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Optimizing a Hybrid Energy Storage System for a Virtual Power Plant for Improved Wind Power Generation: A Case Study for Denmark

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Abstract—This paper describes one approach to find two optimum energy storages (ESs) to build a hybrid system which is part of a virtual power plant. In this paper it means the combination of the hybrid energy storage system and wind power plant (WPP). The discussed approach is applied in a case study on the power market in western Denmark. The optimum ESs are selected based on the highest net present value (NPV) out of many different combinations of ESs in terms of power rating and technologies. Due to its many possible combinations a simulation model has been built which uses historical market data and also the latest available price data for ESs.

Index Terms—Virtual power plant, hybrid energy storage, wind power, sizing energy storage

1. INTRODUCTION

In the last couple of years wind power penetration rates have been increasing all over Europe and the EU renewable directive [1] is even demanding for even higher rates of renewable power generation until 2020. One important source of renewable power generation is wind power and its share is expected to grow further in the future [2]. This also means that there will be more fluctuating power generation sources in the grid due to the intermittency of wind power and other renewable generation sources. Possibilities to overcome this problem are to increase transmission capacities, demand side management, increased flexibility of conventional power plants, and electricity energy storages (ESs) [3]. The focus of this paper is on ESs connected to wind power plants further called virtual power plant (VPP). The VPP should bring wind power as close as possible to the characteristics of conventional generation units in order to make wind power a more valuable source of energy. For this study Denmark was selected as a demonstration country as it already has a high share of wind power penetration with a strong increase expected for the future. Already today, an average of 25% of the electricity consumption of Denmark is produced by means of wind power [4]. This ratio is expected to further increase in the future [2].

The ES enables that a VPP can be used to provide a range of applications like:

- Forecast accuracy improvement
- Grid frequency regulation
- Energy arbitrage
- Ramp rate reduction
- Transmission line upgrade deferral
- Etc (for more applications see [5])

Each application has its specific requirements on the energy storage. Some applications require high power to energy ratios and others require the opposite. Usually, one ES is dedicated to one application. In this paper a design for a VPP is proposed with two different ES technologies, each suitable for one application. By using the two ES in an interactive manner it is expected that higher revenues are obtained compared to two independent operated ESs. The combination of two ESs is further called hybrid ES. Due to the fact that ESs are expensive devices, a simulation tool was developed to find the two optimum ESs in terms of size and technology for the VPP that can generate the highest NPV. Also, the added value of an interactive hybrid ES system is assessed compared to a stand-alone case.

An overview of the approach applied in this study is given in Figure 1. The first step is to find two applications with the

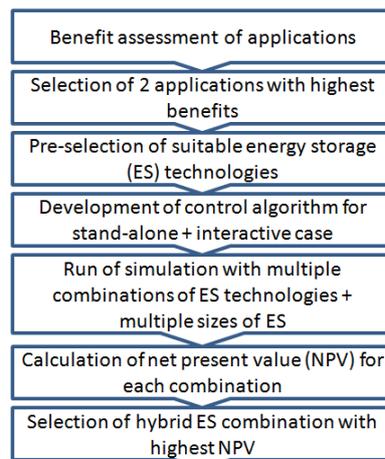


Figure 1: Approach of finding optimum ES storages for hybrid model

highest benefits under present market rules in Denmark (see chapter 2). Data used for the simulation are from 2010 and they are for West Denmark.

Eastern Denmark has not been analyzed yet as that would extend the scope of this paper. In the next step, proper ESs for the VPP are preselected in order to narrow down the selection (chapter 3).

Furthermore, a control algorithm that can operate both ESs interactively was developed; when one ES is idling it can support the other one. The control algorithm is implemented in a simulation model that includes all relevant input information. The model is run with multiple combinations of ES technologies in order to assess which combination yields the highest NPV. Details about the simulation model and the implemented control algorithm are provided in chapter 4 and 5, respectively. Chapter 6 shows the results of the simulation and in chapter 7 conclusions are drawn.

2. DANISH MARKET FOR POWER SYSTEM APPLICATIONS OF ENERGY STORAGES

The first part of this section describes the current regulatory framework of the western Danish power market, also called DK1. The second part discusses the benefit assessment of different applications in this market area.

2.1. Regulations for Storage Applications in Denmark

Regulations are only described in detail for which money is paid or costs can be reduced. These are forecast accuracy improvement, PFR and energy arbitrage in DK 1. Regulations regarding ancillary services in Denmark are described in detail in [6]. Secondary and tertiary regulations are not included in the assessment because secondary regulation is bought on monthly bases and tertiary frequency regulation requires a minimum power rating of 10MW. Both conditions make it unsuitable to use ESs for these applications.

2.1.1. Forecast accuracy improvement (FI): Forecast accuracy improvement means revenues generated by less costs for balancing power due to a better match of forecasted and actual production. Costs for balancing can be seen as a penalty which can be reduced by using ES. In general, every party which operates consumption units or production plants have to predict their consumption or production prior to each operational hour. However, production or consumption may deviate any time from the schedule as it frequently happens with wind power plants, for instance. In the case of deviation the so called balancing responsible parties need to buy balancing power from the Elbas market. More information about the balancing market and balancing prices can be found in [7] and [8].

2.1.2. Primary frequency regulation (PFR): PFR is bought in blocks of 4h on the day before. The minimum required power rating of a unit is 0.3MW. Upward and downward regulation are treated differently, there are two different prices. The energy storage can participate in the market for up and down regulation at the same time. In this market the last accepted bid sets the price for all other units which had cheaper offers. Prices are provided by [8]. PFR requires that within 15s half of the bid power must be available and the full amount must be available after 30s. This services must be provided based upon own measurements as soon as the frequency deviates more than $\pm 20\text{mHz}$ around the reference frequency of 50Hz. The required power output depends on the deviation and must be linearly increased between $\pm 20\text{mHz}$ and $\pm 200\text{mHz}$. If the energy storage is operated for more than 15 consecutive minutes it has the right for a 15min break to re-charge or discharge.

2.1.3. Energy arbitrage: For this application there is no regulation as such available because it is purely based on the difference of spot market prices. In periods when prices are low (during the night) the ES is charged and it is discharged in high-price periods during the day.

2.2. Application Specific Benefits in West Denmark

This section provides the benefit assessment of each previously analysed application.

2.2.1. FI: According to regulations, any time an imbalance occurs during one hour balancing power needs to be procured. This means that for any given hour in which the actual production deviates from the forecasted wind power production this amount of balancing power needs to be bought on the Elbas market. If the production is on average higher, downward balancing power has to be bought or vice versa. The costs for balancing power (up- and downward) are cumulated at the end of the period of interest. These cumulated costs could be reduced if an unlimited ES were applied. Hence, the cumulated costs for balancing are the maximum benefits that can be achieved with FI. In this paper, the benefits are calculated based on Danish wind production data of a 2MW turbine for the year 2010. Due to unavailability of forecasted wind power production data an artificial forecast is generated with a random forecast error of 10% of energy on average. As discussed in [9], 10% is a reasonable forecast error for a forecast of 12 to 36 hours ahead. In total, FI has maximum benefits of 45 055€ for a 2MW WPP for 2010.

2.2.2. PFR: It is assumed that a 1MW ES participates in every block in the market for upwards and downwards regulation. This approach enables that market prices for each block can simply be accumulated. Moreover, it is assumed that the energy storage does not need to be dis-/charged with power from the balancing market if the storage reaches saturation.

2.2.3. Energy arbitrage: To calculate the benefits for this application three hypothetical ESs having 1MW power and 2h, 4h, and 10h discharge time are assumed. A 90% round-trip efficiency was considered. Furthermore, perfect foresight is assumed that means that spot market prices are known in advance. Also, the price-taker assumption is underlying this calculation. Based on these assumptions the cumulated revenues are calculated for each storage for the year 2010. More information about assessing the benefits for energy arbitrage can be found in [10].

2.2.4. Results of benefit assessment: The results of the

Application	Benefits [€]
2h arbitrage	14 899
4h arbitrage	23 632
10h arbitrage	32 160
PFR	324 641
FI	45 055*

Table 1: Results benefit assessment (*For 2MW WPP)

benefit assessment are provided in Table 1. PFR has clearly the highest benefits followed by FI. Energy arbitrage yields comparable little benefits. A storage with higher discharge times has higher benefits,

though doubling the storage size generates less than twice the benefits. Based on the results the two selected applications for the hybrid ES system are PFR and FI.

	Costs for power	Costs for energy	Lifetime	Power to energy ratio	Efficiency	Power/capacity decoupling
Unit	€/kW	€/kWh	[No. of cycles]		[%]	-
VRB	2491 ¹	498 ¹	10000 ¹	0.15 ¹	70 ^{1*}	YES
ZnBr battery	1172 ¹	234 ¹	2000 ⁴	0.2 ¹	70 ^{1*}	YES
Li-ion type 1	920 ¹	3680 ¹	12000 ¹	4 ¹	86	NO
Li-ion type 2	500 ¹	2000 ¹	4000 ¹	4 ¹	90	YES
Ni/Cd	684 ³	2736 ³⁺¹⁰	2000 ³	4 ¹⁰	65 ³	NO
Lead acid	2000 ¹	492 ¹	2200 ¹	0.25 ¹	80 ⁶	NO
NaS	2345 ¹	392 ¹	4500 ¹	0.15 ¹	80 ¹	NO
Flywheel	437 ²	1165 ²	25000 ²	4 ¹	93 ^{1*}	YES
Supercapacitor	616 ⁹	78884 ⁹	1000000 ⁷	128 ⁸	95 ³	NO

Table 2: Overview of ES technologies used for analyses. Sources: ¹[11], ²[12], ³[13], ⁴[14], ⁵[15], ⁶[16], ⁷[17], ⁸[18], ⁹[19], ¹⁰[20], *Assumed power to energy ratio (Exchange rate \$/€: 1.35)

3. OVERVIEW OF STORAGE TECHNOLOGIES

This chapter provides an overview of the current state of the of art ES technologies that are used for power system applications. Due to geographical restrictions hydro-pumped and compressed air energy storages are excluded from further analyses. Also, superconducting magnetic energy storage is not considered because it has very short discharge times of a few seconds and is mainly applied to support voltage stability [21]. All other storage technologies listed below with examples for applications. These are included in the simulation and Table 2 provides an overview over the different ES parameters.

- Vanadium Redox Battery (VRB): The advantage of this technology is the separation of power and capacity. Plants have been built up to 5MWh and 3MW [22].
- Li-Ion batteries: The currently largest li-ion battery station was built on a ridge of Laurel Mountain in West Virginia. It is a capacity of 32MW and is build next to a wind farm. It is based in the PJM market area [23].
- Lead-acid batteries: The largest battery system for energy management applications is installed in Chino, California and has 10MW/40MWh [22]. They can be applied for power quality services, uninterrupted power supply, and for spinning reserve applications [22].
- NaS batteries: The largest installation has 34MW and is located in Japan alongside a 51MW wind farm [24].
- Flywheels: A 20MW flywheel energy storage is in

operation in the state of New York, US [25]. Flywheels are usually used for regulation services and for uninterrupted power supply [26].

- Supercapacitors: So far no commercial application of supercapacitors in power system ESs could be found in the sighted literature [27] but they are included in the analyses because of their comparable low costs for power, high round-trip efficiency, high life-cycle time.
- Zinc-Bromine (ZnBr): Small storages were installed in Australia as an alternative to install new transmission lines.

Test projects with bigger storage sizes are expected to be installed soon. [11]

4. SIMULATION MODEL

As mentioned before, the objective of the simulation model is to find two optimum ESs for the hybrid ES system. Optimum refers to the size and technology of the two single ESs. The selection is based on the highest NPV that can be achieved for the test over a given project period. All inputs into the model are described in section 4.1. A flow chart of the simulation model is depicted in Figure 2. For each simulation run a different combination of ESs is chosen. The control algorithm operates both energy storages in an interactive manner considering limitations like size and round trip efficiency. The control algorithm is described in detail in section 5. The outputs of the control block are the mission profiles of both ESs, the information about the chosen ESs in each run, the power and energy rating of both storages, and the cumulated revenues. The mission profiles are handed over to the life-time model which calculates the loss of life-time for the test period of one year. Then the loss of life-time is extrapolated in order to calculate the life-time in years which each energy storage is expected to have for the given mission profile. The information of the storage life-times plus the remaining outputs of the control algorithm block are put into the NPV calculator which computes the overall NPV for the whole system over a project period of 20 years.

4.1. Input Data

The following input data were used for the simulation model:

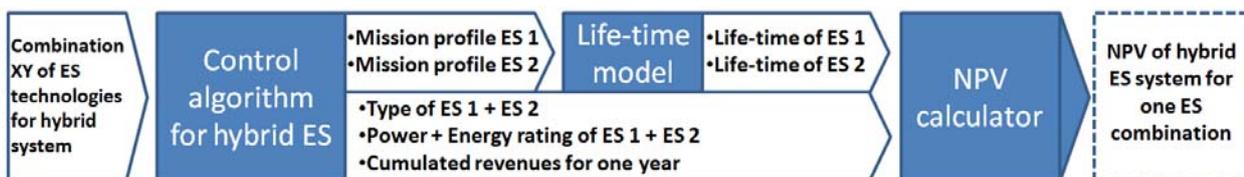


Figure 2: Flow chart of the simulation model

- Wind production data for a 2MW turbine in Denmark from the year 2010
- Frequency data of the ENTSO-E system provided for a one year period beginning with July 2010. These data were adjusted to match with the wind power production during the year 2010. It is assumed that the grid frequency in the whole ENTSO-E system is not influenced by the wind power production of western Denmark. This assumption allows to use the frequency data for a different period than they are originally from.
- Spot market and Elbas (up and down) balancing market prices for West Denmark for the year 2010 [8].
- Market prices for PFR for West Denmark for the year 2010 [8].
- ES data from Table 2

4.1.1. Wind Power Forecast:

Due to the unavailability of forecasted wind power data corresponding to the 2 MW wind power production data, artificial forecast of wind power data was generated. The methodology in creating this data is the following: to the available wind power data a forecast error is added or subtracted. The error has two components: the systematic component and the stochastic component. The systematic component of the forecast error is obtained based on the variation of the forecast error over a 36 hours period in the case of a statistical wind power prediction model, described in [28].

The reason for choosing this time frame is that the wind power predictions are made at maximum 36 hours ahead. Over each 36 hours period the systematic forecast error is increasing, reaching a 10 % value of the nominal wind power at the end of the 36 hours. The stochastic component of the forecasted wind power production is following a Gaussian distribution, and can account up to 5 % of the nominal wind power. The error – composed of the two, previously mentioned components – is added or subtracted of the wind power production. During every 3 hours, the same wind power prediction trend is kept, meaning that if, for example, at the beginning of the interval there is an overestimation of the wind power production, this will continue until the 3 hours have passed. Later, for the next three hours interval, the trend has 50% probability to change.

4.2. Model for Energy Storages

A general model was used for simulating all ES technologies presented in Table 2. The input to the model is the power request that is calculated by the controller (section 5). Outputs are the current value of SOC, power, total energy throughput and cumulative energy lost in storage due to losses during dis-/charging. Technology specific properties of the ES are represented in the model by different values of the round-trip efficiency, maximum power limitation and appropriate power to energy ratio.

4.3. Life-time Calculation Algorithm

This section describes the ES life-time calculation algorithm that is implemented in the block “life-time model” in Figure 2. Based on the inputs – which are SOC profiles of each ES – the block calculates the expected life-time of the ESs by applying the rainflow-counting algorithm [29]. The algorithm is not only able to count the number of cycles, but also separates them according to their magnitude. This algorithm is applied on all ES technologies except supercapacitors and flywheels due to their very high cycle life (compare Table 2). For these two technologies a life-time of 10 years is assumed. For the other ES technologies a calendar life-time of six years is assumed.

The calculation of the expected life-time in years with the rainflow-counting algorithm involves a number of steps. The first step is represented by the extraction of the number of cycles and their depths-of-discharge (DOD's) from the state of charge signals for each ES for an entire year. The second step consists of assigning a weighting factor to each extracted cycle, based on the DOD of the cycle. The weighting factors are assigned based on lifetime graphs obtained from battery manufacturers. These graphs are representing the number of cycles as a function of the depth of discharge. For instance, in the case of the type 1 lithium ion battery technology one 100% DOD cycle is weighing around 541 times more than one 5% DOD cycle, meaning that a cell is expected to have a much shorter lifetime in case it is subjected only to 100% DOD cycles, compared to a cell subjected to only 5% DOD cycles.

Finally, weight factors corresponding to cycles and their DODs are integrated during whole year and are juxtaposed with the total sum of weights which ES can handle during its lifetime. Comparison yields the approximated ES life in years.

4.4. Selection of Optimum Hybrid ES System

The profitability of the hybrid energy storage system is calculated for a 20 year period based on the NPV. This period was chosen because it is the expected life-time of a wind turbine. The NPV is assessed for both storages without taking the wind turbine into account because the ESs are an additional investment which can be made independently of the turbine and thus has to pay off for itself. The fact that the WPP's investment costs are not considered does not interfere with the operation of the storage that allows to act as a unit together with the wind turbine (e.g. for FI). In case the ES' life-time is less than 10years, it is assumed that it can be decommissioned without any costs and that it will be replaced with a new ES for the same costs as for the first ES. This approach was chosen based on the assumption that price increases due to inflation will be compensated by advances in technology development which will result in lower prices.

5. HYBRID ES CONTROL ALGORITHM

This section presents an energy management approach for a hybrid ES system for stand-alone and interactive operation. The goal of the energy management system is to control the hybrid storage system in order to assure that applications are

provided properly, calculate proper power signals for both storages and maximize income. The flow chart of the interactive control algorithm is presented in Figure 3. In the stand-alone case ES1 (providing FI) is working independently of ES2 used for PFR. In the interactive case ES2 is supporting ES1 with FI application during a 15 minutes time period which it has for restabilising its operating point. It will be further demonstrated in section 6 that higher revenues and higher NPV can be achieved with the interactive control algorithm.

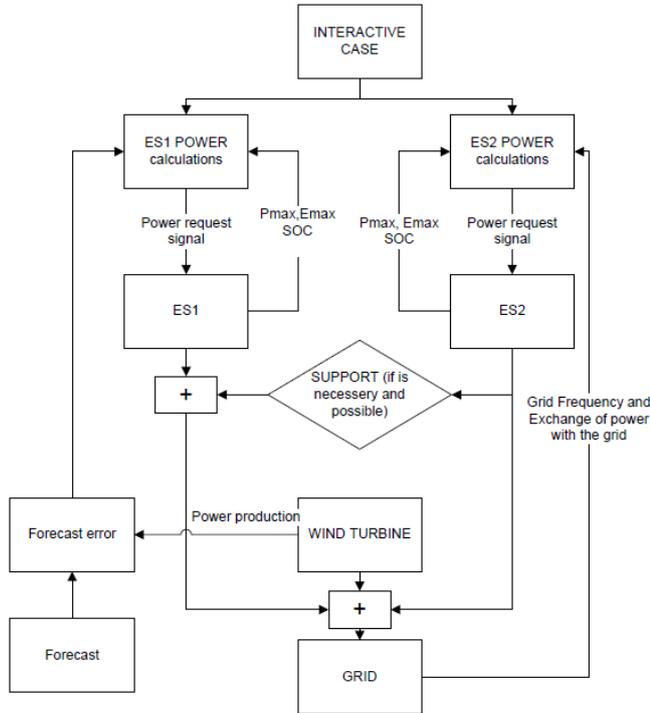


Figure 3 Flow chart of the interactive control algorithm.

ES1 is providing FI service by charging in case of under forecasting or discharging when forecast power is higher than power produced by the wind turbine. This allows for avoiding wind power curtailment in under forecasting scenario or allows for decreasing the amount of energy which otherwise would have to be bought on Elbas market.

ES2 is responsible for PFR in both upward and downward direction. 50% SOC was chosen as a base point for bidirectional frequency support. The power provided by the storage is dependent on the magnitude of frequency deviation and is adjusted linearly between $\pm 20\text{mHz}$ and $\pm 200\text{mHz}$. After 15 consecutive minutes ES has a right for 15 min to re-establish its SOC. In the stand-alone case the ES is restabilising SOC to 50% immediately when 15min break time is started. However, in the interactive case, the controller first checks how much time ES2 needs for restabilising its SOC. If this time is longer than the remaining break time, then ES2 is supporting ES1 with FI. Depending on the operational condition, the required power for ES2 SOC restabilising could be gained by supporting ES1. This is the case if ES2 has to be recharged and ES1 needs to be discharged or vice versa, otherwise power has to be bought on the Elbas market.

6. RESULTS OF SIMULATION

Due to the fact that the model is computational intensive, only a limited amount of runs could be tested. For this reason the NPV in step 1 and step 2 are calculated only for the interactive case. After the ten best combinations are defined the simulation will be run again for these cases in order to define the NPV for the stand-alone case. In the following each step is explained in detail to find the optimum pair of ESs with the highest NPV.

	ES FI power	ES FI energy	ES PFR power	ES PFR energy	Type ES FI	Type ES PFR	NPV	Income*	Life-time ES FI	Life-time ES PFR	Improvement interactive vs. stand-alone operation
	MW	MWh	MW	MWh			k€	k€ per year	years	years	%
Step 1	0.1	0.67	0.1	0.03	NaS	Flywheel	1151,2	122.6	6	10	0.86
	0.1	0.67	0.1	0.03	NaS	Li-ion 2	1146,1	122.5	6	6	0.88
	0.1	0.67	0.1	0.03	NaS	NiCd	1138,2	122.1	6	6	0.85
	0.1	0.67	0.1	0.03	NaS	Li-ion 1	1136,0	122.4	6	6	0.88
Step 2	0.2	1.33	0.4	0.10	NaS	Flywheel	2554.6	291.0	6	10	1.45
	0.2	1.33	0.4	0.10	NaS	Li-ion 2	2483.6	290.7	6	6	1.48
	0.4	2.67	0.4	0.10	NaS	Flywheel	2445.4	341.1	6	10	0.58
	0.2	1.33	0.4	0.10	NaS	NiCd	2404.5	289.1	6	6	1.46
	0.4	2.67	0.4	0.10	NaS	Li-ion 2	2374.5	340.7	6	6	0.59
	0.2	1.33	0.4	0.10	NaS	Li-ion 1	2334.5	290.3	6	6	1.57
	0.4	2.67	0.4	0.10	NaS	NiCd	2295.8	339.2	6	6	0.55
	0.4	2.67	0.4	0.10	NaS	Li-ion 1	2225.4	340.3	6	6	0.62
	0.2	1.33	0.2	0.05	NaS	Flywheel	2049.3	231.7	6	10	0.92
	0.2	1.33	0.2	0.05	NaS	Li-ion 2	2030.8	231.6	6	6	0.92

Table 3: Results of ten best hybrid ES combinations (*Income means here revenues from applications minus expenses for applications)

1. *Finding the type of ES technologies:*
In this step the NPV is calculated for ESs that have the same power rating. It was set to 5% of the nominal WPP capacity which is equal to a power rating of 0.1MW. Then, all possible combinations of storage technologies were tested but the storage technologies for each application were pre-selected in order to minimize the necessary runs. The storage technologies tested for FI are VRB, ZnBr, lead acid, and NaS while the storages tested for PFR are li-ion 1+2, NiCd, flywheels and supercapacitors. In total 20 different combinations are tested in step 1. The results of the simulation runs are sorted by the NPV and the four combinations with the highest NPV are chosen as input for the next step. Results of step one are displayed in Table 3.
2. *Finding the optimum power and energy rating:*
Based on the results of the previous step, step 2 defines the optimum combination of ESs for different power ratings. Combinations are built based on power ratings for 1%, 2.5%, 5%, 10%, and 20% of the WPP nominal power rating as well as for the four best results of step 1. In total 100 different combinations are analysed in this step. The results are selected again based on the highest NPV. The results are depicted in the lower part of Table 3 (Step 2).
3. *Calculation of the NPV for the stand-alone case:*
In order to define the added value of the interactive case the simulation has to be run one more time for the best ten combinations. However, this time the storages are operated in stand-alone mode so they do not support each other when idling. The added value is shown in the last column in Table 3. It quantifies how much higher the NPV is in interactive mode compared to stand-alone mode.

First of all, the results show positive NPVs which would justify the investment and that the highest NPV is not necessarily achieved with the highest income from applications (revenues from applications minus expenses for applications) (compare Step 2, Table 3). Furthermore, the four combinations with the highest NPV show a comparable low difference to each other with absolute values being high. The reason can be that in reality, the ES for PFR will not participate in this market for each hour during a whole year because it is very unlikely that the operator of the ES will be always accepted. So the revenues from PFR can be much lower in reality. And this will cause lower NPVs as the revenues coming from PFR will be lower.

Regarding storage life it can be seen that for the ten best combinations in step 2 the calendar life is always higher than the cycle life. In this case the ES life-time is assumed with 6 or 10 years depending on the technology. Another observation that can be made is that NaS batteries are always the best solution for FI because no other ES technology than the ones defined under the four best combinations during step 1 is tested in step 2. Moreover, the best combination selected in step 2 has neither the smallest nor the highest power rating. A power rating of 10% of the WPP nominal capacity is best suited

in this case. In contrast, the power rating of the ES for PFR is at the maximum which was tested and it is clarified if higher power ratings will yield even higher NPVs.

7. CONCLUSIONS

In this paper the optimum combination of ESs for a hybrid system is defined. Optimum means the selection of the two ES technologies that have the highest NPV over the selected study period of 20 years. For these analyses different combinations of power ratings (that also implies different energy ratings) as well as different ES technologies combinations are used to find the optimum pair. A simulation model has been developed that is able to find such an optimum pair for the Danish (DK1) market. FI and PFR are the two selected services which the ESs should provide. The model uses a control algorithm which operates both ESs in an interactive manner so that the hybrid system shows an advantage compared to two single ES technologies each operated for one application. The interactive control algorithm provides an added value of 1.45% of the NPV for the best combination of ESs under step 2.

In all cases, the calculated NPVs have rather high absolute values due to the assumptions on which the simulation is built. In reality, the NPVs will probably be lower but the relative values of the NPVs remain important to make a proper selection of the two ESs. Another aspect that has to be considered while interpreting the results is the artificial forecast generation. This forecast does not necessarily reflect the behaviour of a real forecast because it is based on random numbers. Different forecasts can have an important impact on the revenues coming from one application. For future work real forecast data has to be used for more reliable results.

In addition, more simulation runs need to be performed in order to ensure that none of the not simulated ES combinations is more favourable than the best one identified with the underlying approach. However, this process will require a large computational time.

Moreover, in all ten cases which are identified in step 2 the ESs could be utilized much more because none of them reaches the end of the cycle life. A future control algorithm has to consider this fact in order to increase revenues.

Under current regulations, ESs with less than 0.3MW for PFR are not eligible but were also tested. The results show that small sizes of ESs are not more favourable meaning there is no need for adjustment of current regulation.

Finally, the size of the power and energy rating for FI is essential. Results show that the optimum power rating for NaS batteries is about 10% of the nominal power rating of the WPP. However, it is not clear if there is an optimum size or not for the ES for PFR under the taken assumptions due to the fact that the bandwidth of power ratings simulated is narrow and the best size is at the highest selected power rating. For future work it is recommended to analyse NPVs also for higher power ratings of the ES for PFR.

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