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Techno-economic analysis of I-CAES systems to increase dispatchability of wind power

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Abstract. The variability of energy production from renewable sources remains the main issue hampering their larger penetration in current energy grids. While batteries have been proven to work well in many applications, their cost and environmental footprint are opening room for alternative systems. In this study, the innovative isothermal compressed air energy storage (I-CAES) system proposed by Sadaat et al. in 2014 is analyzed. In this system layout, a wind turbine is coupled with a CAES system through a hydraulic circuit including a liquid piston. The original work theorized the system and focused only on a preliminary verification under an energy perspective, using data referring to very short time series. In the present study, a long-term techno-economic analysis is performed to provide a more representative insight into the real feasibility of the proposed plant configuration. The analysis is carried out using yearly wind speed data and a 1-minute average approach, so as to correctly track the energy fluxes. A parametric analysis of the system, varying the size of the storage vessel and generator is performed to identify the optimal configuration. Finally, the overall performance is compared with that of a traditional standalone turbine. The effect of fluctuations in the energy price during the day is considered, as well as the impact of possible future scenarios, where traditional systems are penalized due to significant oscillations in power production. Results show that, despite the high compression and expansion efficiencies achieved through the liquid piston, the complexity of the system causes a significant reduction of total energy production affecting the economic performance, although interesting prospects can arise whenever constant-load off-grid users are about to be fed.

1. Introduction

The current share of renewable energy in power generation is limited by the stability requirements of the electrical grid. Indeed, due to the stochastic oscillations of renewable energy, the grid-connected ancillary devices must be always able to compensate for such fluctuations. In this framework, multiple solutions have been proposed to limit the variability of wind and solar generation, mainly by the introduction of energy storage systems [1]. While batteries have been proven to work well in many applications [2], among alternative solutions compressed air energy storage (CAES) systems represent an interesting technology for large capacities and high power rates [3,4]. In these systems, air is compressed using the excess of energy produced by renewables, stored, and eventually re-expanded when needed. This technology may achieve good round-trip efficiency with lower specific costs compared to batteries [5].

In particular, Sadaat et al. [6] proposed an innovative system to integrate wind power with a CAES system. In such design, the wind turbine generator is substituted by a hydraulic circuit, used to transfer the mechanical power to a generator and CAES system. The system takes advantage of a liquid piston to perform the compression and expansion of air with high efficiencies. Additionally, generator and components are placed on ground level, reducing structural and maintenance costs. The analysis of the system was carried out on a limited 72-hour timeframe to prove the feasibility of the system. Therefore, a long-term techno-economic analysis of the system has not been performed to date.

In the present study, the system is analysed over a one-year time period, providing further insights into the behaviour of the system. The economic performance is evaluated and compared with a standalone, grid-connected system. Additionally, the ability of the system in feeding a constant load is compared against a battery energy storage system (BESS) solution, to show the possible advantages of the proposed system in specific applications. The study is structured as follows: Section 2 provides a description of the system. The main equations and definitions used in this work are defined in Section 3, followed by an overview of the main results in Section 4. Finally, conclusions and future work are presented in Section 5.

2. System description

In the system proposed by Saadat et al. [6], a wind turbine is coupled with an isothermal compressed air energy storage (I-CAES) system. The connection between the wind turbine and the storage system is achieved through a hydraulic circuit (Figure 1). The nacelle generator is replaced by a variable displacement pump (B), which uses the torque provided by the wind turbine (A) to pressurize a hydraulic fluid. The hydraulic fluid is then expanded in the variable displacement reciprocating compressor/expander (C) to generate power at the generator shaft (F). In this way, fluctuations in energy production are reduced, allowing the downsizing of the electrical components, thus reducing costs. Furthermore, this system configuration makes use of a fixed-speed electrical generator rather than a variable-speed one, further reducing the cost of electrical components. When excess energy is produced by the turbine, this is used to compress ambient air through a liquid-piston compressor/expander. The liquid piston is fitted with a mesh of porous material in order to achieve an almost iso-thermal transformation, improving efficiency. The motion of the piston (E_1) is controlled by the variable displacement reciprocating machine (E_2) connected to the generator shaft. The air compressed by the liquid piston is then stored in a pressurized vessel (D). In a traditional CAES system, the pressure in the accumulator is a function of the mass of air stored. Instead, in this system the pressure is maintained constant by continuously adding or removing the hydraulic fluid from the vessel. In this way, the pressure in the accumulator is kept constant. Moreover, both the compressor and the expander work in design conditions independently on the amount of energy stored. Hence, when mass is added to the pressure vessel, the hydraulic fluid is removed from the vessel and is expanded in the down-tower reciprocating machine. Otherwise, during the discharge phase, part of the energy produced by the turbine or by the expansion of the compressed air is used to maintain the air pressure in the vessel constant.

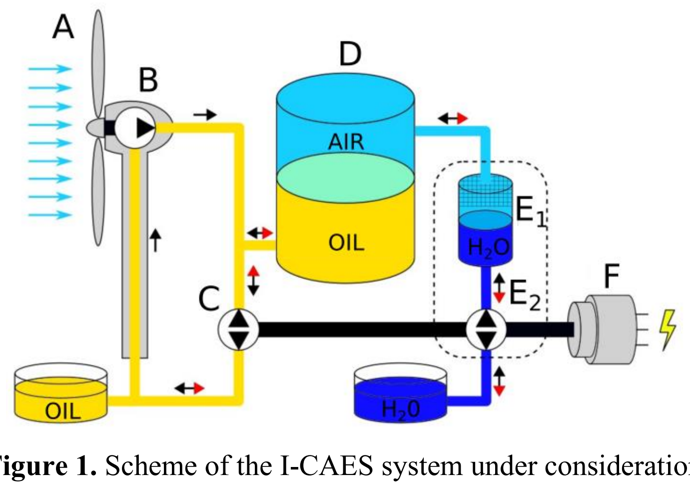

Figure 1. Scheme of the I-CAES system under consideration.

3. Methodology

The analysis of the system is carried out using a 1-minute average approach. Simulations are performed over the span of one year using real wind data in order to provide representative results of the behaviour of the system. The various components are simulated using an approach analogous to Saadat et al. [6]. For the sake of brevity, only the main equations are provided here, and the interested reader is referred to the original publication for additional details.

The NREL 5MW reference wind turbine [7] is used in this work to perform the simulations. Figure 2 shows the aerodynamic power and tip speed ratio curves as a function of wind speed.

For a given wind speed, the turbine power P_A is calculated from the power curve and consequently the torque is estimated as,

$$T_A = \frac{60}{2\pi}\frac{P_A}{\omega}, \quad (1)$$

where ω is the rotational speed of the turbine, calculated from the TSR-wind speed curve as,

$$\omega = \frac{v_\infty * \lambda}{R}. \quad (2)$$

In Eq. (2) v_∞ is the wind speed, λ is the tip speed ratio and R is the turbine radius.

The flowrate of the reciprocating pumps/expanders is controlled by modifying the displacement. The flowrate Q is calculated as,

$$Q = \frac{D}{2\pi}\frac{\omega}{\eta}, \quad (3)$$

where D is the displacement ($D > 0$ when the reciprocating machine is working as a compressor and $D < 0$ when the working cycle is inverted, and the machine is used as an expander). The rotational speed of the nacelle pump is set by the speed of the turbine. Instead, the rotational speed of the other pumps is constant and set by the generator shaft, and consequently by the grid frequency. The efficiency of the pumps/expanders η is calculated as a function of the displacement, using the efficiency map shown in Figure 3 (a). The torque required by each pump is calculated as,

$$T = -\frac{\frac{D}{2\pi}\Delta p}{\eta}, \quad (4)$$

where Δp is the pressure difference across the machine.

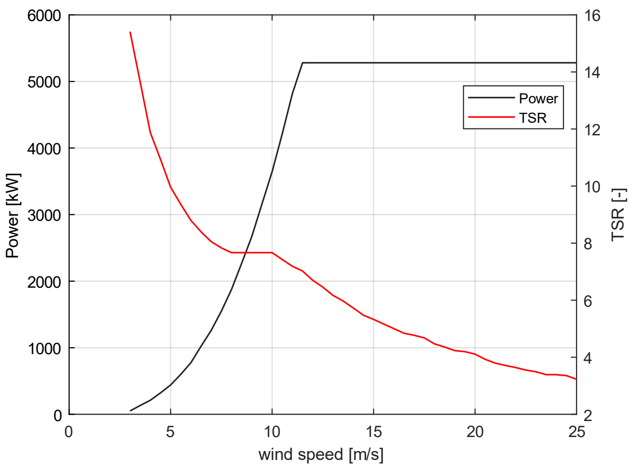

Figure 2. Aerodynamic power and TSR curve for the NREL 5MW reference turbine. Data from [7].

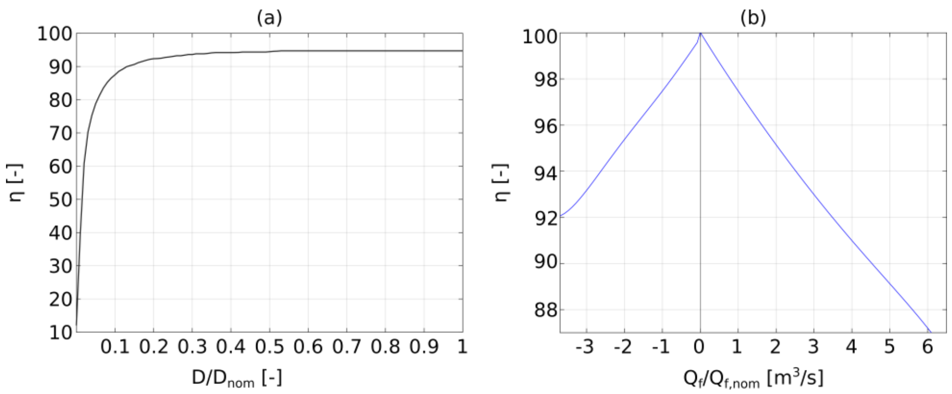

Figure 3. Efficiency curves of (a) variable displacement reciprocating machine and (b) liquid piston.

The compression and expansion of air is performed by the liquid piston. By controlling the reciprocating pump and expander (E_1), the trajectory of the transformation can be altered. Previous studies by Sadaat et al. [8] have shown that an Adiabatic-Isothermal-Adiabatic trajectory leads to an optimal tradeoff between efficiency and power density. Indeed, if the speed of the compression or expansion is increased, the same flowrate can be achieved with a reduced size of the compressor. However, increasing the rotational speed has a negative impact on the efficiency of the transformation, as the time available to exchange heat during the isothermal transformation is reduced.

The proposed transformation represents the optimal solution. Since the liquid piston performs the compression cycle at a frequency of about 1 round per second, a cycle average approach is used. Hence, the mass flowrate of air is calculated as:

$$\dot{Q}_F = \frac{hA\,|1 - T_0/T_1|}{\rho R\left[\frac{2\gamma}{\gamma - 1}\ln\left(\frac{T_0}{T_1}\right) \pm \ln(r)\right]} \tag{5}$$

where h and A are the heat transfer coefficient and surface of the porous media, respectively. For this study, the value of hA is assumed equal to 59 kW/K. The parameter R is the gas constant, γ is the ratio of the specific heats and r is the compression ratio. T_0 is the air suction temperature and T_1 is the temperature of the isothermal transformation which guarantees an optimal trade-off between power density and efficiency [9], defined as a function of the suction and discharge temperatures T_f,

$$T_1 = \sqrt{T_0 * T_f}. \tag{6}$$

3.1. Technical analysis

The analysis of the system is carried out over the span of 1 year. Real wind speed data measured in the offshore wind park of Kedros, Greece, is used. The wind data, measured in 2015, was provided by the owner of the wind farm and was measured from a mast at intervals of 10 minutes. The time resolution of the wind data was increased using the methodology described by Galli et al. [10]. The Weibull distribution of the resulting dataset is shown in Figure 4.

The performance of the system is evaluated in terms of Annual Energy Production (AEP) and Capacity Factor (CF). AEP represents the total energy production over the span of 1 year. CF is defined as the ratio between the AEP and the energy that the system would produce working at nominal power over the same time span,

$$CF = \frac{AEP}{P_{nom} \cdot T} \tag{7}$$

where P_{nom} is the nominal power and T is time span duration in hours.

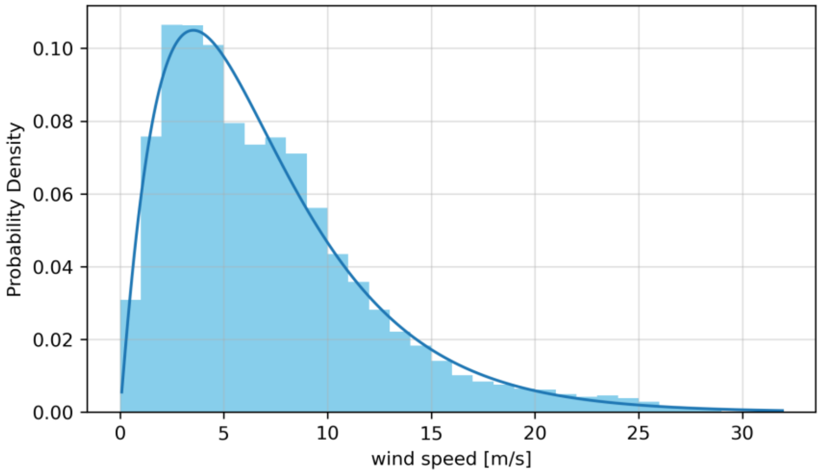

Figure 4. Weibull distribution of the input wind dataset.

3.2. Economic analysis

The economic performance of the system is evaluated in terms of Net Present Value (NPV). The NPV is defined as,

$$NPV = I_0 + \sum_{n=1}^{N} \frac{R_n}{(1+i)^n} \tag{8}$$

where R_n is the cash flow for year n, and i is the interest rate, which is set to 5% in this work. The cash flow is calculated multiplying the energy generation by the hourly averaged energy price in Italy. The average price was calculated for each hour of the year averaging the historical hourly national price (PUN) from 2013 to 2020. In this way, the analysis accounts for daily and seasonal differences in energy prices, such as those between day and night.

The initial investment cost is calculated for each component from available correlations. The total capital investment for a traditional wind turbine is calculated assuming a cost of 1000 €/kW [11]. For the analysed CAES system, no gearbox is required, hence the cost $C_{gearbox}$ is calculated as function of the rated power P_n [12],

$$C_{gearbox} = 15.134 \cdot P_n^{1.249} \tag{9}$$

and is subtracted from the investment cost. Analogously, the cost of the generator $C_{generator}$ is calculated as a function of P_n [12],

$$C_{generator} = 65 \cdot P_n \tag{10}$$

Hence, the reduction in initial investment obtained by downsizing the generator is estimated.

The cost of the reciprocating machines C_P is calculated as a function of the peak power P_p as [13],

$$C_P = 3279.4 \cdot P_p^{0.5787} \tag{11}$$

The capital investment for the pressurized vessel C_{vessel} is calculated as function of its volume V as in [14]:

$$C_{vessel} = 6051 \cdot V^{0.6488} \tag{12}$$

The same approach is used to estimate the NPV for both the CAES system and a traditional one. However, in the case of the traditional system, the effect of a penalty scenario is included. As the penetration of renewable energy increases, national grids may introduce economic penalties in case of excessive oscillations in energy production, which have a negative effect on system stability. In this work, the penalties introduced are about 21.52 €/MW in case of a ramp up violation higher than 10% over a 1-minute timeframe and 26.50 €/MW in case of a ramp down violation. Values are selected in analogy with the study in [15]. The penalties are applied only to the traditional system, as it is assumed that the CAES system allows the reduction of energy production oscillations.

4. Results

Results are organized as follows. First, Sect. 4.1 shows a grid-connected application of the analysed system, where electricity is sold to the grid at a constant power equal to the generator size. Then, in Sect. 4.2, the system is analysed in a stand-alone configuration with the aim to cover a 1 MW constant load. In this case, results are compared with an equivalent battery storage system.

4.1. Grid connected system

Results of the grid-connected configuration compare the techno-economic outcome of a traditional turbine with the proposed design, that includes the CAES system, considering a parametric analysis varying both storage and generator sizing. Generator sizes from 0.5 MW to 2.5 MW are considered and coupled with storage sizes from 1000 to 7000 m^3, obtained by scaling the sizing of the analysis performed by Saadat et al. [6]. Figure 5 (a) and (b) show the wind speed and corresponding power production of the standalone wind turbine during the first three months of the dataset. During these three months, it can be observed how the site is characterized by multiple days where the wind speed is below 5 m/s, resulting in minimal energy production by the wind turbine. This in turn results in a capacity factor of 36% during this time frame. Additionally, large variations in power output are observed.

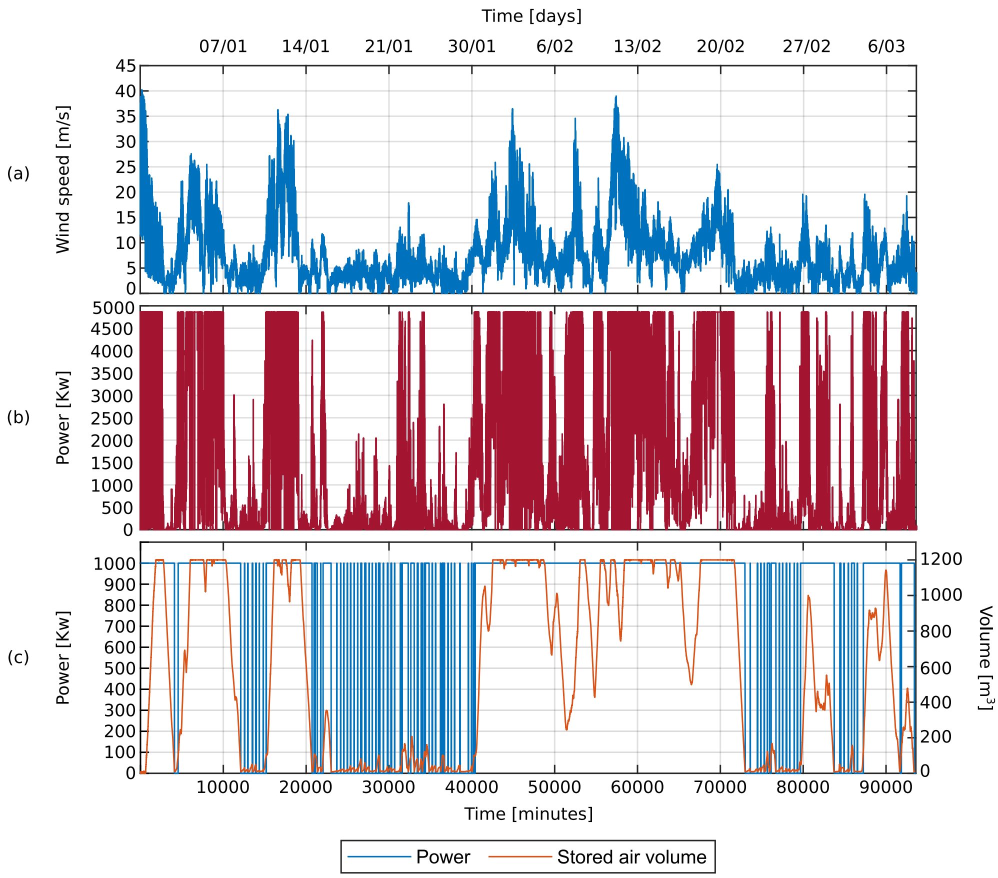

Figure 5. Results of three-month sample analysis. (a) Wind speed time-series (b) Power output of standalone turbine (c) Power output and volume of compressed air stored in the pressurized tank.

In contrast, Figure 5 (c) shows the power production of the wind turbine coupled with the CAES system during the same time period, together with the trend of the volume of compressed air stored in the vessel. The results are presented for a generator size of 1 MW and a storage volume of 1200 m^3, resulting in a CF of 71%. Over these three months, the capacity factor of the CAES system is almost double in comparison to the standalone wind turbine. However, for this combination of generator and vessel size, the energy production is reduced by 60%. Indeed, when the wind production is high, and the storage reaches maximum capacity, part of the energy is not captured due to the reduced generator size. Additionally, the reduced energy production is caused by the limited efficiency of the system. Figure 6 shows the efficiency of each component of the system under charge and discharge states. Even though the liquid piston reaches an efficiency up to 90% during loading and unloading of the system, the inclusion of multiple components and higher complexity of the powertrain leads to a significant reduction in efficiency. Overall, the system achieves an efficiency of 75% under charging conditions, and 68% under discharge conditions, resulting in a round-trip efficiency around 51%. As previously observed by Saadat et al. [6], the down-tower pump achieves the smallest efficiency during discharge. Indeed, during this condition, the pump elaborates small amounts of liquid to maintain the pressure in the vessel constant, working in sub-optimal conditions.

Different configurations were analysed during the same one-year time frame to test different storage dimensions and generator sizes, as the sizing of these two components is crucial for the performance of this system. For different configurations, Figure 7 shows the capacity factor (continuous lines), and the annual energy production of the I-CAES system divided by the production of the stand-alone wind turbine AEP_0 (dashed lines). Increasing the capacity of the high-pressure vessel leads to an increase of the capacity factor, as the system can store more excess energy and deliver it in low-wind conditions. For a generator ten times smaller than design (500 kW), the wind turbine produces a significant amount of excess energy. Due to the small size of the generator, the storage is filled frequently, and the system cannot extract energy fast enough. Above certain tank sizes, the annual energy production and capacity factor only improve slightly with an increase in storage capacity.

Similarly, if the size of the generator is only reduced by a factor of two (2.5 MW), the capacity factor is not affected significantly by an increase of the volume of the storage, as the excess energy is used to maintain the higher load and a high capacity storage tank never reaches full capacity. From the results of the parametric analysis performed with varying generator sizes and storage volumes, the best configuration of the system can be identified depending on the application. Despite the increases in capacity factor and annual energy production shown in the previous section, the sizing of the storage vessel and generator is carried out by comparing the economic performance of the different plant configurations. In particular, the optimal sizing of the high-pressure vessel is crucial as it accounts for up to 25% of the initial investment cost.

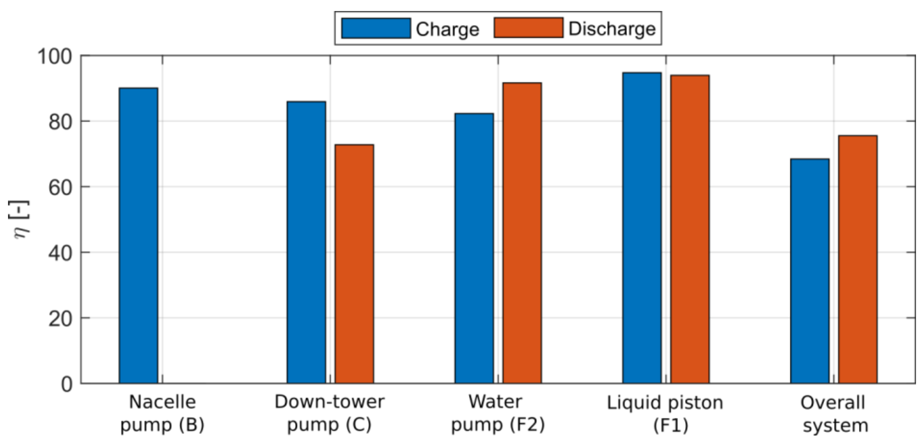

Figure 6. Summary of efficiencies for each component under charge and discharge states

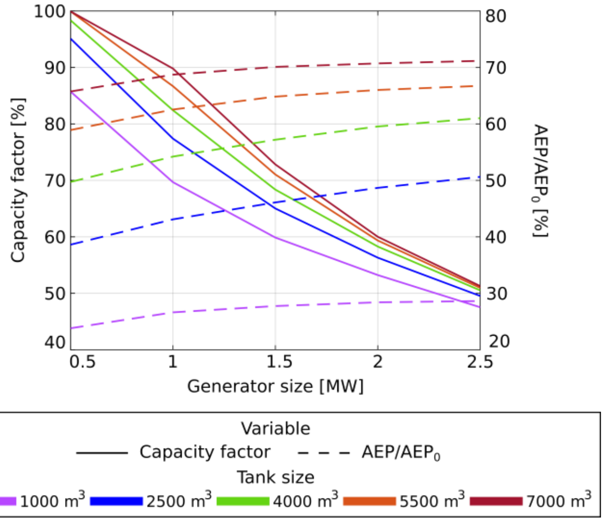

Figure 7. Capacity factor (CF) and normalized Annual energy production (AEP/AEP_0) of the system as a function of generator and storage size. Solid lines represent the CF and dashed lines the AEP.

Figure 8(a) shows the comparison of the NPV for the 1 MW generator size with varying storage size, and the NPV deriving from the installation of the stand-alone 5 MW wind turbine (black line). In this case, the CF of the I-CAES system reaches a value of up to 70% for the smallest storage size. However, the system is never profitable over a 40-year period. This is due to the reduced AEP, as when the vessel is full, part of the energy extracted by the turbine must be discarded. Indeed, the best option in this case is represented by the largest storage, even though the large investment costs are never recovered.

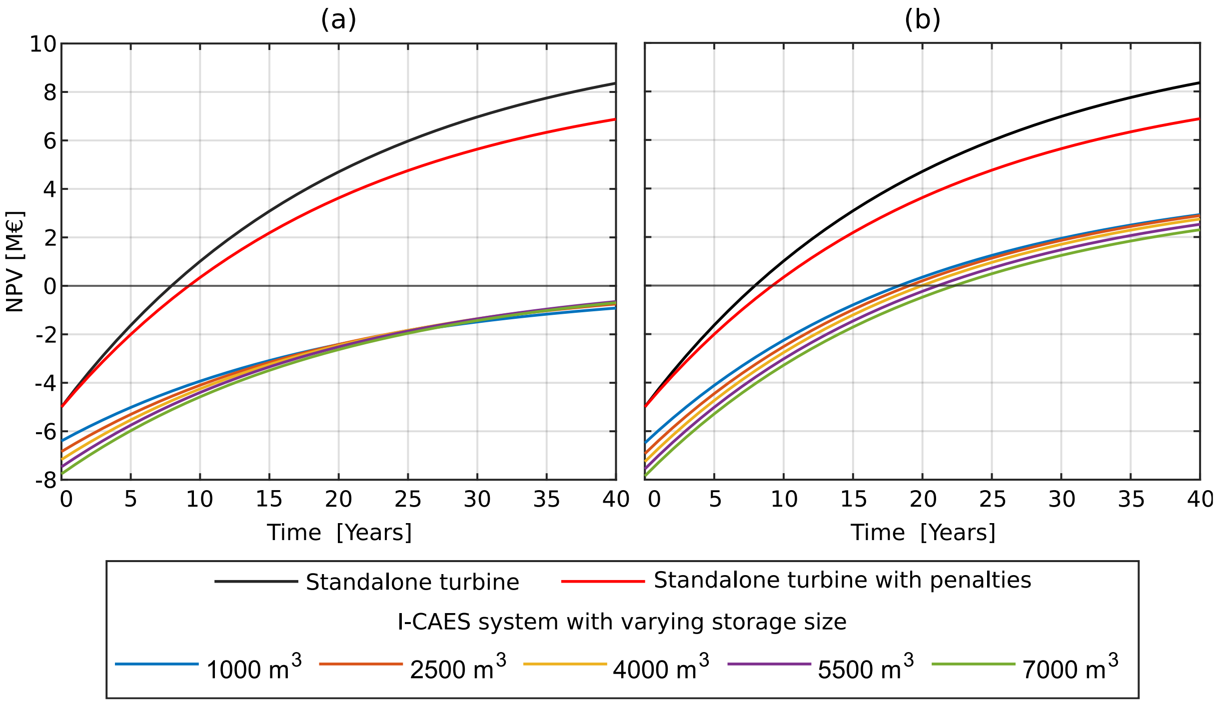

Figure 8. NPV of the analysed system in a grid-connected configuration for varying storage sizes. (a) 1 MW generator (b) 2.5 MW generator size.

No major differences are observed even when an economic penalty is applied to the standalone wind turbine (red line) in case of power oscillations larger than 10 % in a 1-minute time window (see Section 3 for further details on the introduced penalties). Significant improvements are instead observed if the size of the generator is reduced to only half of the standalone value (Figure 8(b)). In this case, the system becomes profitable after 18 to 22 years, depending again on the size of the pressure vessel. The best performance after a 40-year lifespan is achieved by the configuration with a storage size of $2500\ \mathrm{m}^3$. The introduction of a storage with even higher capacities increases the investment cost and is not compensated by a significant raise of the energy production. Nevertheless, the traditional system is considerably more profitable than the optimal solution of the analysed study, even when penalties are introduced. Despite the reduction of the investment cost achieved by downsizing the electrical parts, the shifting of energy production with the CAES does not compensate for the increase in investment costs due to the additional components.

4.2. Standalone system

The analysis of the grid-connected turbine coupled with the I-CAES shows that this solution is presently economically inconvenient. Nevertheless, this system could represent a valid alternative to battery energy storage systems to satisfy fairly constant loads, i.e., whenever high capacity factors are needed, such as, for example, in desalinization plants and data centres. To prove this assumption, it is here hypothesized a scenario in which a 1 MW constant load must be covered by the generator so as to achieve a self-consumption of 90%. Although the coupling of the system with a load profile is out of the scope of this work, this analysis can provide insight into possible scenarios where the proposed system could perform better than traditional battery systems. The I-CAES system is then compared with an equivalent battery energy storage system using lithium-ion batteries to achieve an analogous self-consumption. In this case, the generator size is kept at 5 MW, and the excess power produced is used to charge the battery. The li-ion battery storage model applied in this work is the same used and described in [16], and is characterized by a round-trip efficiency around 80%. The required capacity of the battery was estimated to 90 MWh in order to achieve the target self-consumption in feeding a constant load of 1 MW. In terms of energy storage, the size of the battery is 43% smaller than the compressed energy storage with a capacity of 160 MWh. This is the case due to the reduced round-trip efficiency of the I-CAES energy system, which requires a larger storage size to guarantee the same self-consumption. Figure 9(a) shows the hourly average power production of the standalone turbine and of the wind turbine coupled with a BESS. As it can be observed, the power produced by the wind turbine shows significant oscillations during the year. When the battery storage is added, the system can cover the 1 MW load, similarly to the I-CAES system (Figure 9(b)). In comparison to the standalone turbine, the self-consumption is increased from 58.2% to about 90%.

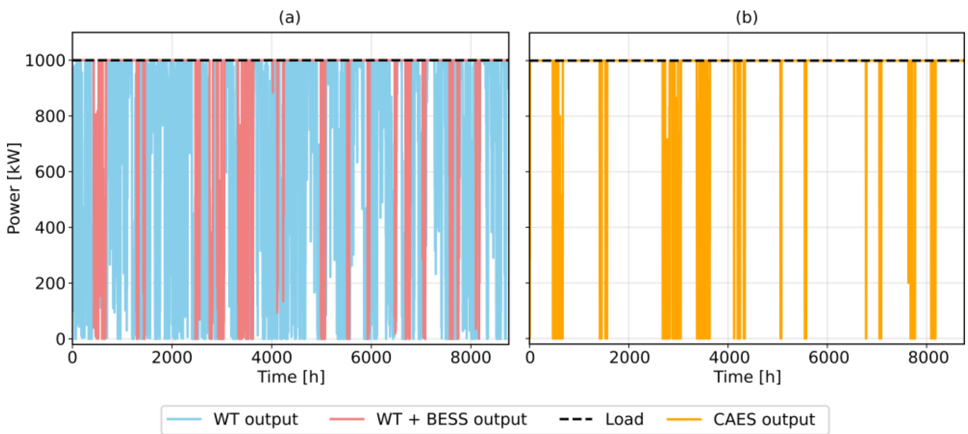

Figure 9. Power output of a) the standalone wind turbine and BESS and b) I-CAES system to feed a 1 MW constant load.

Despite the higher round-trip efficiency of the BESS, the CAES system represents a good candidate to reduce costs when feeding a constant load. Indeed, assuming a 200 €/kWh [17] cost for lithium-ion batteries, the total investment cost is about 22 M€, hence three times larger than the one achieved with the equivalent I-CAES system. The significant difference in terms of capital cost shows how the proposed solution may prove a valid alternative to battery storage system, when working in a standalone configuration. The main difference between the two cases is represented by the cost of the storage system, as the pressure vessel makes up only 25% of the total investment, offsetting the cost of the additional reciprocating machines (Figure 10). The downsizing of the electrical components is also favourable for the I-CAES system, even though the advantage is limited as they make up only 4% of the cost in the BESS solution.

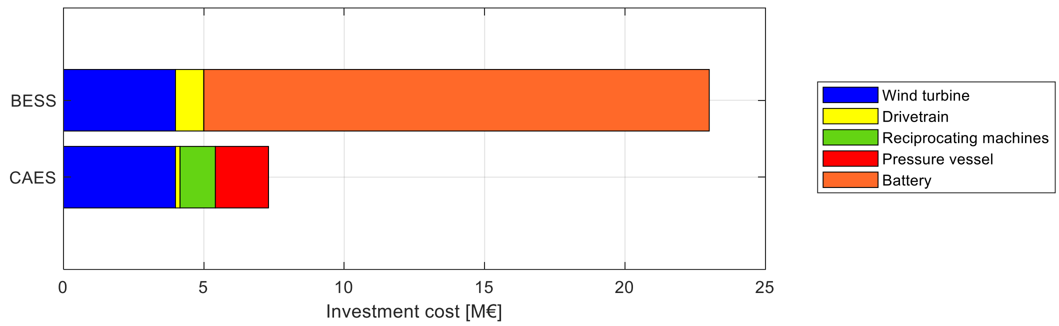

Figure 10. Breakdown of investment cost for required CAES and BESS sizes to feed a constant 1 MW load with a 90% self-sufficiency.

5. Conclusions

In the study, the innovative system proposed by Saadat et al. in 2014 is analysed to assess the real techno-economic outcome of the direct coupling of a wind turbine with a compressed air energy storage system. Even though the integration of CAES and hydraulic drive systems represents an interesting alternative to other storage means, a long-term techno-economic analysis of the system was still lacking.

The performance of the system has been evaluated using one-year wind data. Results show how the downsizing of electrical components and the elimination of the gearbox do not lead to a better economic performance of the system in a grid-connected configuration. Even current penalty proposals for fluctuating power outputs are insufficient to make the system feasible, despite a significant increase in capacity factor.

On the other hand, the system shows significant advantages in comparison to the introduction of lithium batteries as energy storage when a fairly constant load, such as that characteristic of a desalinisation plant or a data centre, needs to be satisfied. In that case, the analysed system requires a total investment cost that is three times smaller than the battery storage alternative.

Given the significant advantages of the system for these specific load cases, future work could evaluate the performance of the system in a micro-grid, where a time-varying load needs to be satisfied completely by wind energy.

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