5	5
Max. ambient charge temperature	°C	100	100	100	100	100	100	100	100	100	100	100	100
Min. ambient discharge temperature	°C	-20	-20	-20	-20	-20	-20	-20	-20	-20	-20	-20	-20
Temp. increase during charging[c]	K @ 0.1 x C_{10}	20	20	10	10	10	10						
	K @ 0.2 x C_{10}							20	20	10	10	10	10
Recycling capability	1 ... 5	5	5	5	5	5	5	5	5	5	5	5	5
Greenhouse gas emissions[g]	1 ... 5												
Health & safety	1 ... 5	3	3	4	4	4	4	3	3	4	4	4	4
Maintenance	1 ... 5	3	3	4	4	4	4	3	3	4	4	4	4
Efforts for SOC & SOH monitoring	1 ... 5	3	3	4	4	4	4	3	3	4	4	4	4
Electronic efforts (charger, safety)	1 ... 5	3	3	5	5	5	5	3	3	5	5	5	5

Parameter	Unit	Category 3						Category 4					
		today		in 5 years		future		today		in 5 years		future	
		min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.
Price[d] (energy)	Wh/€ [E_1]	10	10	100	100	100	100	10	10	100	100	100	100
Price[d] (power[e])	W/€ [E_1]	5	5	20	20	20	20	5	5	20	20	20	20
Energy efficiency[h]	%	50	60	60	70	70	80	50	60	60	70	70	80
Self discharge[b] @ 20°C	days/%	30	40	60	70	70	80	30	40	60	70	70	80
Gravimetric Energy density	Wh/kg [E_1]	80	120	80	200	80	200	80	120	80	200	80	200
Volumetric energy density	Wh/l [E_1]	60	80	70	80	70	100	60	80	70	80	70	100
Specific power[e]	W/Wh [E_1]												
Time to full power[4]													
Cycle life @ 20°C @ 100% DOD	cycles												
Cycle life @ 20°C @ 10% DOD	equiv. cycles[f]	30	50	50	60	70	80	30	50	50	60	70	80
Float life[a] @ 20°C (SOC = 90%)	years												
Shelf life[b] @ 20°C	month	100	100	100	100	100	100	100	100	100	100	100	100
Decrease in life-time with temp.	1 ... 5	4	4	5	5	5	5	4	4	5	5	5	5
Max. ambient charge temperature	°C	100	100	100	100	100	100	100	100	100	100	100	100
Min. ambient discharge temperature	°C	-20	-20	-20	-20	-20	-20	-20	-20	-20	-20	-20	-20
Temp. increase during charging[c]	K @ 1.0 x C_{10}	20	20	10	10	10	10						
	K @ 100 x C_{10}							20	20	10	10	10	10
Recycling capability	1 ... 5	5	5	5	5	5	5	5	5	5	5	5	5
Greenhouse gas emissions[g]	1 ... 5												
Health & safety	1 ... 5	3	3	4	4	4	4	3	3	4	4	4	4
Maintenance	1 ... 5	3	3	4	4	4	4	3	3	4	4	4	4
Efforts for SOC & SOH monitoring	1 ... 5	3	3	4	4	4	4	3	3	4	4	4	4
Electronic efforts (charger, safety)	1 ... 5	3	3	5	5	5	5	3	3	5	5	5	5