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Techno-economic Evaluation Of A Modular Compressed Air Energy Storage To Support Integration Of Wind Generation On El Hierro

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***Abstract*—In order to reduce the dependence on fuel imports as well as CO_2-emissions, islands are switching from diesel to renewable generation. Energy storage systems are used to avoid curtailment of the renewable generation as well as to reduce cycling of the diesel generator. This paper evaluates the operation of a modular, low temperature adiabatic compressed air system (KompEx LTA-CAES ®) on El Hierro using mixed-integer linear programming. Optimal dimensions for charging power and storage capacity are determined and a sensitivity analysis concerning fuel prices and storage efficiency is presented. The economic situation is assessed for the KompEx LTA-CAES as well as for the existing pumped hydro storage.**

***Index Terms*—CAES, MILP, island grid**

I. Introduction

In order to reduce the dependence on fuel imports as well as CO_2-emissions, islands are switching from diesel generators to renewable generation. To provide a reliable power supply energy storage systems are added to such systems to compensate the volatility of the renewable generation. While batteries are the most common choice at the moment, due to their limited storage capacity, they are only able to balance over short time periods. Accordingly they are mostly used to smooth small fluctuations in the generation curve of PV to avoid frequent part load operation of the remaining diesel generators. If load shifting over longer periods is required, long term storage systems, such as pumped-hydropower storage (PHS) or compressed air energy storage (CAES), are necessary.

While PHS are a mature technology with high efficiencies, they have some disadvantages as well. In order to build the required water reservoirs appropriate geological conditions as well as a sufficient height difference are necessary. And even if those requirements are met, PHS have a significant impact on the surrounding environment, because of their high land consumption. CAES systems need significantly less space, since higher energy densities compared to PHS are achievable [1]. In addition the compressed air can be stored in underground caverns, reducing the required surface area. If caverns are not viable, steel pipe storages or lined rock caverns (LRC) can be used instead [2].

In the literature CAES systems on islands have been object of research in the following ways.

Zafirakis and Kaldellis [3] discuss the use of a dual-mode (diabatic) CAES on the island of Crete in order to integrate a higher share of wind generation. The CAES stores excess wind production and delivers a guaranteed amount of electricity during peak demand. Life-cycle electricity production costs are calculated and compared to the existing peak power plants on Crete, establishing profitable operation of the CAES in a low price scenario. A numerical algorithm is used to determine the size of the CAES, which yields an optimal storage capacity of 15 MWh in combination with an 25 MW wind farm. In a sensitivity analysis the turbine power is varied from 1 to 5 MW, with 5 MW having the lowest energy production costs.

The same dual-mode CAES is analyzed by Zafirakis et al. [4] in combination with PV production on an island with a peak demand of 2 MW and a consumption of 7.5 GWh per year. The target of the CAES operation is to reach self-sufficiency. The influence of solar radiation, fuel costs and storage volume on the self-sufficiency are evaluated. In a sensitivity analysis the PV production is varied between 2 and 15 MW and the storage capacity between 1 000 and 20 000 m^3.

5 000 m^3 are identified as optimal, while 1 000 m^3 do not provide self-sufficiency.

Karellas and Tzouganatos [5] compare different configurations of micro CAES as well as a hydrogen storage in respect to their ability to integrate wind farms in island grids. The CAES types are analyzed using a steady state analysis, while the hydrogen storage is evaluated with HOMER. The analyzed wind farm has a power of 500 kW and the charging power was set to 500 kW correspondingly for both CAES and hydrogen storage. The discharging power is set to 450 kW in order to supply a peak demand of 403 kW and a mean consumption of 4.98 MWh per day. The efficiency of the CAES is proven to be higher than the hydrogen storage, but an investment cost analysis shows an advantage for the hydrogen storage.

Behera and Nandkeolyar [6] and Sheng et al. [7] use simulations to show the viability of CAES operation in island grids with renewable generation. Behera and Nandkeolyar [6] develop a control algorithm for the CAES in order to minimize frequency deviations in the hybrid island grid. Sheng et al. [7] analyses a hybrid island grid consisting of diesel generators, marine current turbines and an underwater-CAES. Typical days and weeks are simulated to demonstrate the technical feasibility of supplying a 3 MW load with six 1.5 MW marine current turbines and a 6 MW_{comp}/3 MW_{exp} CAES with a storage capacity of 15 MWh. No information on economic aspects is given in either.

The previous evaluations of CAES on islands focus on diabatic CAES systems, which require additional combustion of natural gas. Since this is opposing the goal of reducing fuel costs and CO_2-emissions, this paper analyses an adiabatic CAES (A-CAES) system. A-CAES systems store the thermal energy that is occurring during the compression of air and utilize it during the expansion.

This paper investigates the operation of a KompEx LTA-CAES® plant on El Hierro as a case study. The economics of the storage operation as well as the optimal dimensions of storage power and storage capacity are evaluated. A MILP model is developed to optimize the annual revenues, which are used to calculate break-even capital costs.

A. *KompEx LTA-CAES Design*

In the research project KompEx LTA-CAES® modular[1] the design of a modular, adiabatic CAES is developed, based on the low-temperature CAES approach presented by [8]. In order to reduce the capital costs of the storage system, the machines for compression and expansion are combined into one reversibly operable machine (KompEx-machine). During the charging process, ambient air is compressed to the pressure level of the compressed air storage volume by the combination of a multi-stage radial turbo machine and a single-stage piston machine. After each compression stage, the heated compressed air is cooled down and the occurring thermal energy is stored in a thermal energy storage (TES). Therefore, a sensitive liquid storage in the turbo machinery train and a sensitive solid storage after the piston machine due to its higher pressure ratio and thus higher temperatures is used. During the discharging process, the compressed air passes the components in the opposite direction. The turbo and piston engines work as expansion machines in this case and the compressed air is preheated by the respective TES systems before entering the machines. The KompEx LTA-CAES is designed modular with an compressor size of one module being 2 MW. Higher charging powers are achieved by installing several modules in parallel. This makes the dimensioning of the power unit for different applications faster and cheaper, since there is no need for an individual machine design for each desired use case. The expander size of the module is a variable design parameter (cf. Section (IV-C1)). The gas storage can be sized independently of the power unit, depending on the requirements of the application.

B. *Study Case El Hierro*

As a study case the island of El Hierro was chosen based on the availability of public data as well as the assumption that a long term energy storage system operates profitable under the given conditions, since a PHS has already been implemented.

El Hierro is the most western island of the Canary Islands with an area of 268.71 km^2 [9] and 10 679 inhabitants in 2017 [10]. The electricity consumption in 2017 was 45.25 GWh with a peak power demand of 7.7 MW [11]. Until the year 2015, the entire electricity demand of El Hierro was met by conventional diesel generators at the Llanos Blancos power plant, with an installed plant capacity of 13.3 MW [12].

In accordance to the El Hierro sustainability plan, approved in 1997, which aims at a 100 % self-sustained island, a pumped hydropower storage was built in 2014. The PHS is used to integrate the generation of five Enercon E-70 wind turbines with a rated power output of 2.3 MW each.

II. METHOD

A. *Optimization model*

Mixed-integer linear programming which is standard in the field of power plant commitment was selected as optimization method. Through optimization of the storage dispatch the maximum annually receivable contribution margin (appropriate for market based storage applications) respectively the minimum annually supply costs satisfying the demand (appropriate for the case study presented in this paper) can be obtained. Over the last years, Fraunhofer UMSICHT has developed the modular Generic Optimization Model for Energy Storages (GOMES®[1]) for the techno-economic evaluation of several stationary storage applications. It covers centralized applications as well as applications close to renewable energy sources or on end-consumer level. Its functional principle is displayed in Fig. (1). Exemplary publications presenting GOMES are [13] and [14].

The general algebraic modelling system (GAMS) was used to formulate the optimization problem [15]; the solution is

[1]LTA-CAES® and GOMES® are registered trademarks of Fraunhofer UMSICHT. For reasons of readability, the registered sign is omitted in the following.

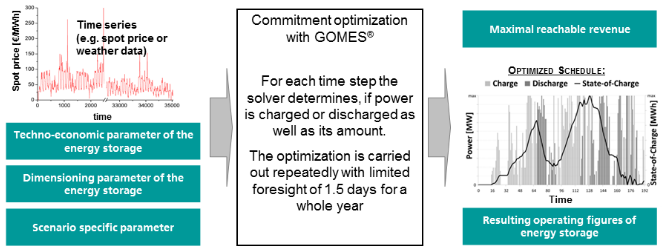

Fig. 1. Functional principle of the Generic Optimization Model for Energy Storages GOMES based on [14]

carried out by the solver CPLEX, Version 12.7 [16]. By applying a rolling horizon, the perfect foresight of the solver is limited to a predetermined time frame, here the following one and a half days. Only the first day's results are taken on record, while the following half day serves as an overlap that is designed to avoid the emptying of electrical energy storage at the end of each day, which could lead to a local instead of the global optimum. A foresight of 1.5 days seems appropriate in context of weather forecast quality and leads to an acceptable computation time simultaneously.

For the presented examination, GOMES has been enhanced by a further scenario module, which describes the support of renewable generation integration in island grids. Therefore, a diesel generator module has been developed and the module for wind energy plants was updated. So far, time series with wind energy generation were deposited in the wind energy plant module. Now, time series of wind velocity serve as input data and are converted into generated wind energy by a constant efficiency factor. The total wind power generation by M wind turbines is thus given by

$$P_{wind}(t) = \sum_{m=1}^{M} [c_p(m) \cdot \frac{1}{2} \cdot \rho_{air} \cdot A_{rotor}(m) \cdot v_{wind}(t)] \quad \forall v_{cut-in} \leq v_{wind}(t) \leq v_{cut-out} \tag{1}$$

.

In addition, the module for electric energy storages has been enhanced by a formulation that allows storage plants to consist of several storage modules (cf. Section (I-A)).

The minimization of power supply costs for El Hierro serves as objective function for the optimization by summing up variable costs of all plants for each time step t in each optimization run T within the rolling horizon (Equation (2)). Even if variable costs for CAES and wind energy plants are part of the objective function, these are assumed to be zero in our case study so that only operational costs and fuel costs of the diesel generator are finally taken into account. Additional to the described plants, an additional emergency source respectively dump has been integrated to ensure the exact power balance and thereby the resolvability of the optimization problem. Emergency source and dump obtain high penalty costs in the objective function to prevent their

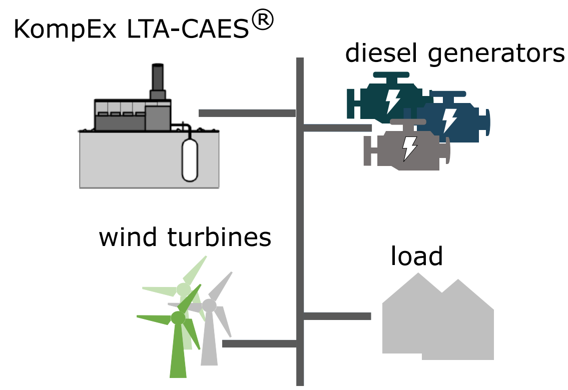

Fig. 2. System configuration for the island grid El Hierro

regular operation[2].

$$\min c = \sum_{T=1}^{365} \sum_{t=1}^{n} (c_{dg,var}(t) + c_{wind,var}(t) + c_{CAES,var}(t) + c_{source}(t) + c_{dump}(t)) \tag{2}$$

The most important optimization constraint against the background of security of supply and a stable grid operation says that residual load has to be covered in each time step t.

$$P_{dg}(t) - P_{load}(t) - P_{CAES,ch}(t) + P_{CAES,dch}(t) + P_{wind}(t) - P_{dump}(t) + P_{source}(t) = 0 \tag{3}$$

Equation 4 to 6 give further constraints concerning the plant's connection of El Hierro as displayed in Fig. (2).

$$P_{dg}(t) = P_{dg,load}(t) \tag{4}$$

$$P_{wind}(t) = P_{wind,load}(t) + P_{wind,CAES,ch}(t) + P_{wind,dump}(t) \tag{5}$$

$$P_{load}(t) = P_{dg,load}(t) + P_{wind,load}(t) + P_{CAES,dch,load}(t) \tag{6}$$

For example the diesel power generation can not be used to charge the CAES (see equation 4).

In addition, several technical constraints concerning the plant operation are applied for the optimization. As already mentioned, the efficiency of the wind energy plant c_p is assumed to be constant.

[2]The emergency source was used for less than 0.007 % of the total electricity consumption.

In contrast to that, charge and discharge efficiency of the CAES as well as the efficiency of the diesel generator are modelled as part-load dependent efficiency curves. For stepwise linearisation of the CAES efficiency curves one node was applied (see [14] for further methodical details).

A similar approach is used for linearisation of the diesel generators efficiency curves, but with only one step with $a_{dg}(i)$ the slope and b_{dg} the y-interception of the curve respectively.

$$\begin{aligned} fuel\,consumption(t,i) = [a_{dg}(i) \cdot P_{dg}(t,i) \\ + b_{dg}(i)] \cdot s_{dg}(t,i) \end{aligned} \quad (7)$$

The binary variable $s_{dg}(t,i)$ represents the status of the diesel generator i in time step t (on: $s_{dg}(t,i) = 1$; off: $s_{dg}(t,i) = 0$).

The variable diesel generator costs $c_{dg,var}(t)$ consist of the fuel costs $c_{dg,fuel}(t)$ and the operation costs of the diesel generator $c_{dg,operation}(t)$ as shown in equation 8.

$$\begin{aligned} c_{dg,var}(t) &= c_{dg,fuel}(t) + c_{dg,operation}(t) \\ &= fuel\,consumption(t,i) \cdot c_{fuel} \\ &\quad + P_{dg}(t) \cdot \Delta t \cdot c_{dg,op} \end{aligned} \quad (8)$$

.

Moreover, receivable ramp rates were modelled for CAES and diesel generators. Equation 9 shows the implementation for the diesel generator.

$$\begin{aligned} P_{dg}(t-1,i) - \Delta P_{dg,down}(i) \leq P_{dg}(t,i) \\ \leq P_{dg}(t-1,i) + \Delta P_{dg,up}(i) \end{aligned} \quad (9)$$

In addition, the CAES is characterized by installed capacity SOC_{max}. In scenarios with several CAES modules, each of these modules underlies the in [14] described technological constraints and the total charging and discharging power of the CAES is given by the sum of all CAES modules power.

$$P_{CAES,ch}(t) = \sum_{n=1}^{N} P_{CAES,ch}(t,n) \quad (10)$$

A further constraint ensures that each CAES module is only allowed to charge or to discharge in each time step t. Nevertheless, it is allowed that one CAES module charges while another module discharges, as this is technically possible, even with a shared storage volume. This helps to balance power generation and demand in island grids, because the resulting total part-load range of the whole CAES is larger than for each single module.

B. Break-Even Capital Costs

The net present value method represents a dynamic method of investment appraisal, which summarizes all finance flows over the whole life cycle to the so called net present value (NPV). An investment is regarded as profitable if net present value is greater than zero. The calculation of NPV considers the initial capital costs as well as present values of all occurring cash inflows and outflows over the lifetime resp. depreciation period of the plant [17]. In our case study the annual costs calculated by GOMES represent the cash outflow. Direct cash inflows do not exist in our case study, because there is no revenue generated by storage operation. Instead, avoided supply costs in comparison to a reference case (no storage, e.g. power supply for El Hierro only by diesel generators and wind energy plants) were accounted. Possible liquidation proceeds after lifetime is neglected. In addition, it is assumed that cash inflows and outflows have the same height in each year of the storage plant's lifetime.

If capital costs for the electric energy storage device are unknown or only specified in form of a wide range, as it is common in scientific studies without specific building intention, the calculation of break-even capital costs (BECC) is advantageous for the comparison of different storage applications and/or storage technologies as well as for the identification of the optimal storage size [14]. BECC mean capital costs that correspond with a net present value of zero. The higher the resulting BECC the higher is the chance for profitability of a certain use case (Equation (11)).

$$\begin{aligned} NPV &= \sum_{Y=1}^{n} \left[\frac{CI\,(Y) - CO\,(Y)}{(1+i)^Y} \right] + \frac{L_n}{(1+i)^n} - CO_0 = 0 \\ \Leftrightarrow CO_0 &= \sum_{Y=1}^{n} \left[\frac{CI\,(Y) - CO\,(Y)}{(1+i)^Y} \right] \end{aligned} \quad (11)$$

C. Technology specific cost ratio

If the dimensioning optimum of the CAES (installed power and installed storage capacity) is to be identified, the total BECC is not sufficient as assesment criterion. When total BECC is referenced to either installed power or installed capacity, the search for the dimensioning optimum leads to different results depending on the reference value used. This shows that both cases represent not the true dimensioning optimum. For its identification, it must be taken into account that the power unit and the storage volume have different specific costs.

As described in [14], this can be solved by dividing the total BECC into BECC for the power unit and BECC for the storage volume (Equation 12) and by introducing the so-called technology-specific cost ratio (TCR). The method assumes that the quotient of the additive energy-specific and power-specific costs is - regardless of the absolute amount of capital costs - approximately constant for each energy storage technology (Equation 13). Accordingly, economies of scale, where power-specific costs and energy-specific costs develop differently with increasing unit size and storage volume respectively, are not taken into account in the methodology.

$$\begin{aligned} BECC_{\text{total}} &= BECC_{\text{total,P}} + BECC_{\text{total,E}} \\ &= BECC_{\text{spec,P}} \cdot P + BECC_{\text{spec,E}} \cdot E \end{aligned} \quad (12)$$

$$TCR = \frac{BECC_{\text{spec,E}}}{BECC_{\text{spec,P}}} \tag{13}$$

By inserting and rewriting the equations, the two unknowns $BECC_{\text{total,P}}$ (Equation 14) and $BECC_{\text{total,E}}$ (Equation 15) can be determined and, in turn, the additive specific costs $BECC_{\text{spec,P}}$[3] and $BECC_{\text{spec,E}}$[4].

$$BECC_{total,P} = \frac{BECC_{total}}{1 + TCR \cdot \frac{E}{P}} \tag{14}$$

$$BECC_{total,E} = \frac{BECC_{total}}{1 + \frac{P}{TCR \cdot E}} \tag{15}$$

Regardless of whether $BECC_{\text{spec,P}}$ or $BECC_{\text{spec,E}}$ is used to search for the dimensioning optimum, the same combination of installed power and installed storage capacity is found, i. e. the real optimum is identified.

III. Model parameters

In order to evaluate the operation of the KompEx LTA-CAES the following model parameters were used:

A. Energy system - El Hierro

The power demand of El Hierro in the year 2017 is given as a time series in a 10 minute resolution [11]. The time series of wind speed is taken from a typical year calculated by Meteonorm [18] in a one minute resolution, which is used to calculate the mean value for every 10 minute period.

Since there exists conflicting data for the power output of the diesel generators in operation on El Hierro (11.180 MW [19], 13.300 MW [12], 10.015 MW [20]), the details on the individual diesel generator type given in [12] was used to find the corresponding data sheets. Table (I) gives an overview over the employed diesel generator units along with their maximum power output, which has been obtained from the data sheet analysis.

TABLE I
Diesel generators at Llanos Blancos based on [12]

Units	Brand	Model	Power in MW[a]
6	Caterpillar	3516	1.450
1	Caterpillar	D-398	0.600
2	MAN	9L21/31	1.915

[a] according to the data sheets

The efficiency of the individual diesel generator is not modelled as constant, but rather efficiency curves are derived from the fuel consumption at different part load operation points as given in the data sheets. The minimum part load operation point is set at 30 % of the maximum power for each generator, and the ramp rate to 1 % of the maximum power per second [21]. By installing the PHS the annual fuel consumption was estimated to decrease by 6 798 t of diesel per year leading to a cost reduction of 1.8 million Euro [22]. From this, fuel costs are calculated to be 0.95 €/l, using a density of 0.83 kg/l. The operation costs of the diesel generators is assumed to be 0.029 €/kWh. As a constant c_p for the wind turbines a value of 0.45 was assumed and cut-in and cut-off speeds of 2 m/s and 25 m/s respectively [23] are used.

[3] here: referred to the installed charging power
[4] here: referred to the energy within the storage volume

B. Storage system

The parameters maximum power $P_{\max}$, minimum power $P_{\min}$, ramp rate ΔP and operation costs c_{op} for one KompEx module are given in Tab. (II).

TABLE II
Model input parameters for the CAES storage

Parameter	Power Unit	
	Charging Unit	*Discharging Unit*
$P_{\max}$ in kW	2000	1130
$P_{\min}$ in kW	1340	678
ΔP in kW/min	400	226

The assumed efficiency curves for the charging and discharging process of the examined CAES system are shown in Fig. (3). The variable operation costs of the storage are assumed to be zero. The maximum discharging power in this design is 1.39 MW.

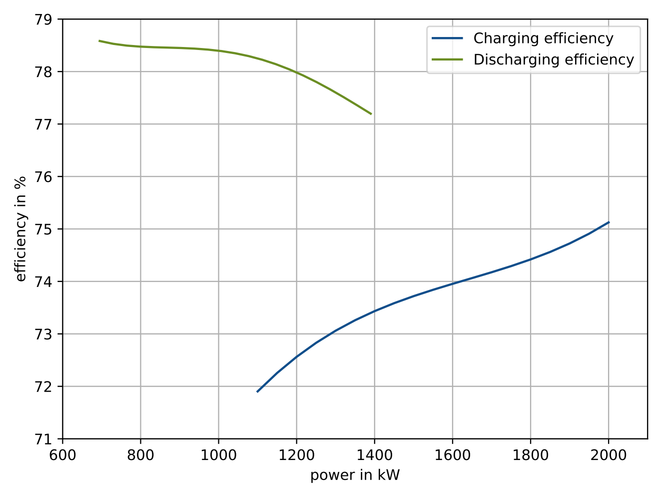

Fig. 3. Efficiency curves assumed for the charging and discharging process of the CAES module

In order to calculate the specific BECC as shown in section (II-C), the TCR for the KompEx LTA-CAES has to be determined. For a CAES system the TCR depends on the type of compressed air storage (CAS) volume used. For steel pipe storage and lined rock caverns (LRC) the ratio between energy related BECC and power related BECC is indeed linear. A typical steel pipe storage has a TCR of 0.33 h^{-1} while an LRC has a typical TCR between 0.14 h^{-1} and 0.23 h^{-1}. The TCR method needs to be adopted in case of using salt caverns as CAS, since the specific capital costs of a salt cavern decrease non-linearly with its size. This results in a TCR that is dependent on the storage capacity as shown in Fig. 4.

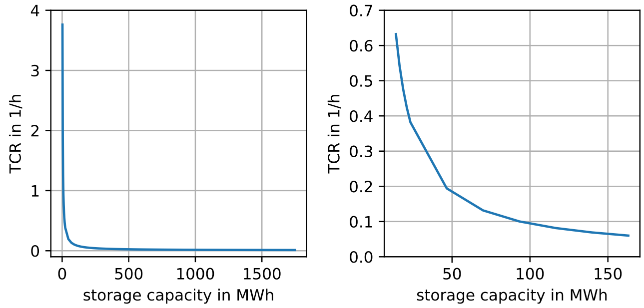

Fig. 4. TCR for different sizes of salt caverns (left) and the evaluated size range in the sensitivity analysis (right)

As economic parameters for the calculation of the BECC a lifetime of the storage of 25 years and a interest rate of 7 % are assumed.

IV. Results and Discussion

A. Optimal dimensions of the storage system

In order to find the economically optimal storage dimensions of power and capacity, the optimization was run with different numbers of power modules and over a range of storage capacities. It was found that a low number of power modules leads to higher specific BECC. In Fig. 5 the specific power related BECC in €/kW for one, two and three power unit modules and storage capacities between 6 and 144 MWh are shown. As TCR 0.33 is used, which is suitable for a steel pipe storage.

The optimal size of the CAES system is found to be one power module in combination with a storage capacity of 6 MWh. The specific power related BECC in this case are 170.71 €/kW and the specific energy related BECC are 56.33 €/kWh.

In general the BECC are considerably too low over the whole range of storage capacities for a positive business case. It is assumed that the wind power generation on El Hierro is dimensioned too small to enable enough possibility to shift energy. Therefore the same calculations are done with ten wind turbines, which leads to higher break-even capital costs as shown in Fig. 6.

The optimal size in the scenario with ten wind turbines is found to be one module and a storage capacity of 12 MWh, as well. The specific power related BECC in this case are 398.41 €/kW and the specific energy related BECC are 131.48 €/kWh which is more than two times higher than in the scenario with five wind turbines. In order to compare these absolute values with other similar projects, it is necessary to keep in mind, that the values given are solely for the investment in the storage technology.

In literature it can often be observed that the economy analysis is done for the storage technology together with the installation of the renewable generation, referred to as hybrid

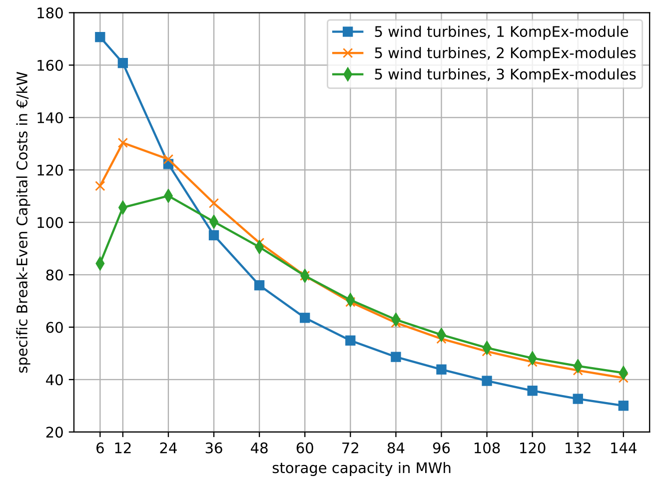

Fig. 5. Specific power related BECC for one and two power modules in combination with 5 wind turbines

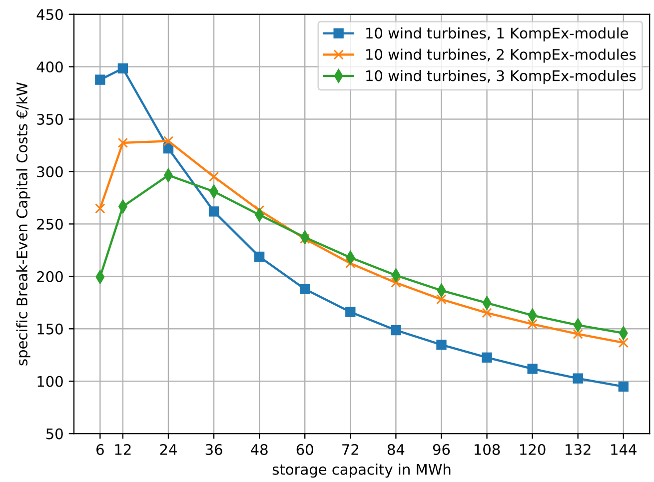

Fig. 6. Specific power related BECC for one and two power modules in combination with 10 wind turbines

power plants. This usually results in positive business cases. In order to compare the results obtained above to similar projects, the same calculation is done here using capital costs for wind power of 1000 €/kW. The capital costs for the installation of the wind turbines get subtracted from the present value of the annual revenues before calculating the BECC for the storage as shown earlier. The results are shown in Fig. (7) for five as well as ten wind turbines.

The obtained BECC using the hybrid power plant approach are substantially higher than the BECC of only the storage technology. The reason behind this is that the installation of ten wind turbines alone saves already 41 % of the annual operation costs (27 % for five wind turbines), while the storage system reduces operation costs only by additionally 1 to 6 %. If the sole goal therefore is to reduce the electricity costs it is sufficient to install wind turbines without a storage unit. If on the other hand the share of renewable generation is to be

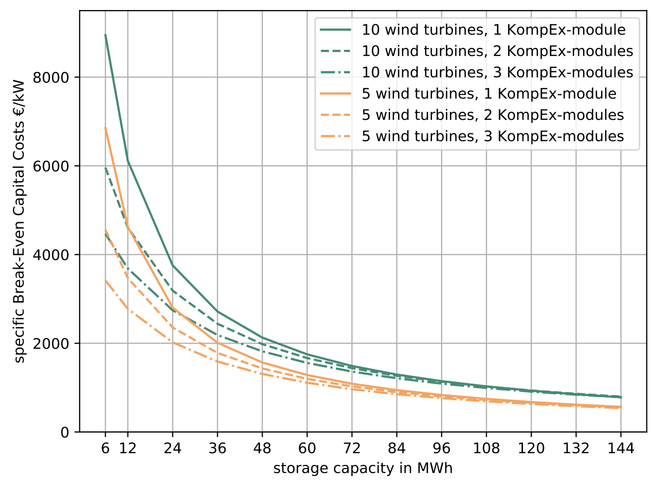

Fig. 7. Specific power related BECC for one and two power modules in combination with 10 wind turbines and 5 wind turbines; calculated as hybrid power plant

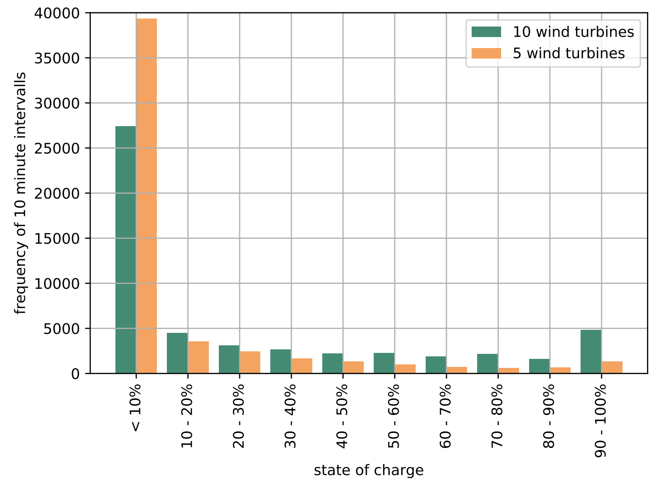

Fig. 8. Histogram of the state of charge for one power unit and five and ten wind turbines respectively

increased above a certain limit, a storage system is required to insure the reliability of the system. In that case the hybrid power plant approach is adequate, since the wind turbines could not be installed alone and thus the project as a whole should be evaluated. In Fig. (7) the optimal storage capacity is at the border of the analysed range, i.e. 6 MWh, which is in line with the explanation above, that shows that the storage system is not actually necessary to reduce the system operation costs. This leads to the conclusion that for the economical analysis and appropriate sizing of such projects it is very important to keep in mind what the scope of the investment is. Is the interest only to reduce the fuel costs or is it to increase the share of renewable generation in total.

B. Operational behaviour

In the following section the operational behaviour of the storage unit and the diesel generators is analysed in more detail for the storage dimensions of 1 KompEx module and a storage capacity of 12 MWh found to be optimal for 10 wind turbines in section (IV-A). Fig. (8) shows the histogram of the state of charge in frequency of 10 minute intervals, for both the case with five and with ten wind turbines.

In general the state of charge is between 0 and 10 % almost half of the year. A more detailed analysis yields that the storage is completely empty for 804 hours in combination with ten wind turbines and 222 hours with five wind turbines. This indicates that periods of charging and discharging alternate frequently and the storage volume is charged only a bit before it is discharged again. This confirms that in the given scenario no real time shifting of energy is possible and thus that the installation of the wind turbines alone would be sufficient. In the scenario with five wind turbines this behaviour is more pronounced than with ten wind turbines. In the ten wind turbine scenario the other state of charge classes are used more often, most noticeable at 100 % state of charge. This supports the assumption that five wind turbines are too few for the combination with a storage system, while in the scenario with ten wind turbines, more energy is stored over longer time periods, leading to higher states of charge in general. It is noticed that the storage capacity is not a limiting factor for the amount of energy that is stored, rather the available wind power establishes limits for time shifting of energy.

In Fig. (9) histograms of the part load operation for charging and discharging are shown for the case with 10 wind turbines. On the left side it can be seen that the compressor as well as the expander were not in operation for more than 85 % of the time. The main reason for that is that in 7012 hours of the year the demand is higher than the wind generation, leading to a positive residual load and the complete wind generation is directly consumed. The rest of the time the wind power generation is between zero and 1.34 MW for 419 hours, leaving 1329 hours in which charging is possible. This results in 19.42 GWh of wind generation that are directly consumed and only 1.43 GWh of wind generation that are stored, while the 7.89 GWh have to be dumped. Doubling the charging power by using two power units the amount of dumped energy is only reduced to 7.56 GWh, while the BECC are decreased by 17.8 % for the same storage capacity. The histogram on the right shows only the part load range that is accessible by the storage. The storage is preferable operating at maximum power or at the lower part load limit, both for charging and discharging but the charging unit operates at full load more often than the discharging unit. The reason for that is that the discharge unit needs to follow smaller variations in the demand, which leads to a higher use of part load operation points. Overall, a wider part load range might lead to higher revenues, since more operation points could be served by the storage, especially by the discharging unit.

Fig. (10) shows the histogram for the part load operation as well as the number of start per day for each diesel generator. It is observed that the majority of days no start is necessary

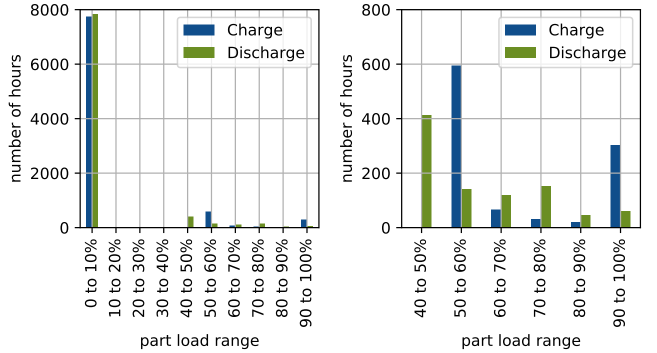

Fig. 9. Number of operating hours of the charging and discharging area, separated by percent of the whole part load range (left) and the allowed part load range (right)

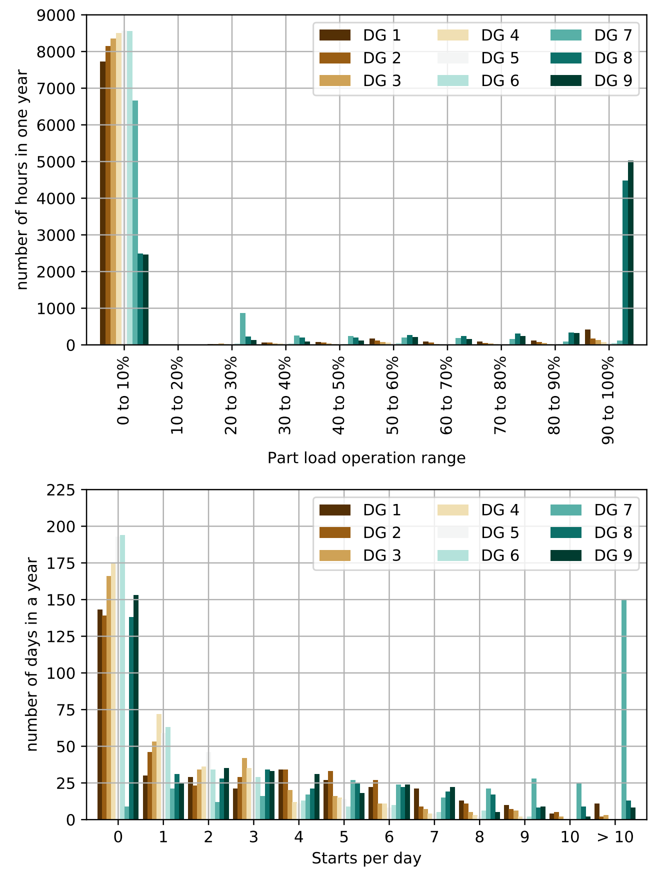

Fig. 10. Part load operation and number of starts per day for each diesel generator (DG 1-6: Caterpillar 3516, DG 7: Caterpillar D-398, DG 8-9:MAN)

and that the number of days with more than one start per day is below 50 days in the year for all diesel generators, except diesel generator 7, which has the smallest rated power (0.6 MW) and thus is able to match small variations in the demand, leading to a higher frequency of starts. It is also noted that diesel generators 8 and 9 have have more than 10 starts, indicating that while generators 1 to 6 are either used as baseload or not at all, generators 8 and 9 are more likely used to balance demand and generation.

From the histogram of the part load operation it can be seen that 1 to 6 are indeed not in operation for more than 90 % of the year, while diesel generator 8 and 9 operate at full load for around 50 % of the time. It can also be seen that the diesel generators overall operate less than 30 % of the time in part load. This is the desired outcome in order to reduce diesel consumption and CO_2-emissions. Diesel generator 7 operates more often in part load, especially at 30% part load than any of the others, which shows again that it is used to match small demand variations.

C. Sensitivity analysis

1) Storage efficiency: In order to analyse the impact of the efficiency three scenarios - low efficiency, medium efficiency and high efficiency - are analysed in the following. The efficiency curves are shown in Fig. (11).

In Fig. (12) and (13) the specific power related BECC for different storage capacities for the analysed efficiencies are shown. As expected higher efficiencies lead to higher BECC, since more of the stored energy can be used to supply the load.

2) Fuel price: Since the fuel price is considered to have a high impact on the BECC, a sensitivity analysis regarding the diesel prices has been done. In Fig. (14) the BECC for one module and ten wind turbines are shown. The fuel costs are varied from 0.85 €/l to 1.05 €/l. The BECC increase with increasing fuel prices, as expected.

3) Types of gas storage: The BECC depend on the TCR, which itself depends on the gas storage volume that is used as described in section (III-B). In Fig. (15) the specific power

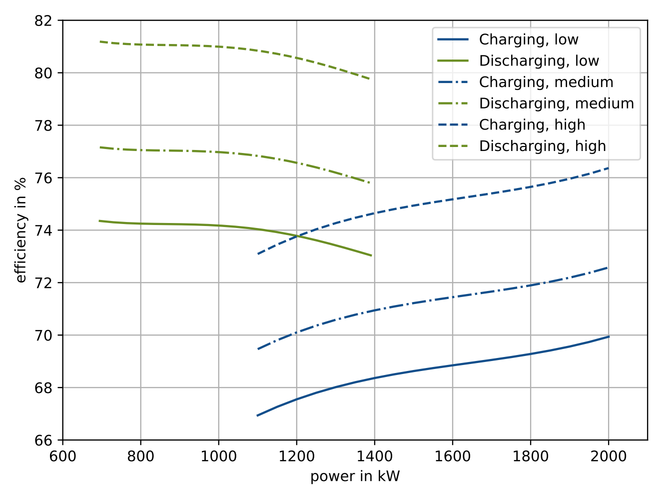

Fig. 11. Different efficiency curves for sensitivity analysis including a low, medium and high efficiency scenario

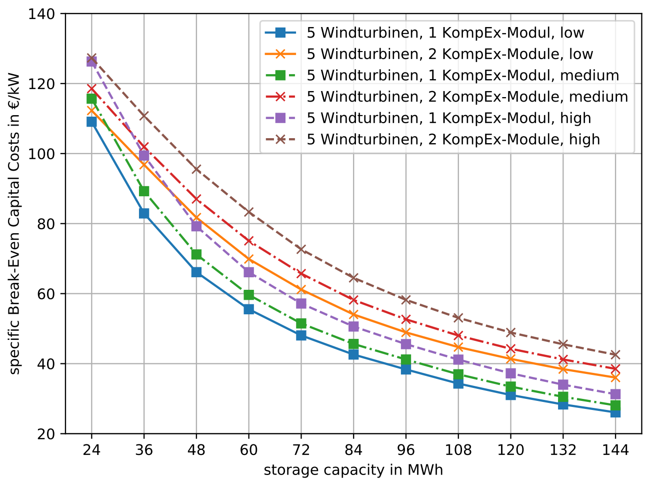

Fig. 12. Specific power related BECC for low, medium and high efficiency scenario with 5 wind turbines

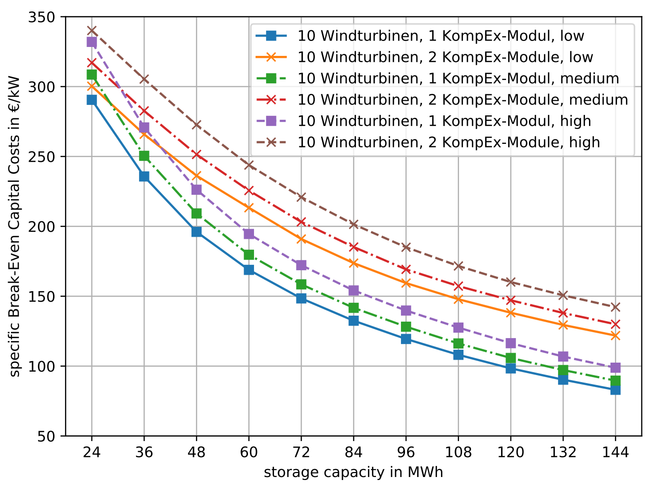

Fig. 13. Specific power related BECC for low, medium and high efficiency scenario with 10 wind turbines

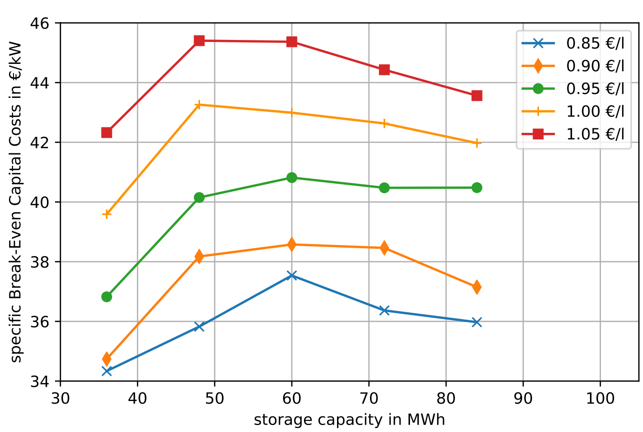

Fig. 14. Specific power related BECC for different fuel prices

related BECC for different gas storage types are shown. For the steel pipe storage (SPS) the TCR is 0.33, for the LRC it is 0.18 and for the salt cavern (SC) the non-linear curve from section (III-B) Fig. (4) is used.

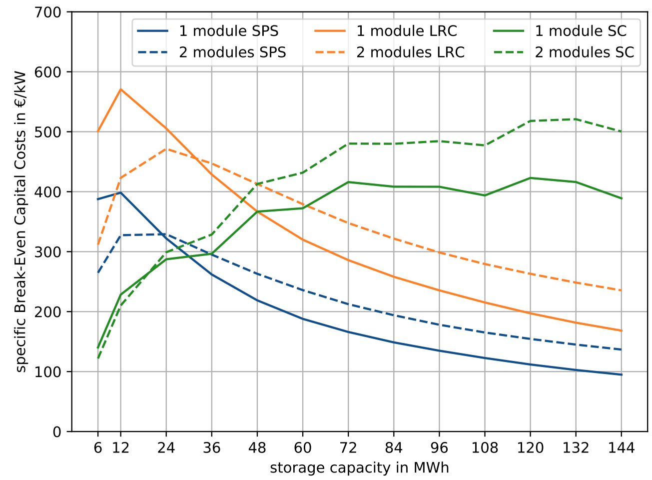

Fig. 15. Specific power related BECC for different types of gas storage volume

The results shown in Fig. (15) cannot be used to find the optimal storage capacity in each case, since the TCR of salt caverns is non-linear, but rather to compare different gas volumes in combination with the same power unit. With the TCR given above, LCR is the best solution for capacities smaller than 48 MWh and for capacities greater than 48 MWh salt caverns lead to the highest power related BECC.

D. Comparison with pumped hydro storage

In order to compare the results for the KompEx LTA-CAES with the PHS that is installed on El Hierro, the optimization is run with the parameters of the PHS.

The pumping station of the PHS on El Hierro consists of two pump units with 1.5 MW and six pump units with 0.5 MW, adding up to 6 MW charging power in total. The turbines employed are four pelton wheels with 2.83 MW each, equal to a total discharging power of 11.32 MW [24]. The storage volume of the upper reservoir has a size of 380 000 m^3, which gives a storage capacity of around 471 MWh [20].

Table (III) gives an overview of the input parameters, that are used to evaluate the operation of the installed PHS on El Hierro.

TABLE III
MODEL INPUT PARAMETER PUMPED HYDRO STORAGE

Parameter	**Power Unit**	
	Charging Unit	***Discharging Unit***
P_{max} in kW	6000	11320
P_{min} in kW	1000	2264
ΔP in kW/min	1200	2264

The lower part load limits are taken from [19]. The charging efficiency is assumed to be 86.4 % and the discharge efficiency to be 89.5 %, which are typical values for pumped hydro power storage plants [25]. The efficiencies are taken to be constant since no further knowledge about the behaviour in part load operation is known and thus with a constant efficiency a upper limit for the avoided costs is obtained.

The annual operation cost savings obtained by the PHS operation in combination with five wind turbines are 303 839 €, which lead to 53.16 €/kW and 6.49 €/kWh break-even capital costs using a TCR of 0.08. These are considerably lower than the BECC of the economically optimized KompEx LTA-CAES. In the project planning of the PHS the hybrid power plant approach was apparently used to show a positive business case as the sole installation of such an PHS is not profitable.

V. Conclusion

The operation of the pumped hydro storage on El Hierro in combination with five wind turbines is profitable if a hybrid power plant approach consisting of the PHS and the wind turbines is employed. But the sole installation of wind turbines would present a more profitable business case, while the installation of the PHS itself is not economically justified. The reason behind this is that there is a relatively low surplus of wind generation that can be shifted by the storage system. The avoided diesel costs are not sufficient to equal the capital costs of the PHS. Therefore the question is if the PHS provides further grid support that justifies the installation.

The same holds true for the analysed CAES storage system. As a hybrid power plant the CAES is profitable, but the additional fuel savings due to the storage operation are not sufficient to outweigh the capital costs of the storage system. Therefore for future hybrid power plants on islands, the KompEx LTA-CAES should be considered as another option for bulk energy storage technology. Especially in cases where land use is a sensitive topic or where up to now CAES were not an option because of the lack of suitable salt caverns. Lined rock caverns could present an interesting alternative in those cases.

These results can not be generalized however, since only one study case and solely wind generation has been considered. Therefore it will be interesting to investigate further case studies in future research in order to obtain more universal results. Especially the combination with pv generation is promising, since the daily generation profile of pv modules is well suited for time shifting with storage systems [26].

It was shown that optimal sizing of storage dimensions has a big impact on the economics of storage systems. Therefore each individual case should be evaluated thoroughly. Furthermore fuel prices proved to have an significant impact on the economics, which is why the future development of fuel prices should be incorporated into the economic evaluation. As has been seen higher efficiencies lead to higher BECC. This is of special interest for storage technology developers and the evaluation of how enhanced technical performance influences BECC and capital costs will be part of future research.

The developed model was proven to be suitable for the analysis of the storage operation in island grids. In the future it will also be used to evaluate the CAES operation on mining sites. Initial investigations have shown positive business cases for bulk storage systems.

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