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ECONOMIC FEASIBILITY OF COMPRESSED AIR ENERGY STORAGE: PORTUGUESE PRE-SELECTED CASE STUDIES

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ABSTRACT

New challenges arise with the increasing integration of renewable energies into the energy grid. One of the possible solutions for challenges such as balancing supply and demand, or the adequacy of power, may be energy storage, which can perform a vital role in future grids. Compressed air energy storage (CAES) is a large-scale energy storage system with long-term capacity for utility applications. This study evaluates the economic feasibility of CAES pre-selected reservoirs case studies for the Portuguese electricity system. It analyzes several scenarios for each case study and assesses two business models: one for the storage of excess renewables and another for energy arbitrage. The novelty of this work is the investment assessment approach using a Monte Carlo Simulation (MCS) methodology applied to CAES, taking into account several uncertainties associated with a CAES project. The financial indicators assessed include Net Present Value (NPV), Internal Rate of Return (IRR), Discounted Payback period, and Levelized Cost of Energy (LCOE). The results suggest a better performance from the CAES RES business model than the CAES arbitrage business model. Furthermore, the diabatic CAES assessed scenarios seem to have more attractive results than their equivalent adiabatic CAES systems in the CAES RES business model.

Introduction

In a world moving towards a low carbon economy where the integration of increasing renewable energy sources (RES) represents a challenge for the energy grids, energy storage plays an essential role. Among several energy storage technologies, compressed air energy storage (CAES) is one of the few technologies that support large-scale energy storage and grid applications having the ability to store tens or hundreds of MW of power capacity (Succar & Williams, 2008).

Portugal is one of the European countries with high shares of electricity generation from RES (APREN, 2019), and it also has several underground formations suitable as potential CAES geological reservoirs (Carneiro et al., 2019). Therefore, the best suitable CAES reservoirs for the country have been selected in the study by Matos et al. (2021). However, to understand if CAES is viable for the country's energy system, it is necessary to perform an economic analysis. So, in this study, the investment assessment of the pre-selected CAES case studies is conducted to evaluate CAES feasibility for Portugal.

Literature Review

In a CAES plant, when power is abundant and demand is low, the off-peak power from the grid or the electricity generated from RES is used to compress ambient air. This compressed air is stored under pressure in underground geological reservoirs (for large-scale CAES) or at surface reservoirs such as tanks or pipes (for small-scale CAES). Later, when power demand requirements are high, the pressurized air is released back up to the surface, where it is heated and expanded, rushing through a turbine and driving a generator to produce electricity (Budt et al., 2016) (Venkataramani et al., 2016). For large-scale CAES, the underground reservoirs are geological formations that may be host rocks (engineered rock caverns or abandoned mines), salt formations (salt domes or bedded salt), and porous media (saline aquifers or depleted hydrocarbon fields)(Matos et al., 2019).

CAES economic concepts and indicators were retrieved from financial literature to establish a background for the investment assessment and to understand the main drivers and factors that should be considered. The financial indicators that are the most often used to assess the economics of a project include Net Present Value (NPV), Internal Rate of Return (IRR), Discounted Payback Period (PBP), and Levelized Cost of Energy (LCOE) (Zweifel & et al., 2017).

The costs of installing a CAES plant are dependent on many factors, such as geological factors, facility size, operating technology, containment vessel, fuel prices, and intended use (Carnegie et al., 2013). Still, (Carnegie et al., 2013) argues that CAES is very site-specific, it has high up-front costs, but low variable Operation & Maintenance (O&M) costs. In addition, the costs of CAES also depend on the CAES technology used, and they may vary within diabatic CAES (D-CAES)[1] and Adiabatic CAES (AA-CAES)[2].

On the one hand, Madlener & Latz (2013) studied centralized and decentralized CAES for enhanced grid integration of wind power parks with 100 MW installed capacity. They stated that CAES is economically viable and that the diabatic systems had more attractive results and are more profitable than the adiabatic systems. However, they state that despite diabatic CAES systems being more profitable than adiabatic systems, the ecological disadvantage of NG use and related CO_2 emissions directly undermines the advantage of feeding on renewable (wind) power. On the other hand, Gu et al. (2013) simulated a CAES model and evaluated its economic performance stating that besides profits from the energy arbitrage, CAES could also get significant profits by providing high-quality reserves in the ancillary services market. The same authors concluded that the siting and sizing of CAES will drastically affect the profitability of CAES as a result of transmission congestions.

More recently, Hammann et al. (2017) assessed the economic feasibility of a CAES system under market uncertainty with a real options approach. They conducted an economic evaluation with different configurations considered for both diabatic and adiabatic CAES. They concluded that investment in a diabatic CAES is the most economical option for load-leveling purposes.

Lately, He et al. (2021) performed a techno-economic assessment of geological resources for bulk-scale CAES and its optimal planning framework combined with solar and wind power generation systems. They utilize existing underground salt caverns in the UK, revealing up to 725 GWh of ready-to-use capacity. Their results indicate the achievable cost-effectiveness of CAES as bulk-scale energy storage for power system decarbonization in countries the geological resources are available.

Methodology

The methodology used for the conducted economic analyses of the pre-selected CAES case studies is based on the evaluation of financial and investment projects and adapted for the particular situation of CAES projects in Portugal.

Thus, two case studies were assessed, one in Monte Real/Carriço and another in Sines LPG (Matos et al., 2021). For those case studies, six scenarios were established, four for Monte Real and two for Sines (Table 1). Scenario 1 and scenario 5 are considered the reference cases in Monte Real and Sines case studies (table 1). The scenarios are distinguished by the CAES technology considering D-CAES and AA-CAES and by utilizing a pre-existing underground cavern or a newly built cavern. Finally, two business models were evaluated for all the scenarios, the first one for a CAES RES business model[3] and a second one for a CAES arbitrage business model[4].

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[1] In Diabatic CAES, the heat resulting from air compression is wasted in the environment by cooling down the compressed air and an external heat source is needed for the discharging process (Budt et al., 2016).

[2] In adiabatic CAES no net external heat source is used, meaning that a Thermal Energy Storage (TES) device is used to avoid the use of additional energy and to capture the heat expelled in the compression process and later uses the stored thermal energy to preheat the air during the expansion process (Budt et al., 2016).

[3] CAES RES business model is based on the principle that a CAES facility can be integrated with RES existing infrastructures like generators such as wind farms or solar PV power plants.

[4] CAES arbitrage business model assumes an energy arbitrage trade, meaning the CAES facility would store energy bought during a low demand period and then sell it in a high demand peak.

Table 1. Definition of CAES scenarios to be assessed in the economic and investment analyses depending on CAES technology (D-CAES or AA-CAES) or cavern type (using a pre-existing cavern or building a new one).

Case Study	Technology	Scenario	Underground Cavern	Reference Case
#1 Monte Real / Carriço	D-CAES	1	Using one pre-existing salt cavern	Ref. Case
		2	Building a new salt cavern	
	AA-CAES	3	Using one pre-existing salt cavern	
		4	Building a new salt cavern	
#2 Sines LPG	D-CAES	5	Using one pre-existing LPG cavern in host Rock	Ref. Case
	AA-CAES	6	Using one pre-existing LPG cavern in Host Rock	

The steps of the defined methodology are: setting all the assumptions, costs, and revenues, establishing probable scenarios for each case study, conducting Monte Carlo Simulations (MCS) and stochastic analyses for risk assessment based on a discounted cash flow approach, and calculating the financial indicators for every probable scenario assumed, both case studies and business models.

To perform an MCS is necessary the selection of input variables that can cause some sort of change in the output parameters (Zaroni et al., 2019). Thus, variables such as the cavern volume, the output power, the electricity production, the electricity prices, the NG prices, the NG heat rate, the CAPEX, the OPEX, and the cost of capital are uncertainties simulated. Next, the MCS method generates random values for the stochastic analysis, with 5,000 simulations for each scenario.

CAES Economic Model

CAES economic model for both case studies and business models has assumed parameters related to the CAES total costs (underground cavern costs, surface facility, and machinery costs). So, investment costs or CAPEX, operation & maintenance costs (O&M) or OPEX, the facility's lifetime, energy prices (electricity and NG), taxes, depreciation rates, the discount rate, and the revenues were assessed.

The CAES plant's useful lifetime is assumed to be 40 years starting at year one of production, based on Huntorf's CAES plant lifetime, running since 1978 (Crotogino et al., 2001), and McIntosh CAES facility running since 1991 (Succar & Williams, 2008). The assumed number of days per year in operation is 350 days or cycles. The CAES plant stops only around fifteen days per year for O&M purposes. The number of hours per cycle is 12h since it was determined that with a twelve-hour daily cycle, according to the REN Data Hub (2021) daily electricity load diagrams for Portugal, CAES could better fit the load variations and the demand needs especially considering RES such as wind and solar. The annual plant production degradation is equal for all the scenarios and assumed to be 0,5%.

For the assumed scenarios (Table 1), D-CAES and AA-CAES round-trip efficiencies assumed are 50% (with a heat recuperator) and 70 % (with a TES), respectively. The used fuel in D-CAES is natural gas (NG), and its consumption is given by the average heat rate (HR) value assumed to be around 4330 KJ/KWh (Table 2) based on the CAES McIntosh value (Bozzolani, 2010).

The CAPEX and OPEX differ according to the case study, the scenario, and the CAES technology type, which is the reason why they are detailed in the section of the results. The CAPEX values are composed of underground investment costs and surface facility equipment and machinery costs. For calculation purposes, CAPEX is accounted for all at once, as if it was released in one tranch of 100% at the beginning of the first year. In the OPEX, the costs are divided into fixed and variable from the underground and surface facilities.

As far as the energy prices, electricity and natural gas prices were assessed for the whole year of 2020 to obtain a period big enough to embrace the variations of these high volatility energy markets. Therefore, the electricity prices (MIBEL, 2020; Omie, 2020) and the NG prices (MIBGAS, 2021) (Omip, 2021) are depicted in table 2. These prices were then used as a proxy for CAES cash flow calculation in the OPEX and the CAES power plant production for all the scenarios.

Table 2. Energy prices (electricity and NG) on the spot market for 2020; minimum, average, and maximum prices for the whole year (Omie, 2020; Omip, 2021), and NG Heat Rate (HR) (Bozzolani, 2010)

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	Electricity Price on Spot Market	**Gas Prices on Spot Market**	**NG Heat Rate (HR)**
(January to December 2020)	*(€/MWh)*	*(€/MWh)*	*(KJ/kWh)*
Minimum	1,02	3,81	4100
Average	**33,99**	**10,51**	**4330**
Maximum	62,38	23,5	4500

Several financial assumptions were also made considering the dimension of the CAES project. First, a significant part of capital should be external based on similar projects, assuming 60% on loan capital and 40% on equity. For loan capital, the maximum amortization period was estimated at 40 years (CAES's project lifecycle duration); however, the years of the loan will be 15 years. The annual average interest rate on loans (greater than 1 million €) to companies at the end of 2019 was 1,85%, according to Banco de Portugal (2021). So, this was the adopted interest rate for 2020 plus the Euribor rate at 12 months (usually used for companies) of -0.442% in October of 2020 (EuriborRates.eu, 2020).

The capital cost on equity is the most uncertain value depending on the type of investor, the company situation, the market, or the business model, but typical values can vary between a minimum of 3,5%, a maximum of 11%, and a most likely value of 8% (Goedhart et al., 2002; McKinsey & Company, 2020)

The inflation rate is challenging to forecast, but an average inflation rate of 2% was assumed for 40 years.

The Portuguese national tax for companies (IRC) is around 21% (eportugal.gov.pt, 2021), plus the municipal tax for companies estimated for 40 years at 4%, which sums up 25% of assumed taxes.

Finally, the equipment depreciation rate varies depending on the type of facility or equipment and can be 2%, 2,5%, and 10%.

Monte Real / Carriço Case Study

Monte Real /Carriço case study is a salt formation with some salt caverns used to store NG reserves for Portugal. Therefore, the uncertainty inputs of this case study are the cavern volume, which directly influences inputs like output power and electricity production (Table 3). In addition, the values of the cost of capital (Table 3) are also uncertain, so they are simulated too.

Table 3. Cavern volume, output power, electricity production, and cost of capital/equity inputs for the MCS of Monte Real / Carriço CAES case study.

	Cavern Volume	**Output Power**	**Electricity Production**	**Cost of Capital/Equity**
	(m3)	***(MW)***	***(€/MWh)***	***(%)***
Minimum	200 000	100	420 000	3,50%
Most Likely	500 000	200	840 000	8,00%
Maximum	800 000	300	1 260 000	11,00%

The CAPEX and OPEX (fixed costs) are also considered uncertainty values for the MCS, varying around 10% down and 15% up (Obi et al., 2017). The values assumed for each scenario and all the components of CAES (Table 4) are capitalized with the simulated cost of capital (from Table 3) and considered the most likely CAPEX and OPEX fixed costs and then used to apply the mentioned variation of less 10% as a minimum and more 15% as a maximum.

Table 4. Table depicting the CAPEX and OPEX values for the Monte Real / Carriço case study.

Monte Real / Carriço Case Study			
Scenario 1 (D-CAES using a pre-existing salt cavern)			
	CAPEX (€)	**OPEX (€)**	***Lifetime***
Sub-Surface facilities:			
Underground salt cavern (500 000m3) and equipment	0	151 000	50
Surface facilities:			
Compression Module (set 3 compressors)	13 500 000	150 000	40
(Plus, automation components)	1 000 000	0	10
Expansion Turbine module (Gas turbine) (set 2 turbines, HP and LP)	13 500 000	150 000	40
(Plus, automation components)	1 000 000	0	10
Heat recuperator unit	20 000 000	80 000	40
and Heat exchangers	3 400 000	0	40
Motor and generator	16 000 000	120 000	40
Total Costs	**68 400 000**	**651 000**	
Scenario 2 (D-CAES using a newly built salt cavern)			
	CAPEX (€)	**OPEX (€)**	***Lifetime***
Sub-Surface facilities:			
Underground salt cavern (500 000m3) and equipment	35 000 000	151 000	50
Surface facilities:			
Compression Module (set 3 compressors)	13 500 000	150 000	40
(Plus, automation components)	1 000 000	0	10
Expansion Turbine module (Gas turbine) (set 2 turbines, HP and LP)	13 500 000	150 000	40

(Plus, automation components)	1 000 000	0	10
Heat recuperator unit	20 000 000	80 000	40
and Heat exchangers	3 400 000	0	40
Motor and generator	16 000 000	120 000	40
Total Costs	**103 400 000**	**651 000**	
Scenario 3 (AA-CAES using a pre-existing salt cavern)			
	CAPEX (€)	**OPEX (€)**	***Lifetime***
Sub-Surface facilities:			
Underground salt cavern (500 000m3) and equipment	0	151 000	50
Surface facilities:			
Compression Module (set 3 compressors)	13 500 000	150 000	40
(Plus, automation components)	1 000 000	0	10
Expansion Turbine module (Gas turbine) (set 2 turbines, HP and LP)	13 500 000	150 000	40
(Plus, automation components)	1 000 000	0	10
Thermal storage system (TES)	36 000 000	120 000	40
and Heat exchangers	3 400 000	0	40
Motor and generator	16 000 000	120 000	40
Total Costs	**84 400 000**	**691 000**	
Scenario 4 (AA-CAES using a newly built salt cavern)			
	CAPEX (€)	**OPEX (€)**	***Lifetime***
Sub-Surface facilities:			
Underground salt cavern (500 000m3) and equipment	35 000 000	151 000	50
Surface facilities:			
Compression Module (set 3 compressors)	13 500 000	150 000	40
(Plus, automation components)	1 000 000	0	10
Expansion Turbine module (Gas turbine) (set 2 turbines, HP and LP)	13 500 000	150 000	40
(Plus, automation components)	1 000 000	0	10
Thermal storage system (TES)	36 000 000	120 000	40
and Heat exchangers	3 400 000	0	40
Motor and generator	16 000 000	120 000	40
Total Costs	**119 400 000**	**691 000**	

Sines LPG Case Study

Sines LPG case study is a host rock cavern used to store liquified petroleum gas (LPG) in the sub-volcanic massif of Sines. Its uncertainty inputs are similar to the previous case study (Table 5); however, its values are different since the cavern volume is smaller.

Table 5. Cavern volume, output power, electricity production, and cost of capital/equity inputs for the MCS of Sines LPG case study.

	Cavern Volume	**Output Power**	**Electricity Production**	**Cost of Capital/Equity**
	(m3)	***(MW)***	***(€/MWh)***	***(%)***
Minimum	50 000	20	84 000	3,50%
Most Likely	80 000	50	210 000	8,00%
Maximum	100 000	80	336 000	11,00%

The input values for components of CAES in all Sines LPG scenarios (Table 6) are capitalized with the simulated cost of capital (from Table 5) and assumed as the most likely CAPEX and OPEX fixed costs, which then vary 10% down and 15% up.

Table 6. Table depicting the CAPEX and OPEX values for the Sines LPG case study.

Sines LPG Case Study			
Scenario 5 (D-CAES using a pre-existing host rock cavern)			
	CAPEX (€)	**OPEX (€)**	***Lifetime***
Sub-Surface facilities:			
Underground host rock cavern (80 000m3) and equipment	0	151 000	50
Surface facilities:			
Compression Module	11 000 000	150 000	40
(Plus, automation components)	1 000 000	0	10
Expansion Turbine module (Gas turbine)	11 000 000	150 000	40
(Plus, automation components)	1 000 000	0	10
Heat recuperator unit	14 000 000	80 000	40
and Heat exchangers	3 400 000	0	40
Motor and generator	14 000 000	120 000	40

Total Costs	**55 400 000**	**651 000**	
Scenario 6 (AA-CAES using a pre-existing host rock cavern)			
	CAPEX (€)	**OPEX (€)**	***Lifetime***
Sub-Surface facilities:			
Underground host rock cavern (80 000m3) and equipment	0	151 000	50
Surface facilities:			
Compression Module	11 000 000	150 000	40
(Plus, automation components)	1 000 000	0	10
Expansion Turbine module (Gas turbine)	11 000 000	150 000	40
(Plus, automation components)	1 000 000	0	10
Thermal Storage	25 000 000	120 000	40
and Heat exchangers	3 400 000	0	40
Motor and generator	14 000 000	120 000	40
Total Costs	**66 400 000**	**691 000**	

Results And Discussion

The MCS conditions and inputs presented in CAES economic model section are valid for both business models (CAES RES and CAES Arbitrage business models), with the particularity that in the arbitrage model, it is necessary to buy all the electricity at its lowest price and then sell it at its highest.

The summary of the average results for all the scenarios, both case studies and business models obtained through the MCS method, are presented in Table 7 for the CAES RES business model and Table 8 for the CAES arbitrage business model. The NPV, the IRR, the discounted PBP, and the LCOE were evaluated for all the scenarios in the MCS probability function graphs.

Table 7. Summary of the mean values of the economic indicators results for the stochastic analysis of all CAES RES business model scenarios.

Stochastic analysis - CAES RES Business Model				
Scenarios	**IRR (%)**	**NPV (€)**	**Discounted Payback (years)**	**LCOE (€/MWh)**
S.1	24,22%	136 478 866	6	4,66
S.2	15,21%	91 463 771	10	5,9
S.3	19,18%	115 683 873	7	5,17
S.4	13,07%	74 662 106	12	6,41
S.5	3,10%	-25 344 566	N.A.	15,05
S.6	-	-39 997 813	N.A.	16,61

After analyzing the probability functions of economic indicators for the CAES RES business model (Table 7), it is noticed that all the four Monte Real scenarios are viable; having positive NPV values, IRR higher than the assumed cost of capital, discounted PBP smaller than the useful facility's lifetime, and small LCOE values. For instance, for scenario 1 (considered as the reference case for Monte Real), NPV has a 95% chance of being between 75,90 M€ and 231,91 M€, with a standard deviation of 40 M€; IRR with a 95% probability of being between 17,70% and 33,57%, with a standard deviation of 4,07; the investment would be recovered after six years of operation; and LCOE has a 95% probability of being between 4,33 and 5,01 €/MWh, and a standard deviation of 0,17 €/MWh.

In the Sines case study, the probability functions show that both scenarios are not feasible since most economic indicators show negative signs (Table 7). Moreover, the reference case for Sines is scenario 5, showing a 99,6% probability of the NPV being negative with a negative mean value of -25 344 566 € and a standard deviation of 8 605 317 €; an IRR with a 95% probability of being between 1,19% and 5,12%, presenting a standard deviation of 0,99%; a discounted PBP that demonstrates that the investment made will never be recovered; and an LCOE with a 95% chance of being between 13,86 and 16,41 €/MWh and a standard deviation of 0,66 €/MWh.

Additionally, the more profitable scenarios are scenarios 1 and 3 (both in Monte Real) since, in both cases, a pre-existing salt cavern is assumed to be used for compressed air storage, significantly decreasing investment costs.

Table 8. Summary of the mean values of the economic indicators results for the stochastic analysis of all CAES Arbitrage business model scenarios.

Stochastic analysis - CAES Arbitrage Business Model				
Scenarios	**IRR (%)**	**NPV (€)**	**Discounted Payback (years)**	**LCOE (€/MWh)**
S.1	6,11%	-11 957 512	N.A.	39,89
S.2	2,14%	-56 972 607	N.A.	41,14
S.3	11,90%	40 476 180	14	30,4
S.4	7,71%	-545 585	N.A.	31,64
S.5	-	-62 454 141	N.A.	50,28
S.6	-	-58 800 216	N.A.	41,84

For the CAES arbitrage business model, five of the analyzed scenarios in both case studies are not feasible. For scenarios 1, 2, and 4 (in Monte Real) and scenarios 5 and 6 (in Sines), the NPV values are mainly negative, IRR is mostly smaller than the cost of capital or is not even possible to calculate it, the discounted PBP is higher than the forty useful years of the CAES facilities, so the investment will never be recovered, and the LCOE reaches higher values. In addition, only scenario 3 (an AA-CAES technology using a pre-existing salt cavern from Monte Real / Carriço case study) seems to have positive economic indicators.

For instance, Monte Real reference case (scenario 1) shows an NPV with a 52,4% probability of being negative, a 47,6% probability of being positive, and a substantial standard deviation of 144 851 528 €; the IRR has a 67,9% probability of being higher than the value of the assumed cost of capital; the discounted PBB indicates that the investment will never be recovered; and the LCOE has a 95% chance of being between 8,60 €/MWh and 71,27 €/MWh, with a standard deviation of 19,04 €/MWh. While for scenario 5 (reference case of Sines), the NPV has a 97,4% probability of being negative, with a substantial standard deviation of 36 196 633 €; the IRR was not possible to be calculated; the discounted PBP shows the investment is never recovered; and the LCOE has a 95% probability of being between 18,84 and 81,62 €/MWh and a standard deviation of 19,04 €/MWh.

Comparing these results with other CAES feasibility analyses makes it possible to establish some similarities and the cost-effectiveness of CAES, although the evaluation methods are different. For instance, in the current CAES assessment, the conducted analysis shows the CAES feasibility for the integration of RES and D-CAES seems to have better results, being more profitable than AA-CAES, similarly to the Madlener & Latz (2013) study where the CAES coupled with wind facilities is also viable and D-CAES also more profitable. At the same time, the present study uses existing underground salt caverns (in Monte Real case study) as a possible scenario demonstrating their cost-effectiveness for CAES as bulk energy storage like in the He et al. (2021) study.

Obi et al. (2017) state that in 2012 Huntorf CAES LCOE value was 16 $/MWh while McIntosh CAES LCOE was 28 $/MWh. Those LCOE values are not significantly different from the range of LCOE values obtained in this economic analysis, despite lower Monte Real LCOE results for the CAES RES business model.

In summary, the obtained results show that the best business model is the CAES RES business model. Four of the six scenarios in this first model are viable, namely the four scenarios of the Monte Real case study. In contrast, in the same six scenarios for the CAES arbitrage business model, only one scenario seems viable, while all the other five scenarios are not profitable. Results suggest a difference between the four Monte Real case study scenarios and the two Sines case study scenarios within the CAES RES business model and its six scenarios. In the Monte Real case study, all four scenarios are feasible for the established assumptions, independently if they consider a D-CAES or AA-CAES technology or use a pre-existing salt cavern or build a new cavern. In the Sines LPG case study, both scenarios (D-CAES and AA-CAES) are not feasible since most economic indicators show negative indicators.

Conclusions and Further Research

The CAES economic analysis of pre-selected reservoirs case studies for Portugal and two business models (one to integrate RES and another for arbitrage) was conducted using an MCS risk assessment approach considering several uncertainties of a CAES project. The results pointed out a better performance from the CAES RES business model than the CAES arbitrage business model.

In the CAES RES business model, the D-CAES assessed scenarios seem to have more attractive results than their equivalent AA-CAES systems, which could be explained due to the higher CAPEX of AA-CAES projects. However, one of the best economic feasibility results on both business models is scenario 3, which corresponds to an AA-CAES technology using a pre-existing salt cavern from Monte Real / Carriço case study. This scenario 3 results make it suitable for RES storage business models and energy arbitrage business models. Moreover, an AA-CAES system has a higher efficiency (around 70%) and is environmentally friendly since it does not need NG to run, decreasing greenhouse gas (GHG) emissions. However, it is important to point out that AA-CAES technology is still not fully mature, and there are no large-scale operating facilities yet.

In conclusion, it was observed that CAES is viable in specific scenarios and can be profitable for the storage of energy from RES, facilitating the management of their variability, decreasing their dependence on weather, and helping in their integration into the grid. However, CAES does not seem a good fit for arbitrage of energy from the grid since it is not feasible in most scenarios simulated for both case studies, except for scenario 3.

For further research, it would be interesting to analyze what would be the stochastic cash flow results for all the scenarios, case studies, and business models with the current electricity and gas prices and conditions since the performed economic analyses and investments assessments were done assuming the 2020 energy market conditions and the MIBEL and MIBGAS prices for the Iberian spot market more than doubled.

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