Applied Energy 329 (2023) 120273

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Economic assessment for compressed air energy storage business model alternatives

Catarina R. Matos [a,b,*], Patrícia Pereira da Silva [a,c,d], Júlio F. Carneiro [b,e]

[a] Energy for Sustainability Initiative, MIT Portugal Program, Faculty of Sciences and Technology, University of Coimbra, Rua Luís Reis dos Santos, Pólo II, 3030-788 Coimbra, Portugal
[b] Institute of Earth Sciences (ICT), University of Évora, Colégio Luís António Verney, Rua Romão Ramalho, 59, 7000-671 Évora, Portugal
[c] CeBER, Centre for Business and Economics Research, Faculty of Economics, University of Coimbra, Av. Dias da Silva, 165, 3004-512 Coimbra, Portugal
[d] INESC Coimbra, Institute for Systems Engineering and Computers at Coimbra, Rua Sílvio Lima, Pólo II, 3030-290 Coimbra, Portugal
[e] Department of Geosciences, Institute for Research and Advanced Training, School of Science and Technology, University of Évora, Colégio Luís António Verney, Rua Romão Ramalho, 59, 7000-671 Évora, Portugal

HIGHLIGHTS

- Assessment of different business models for Compressed Air Energy Storage (CAES).
- CAES feasibility for renewable energies integration is higher than for arbitrage.
- Adiabatic CAES viability in different business models.
- Underlines CAES's importance as a feasible energy storage solution for RES.

ARTICLE INFO

Keywords:
Compressed air energy storage
Economic analysis
Business models
Monte Carlo simulation

ABSTRACT

Compressed air energy storage (CAES) is a large-scale energy storage system with long-term capacity for utility applications. This study evaluates different business models' economic feasibility of CAES pre-selected reservoir case studies. It assesses several scenarios for each case study and analyzes two business models: one for the storage of excess renewable energy sources (RES) and another for energy arbitrage. The novelty of this work is performing the economic investment assessment using a Monte Carlo Simulation (MCS) methodology applied to CAES, considering the uncertainties associated with such types of projects and evaluating different business models for the technology.

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. However, adiabatic CAES can be economically feasible in both business models. In addition, 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 their integration into the grid. However, CAES does not seem a good fit for grid energy arbitrage in the generality of the scenarios evaluated.

1. Introduction

The decarbonization of world economies relies on several pillars from which the increase of energy production from clean sources such as renewable energy sources (RES) plays a key role. However, RES can be a challenge for the energy grids in balancing supply and demand or power adequacy. Thus, energy storage is one of the possible solutions for those challenges and is an essential component of future energy grids.

Compressed air energy storage (CAES) is one of the few large-scale energy storage technologies that support grid applications having the

---

* Corresponding author at: Energy for Sustainability Initiative, MIT Portugal Program, Faculty of Sciences and Technology, University of Coimbra, Rua Luís Reis dos Santos, Pólo II, 3030-788 Coimbra, Portugal; and, Institute of Earth Sciences (ICT), University of Évora, Colégio Luís António Verney, Rua Romão Ramalho, 59, 7000-671 Évora, Portugal.
E-mail addresses: catarina.matos@uevora.pt (C.R. Matos), patsilva@fe.uc.pt (P. Pereira da Silva), jcarneiro@uevora.pt (J.F. Carneiro).

https://doi.org/10.1016/j.apenergy.2022.120273
Received 26 May 2022; Received in revised form 18 September 2022; Accepted 30 October 2022

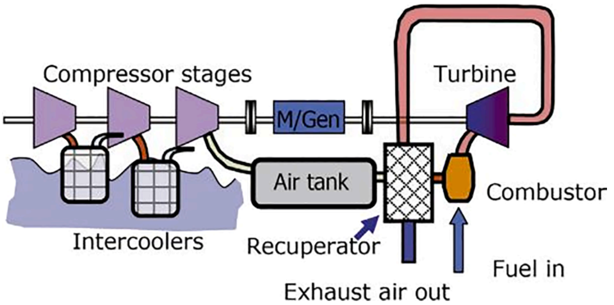

Fig. 1. Schematic configuration of a diabatic CAES system with heat recuperator, such as the one implemented at McIntosh (USA). Adapted from [6].

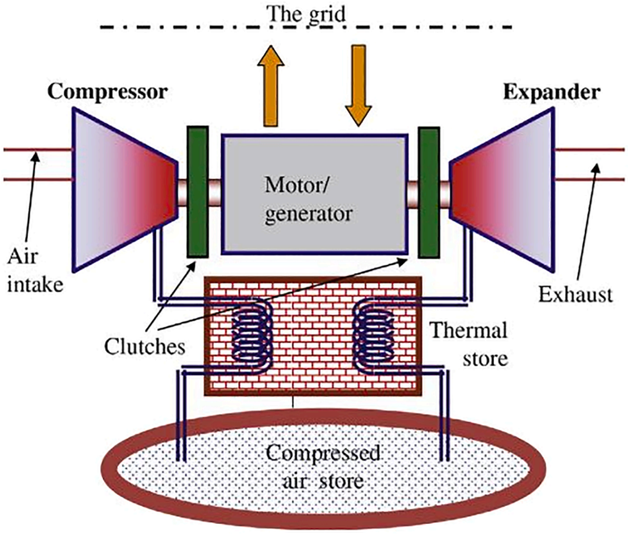

Fig. 2. Schematic configuration of an advanced adiabatic CAES system (AA-CAES) with thermal energy storage (TES). Adapted from [6].

ability to store tens or hundreds of MW of power capacity [1], which may be used to store excess energy from RES, according to [2].

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, heated, and expanded, rushing through a turbine and driving a generator to produce electricity [34]. For large-scale CAES, the underground reservoirs are geological formations. They consist of underground formations such as host rocks (engineered rock caverns or abandoned mines), salt formations (salt domes or bedded salt), and porous media (saline aquifers or depleted hydrocarbon fields) [5].

CAES can be classified and differentiated into three different types (according to how it manages the heat generated in the compression phase and used in the expansion phase): diabatic, adiabatic, and isothermal CAES. The diabatic CAES (D-CAES) system uses external heat sources to extract additional work (electricity) from the stored high-pressure air. In contrast, an adiabatic CAES (A-CAES) system does not use any external source of heat [6]. Finally, an isothermal CAES (I-CAES) system is a nearly ideal CAES where all the heat released during compression should be reinjected into expansion at the same pressures and temperatures.

Diabatic CAES (D-CAES), also called conventional CAES, is the most mature technology. It uses conventional gas turbines where the compression of the combustion air is separated and independent from the actual gas turbine process [7]. In a D-CAES plant, the heat resulting from air compression is wasted in the environment by cooling down the compressed air [3]. Therefore, an external heat source is needed for the discharging process to prevent condensation and icing of the expansion machinery by pre-heating the compressed air upstream of the expander [3]. Fig. 1 shows the configuration of a D-CAES system with a heat recuperator that absorbs heat that is left in the exhaust gas, leaving the (final stage of the) expander and transferring this heat to air coming from the high-pressure air store before it reaches the (first stage of) expansion [6].

The recent advanced adiabatic CAES (AA-CAES) technology is an evolution of conventional CAES. It uses thermal energy storage (TES) device to avoid the use of additional energy and capture the heat expelled in the compression process, and then uses the stored thermal energy to preheat the air during the expansion process [3,8,9]. For instance, in Fig. 2, one single compression stage raises the temperature and pressure of air. Then, that heat is drawn from the air and stored in a thermal store before the air is fed into storage, and finally, the same heat is injected back into the air when the air is withdrawn from storage before expansion [6]. In this CAES configuration, the heat of compression is recovered and used to reheat the compressed air during turbine operations [4]. Therefore, it is no longer needed to burn NG to warm up the decompressed air, which diminishes carbon emissions and increases the efficiency of the process to up to 70 % [7], alleviating most of the economic uncertainties of CAES [10].

Among European countries, Portugal has one of the higher shares of electricity generation from RES [11]. It also has several underground formations suitable as potential CAES geological reservoirs identified by [12] with the best suitable CAES reservoirs selected by [13]. However, an economic analysis must be performed to understand if CAES is viable in the Portuguese energy system. Thus, this study aims to determine the economic feasibility of CAES in the country by conducting investment assessments of the pre-selected CAES case study reservoirs.

The assessment method of the economic feasibility of an energy investment project does not differ substantially from that of investments in other commodities or services. However, there are some particularities related to long-term aspects, such as planning, construction, and operation periods, making an energy investment decision strongly dependent on the discounting of future cash flows [14].

CAES economic concepts and indicators were retrieved from financial literature to establish an investment assessment background and understand the main drivers and factors that should be considered. The financial indicators most often used to assess the economics of a project such as these include Net Present Value (NPV), Internal Rate of Return (IRR), Discounted Payback Period (PBP), and Levelized Cost of Energy (LCOE) [14].

The costs of installing a CAES plant depend on many factors, such as geological factors, facility size, operating technology, containment vessel, fuel prices, and intended use [9]. Still, [9] argues that CAES is very site-specific and 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 may vary within D-CAES and AA-CAES.

Madlener & Latz [15] 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 showed more attractive results and are more profitable than the adiabatic systems. However, they say 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. [16] simulated a CAES model and evaluated its economic performance, stating that besides profits from energy arbitrage, CAES could also get significant gains by providing high-quality reserves in the ancillary services market. However, the same authors concluded that the siting

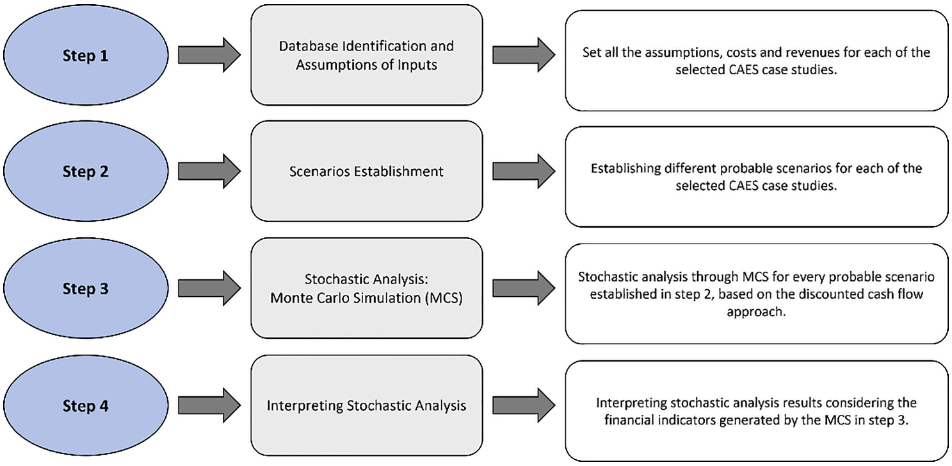

Fig. 3. Schematic representation of the methodology used for the economic analyses of CAES case studies in Portugal.

and sizing of CAES will drastically affect the profitability of CAES as a result of transmission congestions.

More recently, [17] 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 diabatic and adiabatic CAES and concluded that investment in D-CAES is the most economical option for load-leveling purposes.

Lately, [18] 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 where geological resources are available.

Because each CAES project and country has its own specificities and market, the CAES project's economic analysis will be unique. Thus, the novelty of this work includes the economic feasibility and investment appraisal for the Portuguese CAES systems according to the previously determined reservoir case studies.

This study is structured as follows: Section 2 presents the methodology used for the investment assessment in order to determine the economic feasibility of specific CAES case studies; Section 3 describes the CAES economic model used for each case study; Section 4 presents and discusses the results obtained; and Section 5 presents the key outcomes and findings of this CAES economic feasibility study.

2. Methodology

The methodology used for conducting the business models' economic assessment of the pre-selected CAES case studies is based on the evaluation of financial and investment projects and is adapted to the particular case of CAES projects in Portugal.

The methodology for the CAES scenarios is divided into steps (Fig. 3). The first step is setting all the CAES assumptions, costs, and revenues. Step two establishes probable scenarios for each of the two case studies. Moreover, the first and second steps of the adopted methodology are intrinsically linked and happen simultaneously. In step three, the stochastic analysis of every scenario and uncertain inputs through Monte Carlo Simulation (MCS) is conducted based on a discounted cash flow (DCF) approach. Finally, the results of this stochastic analysis are evaluated in step four, calculating the financial indicators for every probable scenario assumed, including case studies and business models.

A DCF approach estimates an investment's value using its expected future cash flows [19]. DCF is equal to the sum of the cash flow in each period divided by one plus the discount rate or cost of capital raised to the power of the period number [20]. Therefore, DCF is represented by Eq. (1).

$$DCF = \left(CF/(1+k)^{1}\right)+\left(CF/(1+k)^{2}\right)+\left(CF/(1+k)^{3}\right)+\ldots+\left(CF/(1+k)^{t}\right) \tag{1}$$

where *CF* is the cash flow in the period of time of the project, *k* is the interest rate, discount rate, or capital cost, and *t* is the time period number.

The financial indicators evaluated are the net present value (NPV), the internal rate of return (IRR), the discounted payback period (PBP), and the levelized cost of energy (LCOE).

The NPV represents the project's total value at its current value, considering a discount rate that reflects the risk the investor demands to be paid [21], which is given by Eq. (2).

$$NPV = \sum_{t=1}^{n} \frac{CFGt}{(1+k)^{t}} \tag{2}$$

where *CFGt* is the global cash flow during period *t*, and *k* is the discount rate. From the assessment of the NPV, a project can be accepted or rejected, and its feasibility is determined. If the NPV is positive, it means that the project is profitable, and the investment should be taken since it ensures throughout the life of that investment a return rate k, including a premium risk when the environment is characterized by uncertainty [22]. On the other hand, if the NPV is zero, the investment is neutral. And finally, if the NPV is negative, the project is not profitable, and the investment should be rejected [19,22]. Therefore, when choosing between alternative projects, the one with the highest NPV should be undertaken [23].

The IRR measures the periodic rate of return on invested capital. Therefore, IRR is the discount rate for which the NPV is equal to zero (Eq. (3)) [19], which means it is the project break-even rate of return, and as such, should be greater than the required rate of return (or cost of capital) [23].

$$IRR = k \equiv NPV = 0 \tag{3}$$

The IRR is usually calculated by iterations until the rate that equals the NPV to zero is found (Eq. (4)) [19].

$$0 = NPV = \sum_{t=1}^{n} \frac{CF0t}{(1+IRR)^{t}} - Io \tag{4}$$

where *CFO* is the net cash inflow (or operational cash flows) during the period *t*, *Io* is the total initial investment costs, *t* is the number of time periods, and *IRR* is the internal rate of return. An investment will be

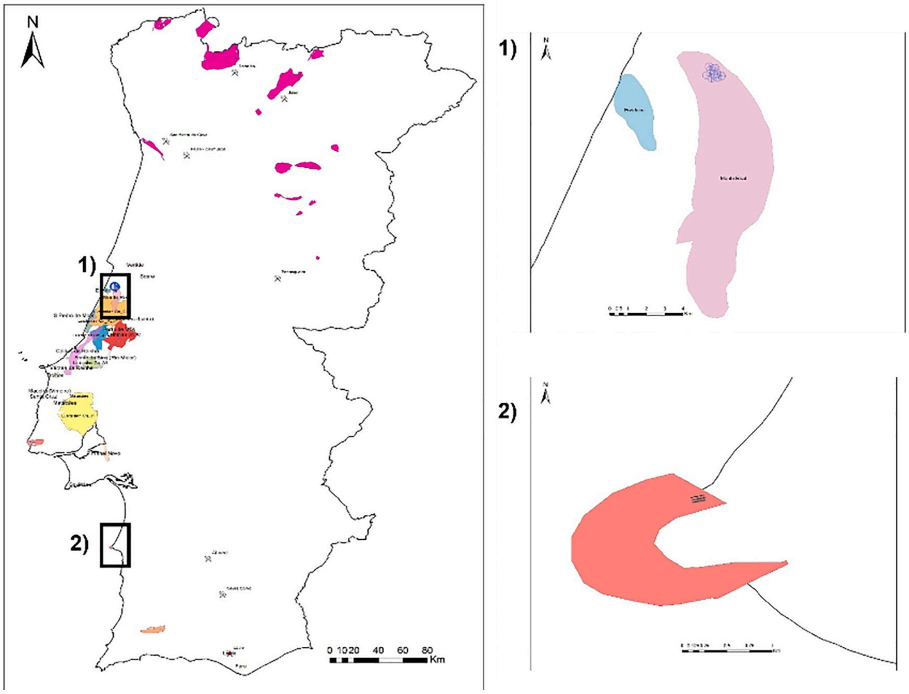

Fig. 4. Pre-selected reservoir case studies for CAES in mainland Portugal [13]: 1) Monte Real salt dome and Carriço salt caverns case study; 2) Sines sub-volcanic massif and Sines LPG case study.

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

accepted if its IRR is superior to k, the investors' cost of capital (or discount rate). So, an IRR higher than the cost of capital indicates that the project is profitable, while an IRR smaller than the cost of capital shows that the project is not profitable and should be rejected [19,23].

The Discounted PBP is the number of years it takes for an investment to recover its initial cost after accounting for inflation, interests, and other matters affected by the time value of money to be worthwhile to the investors [24]. It can be calculated through the expression represented in Eq. (5).

$$PBP = \frac{I}{\sum_{t=1}^{Np}\frac{CFt}{(1+k)^{t}}} \tag{5}$$

where I is the initial investment, CF is the cash flow in year t, k is the annual discount rate, and Np is the number of years until the investment is recovered. An investment will be acceptable if its PBP is smaller than the number of years of the useful life of the project in which it is invested [22]. Usually, the shorter the Discounted PBP, the more desirable the investment.

The LCOE can be defined as the constant and theoretical cost of generating one MWh of electricity, whose present value is equal to all the total costs associated with the power plant over its lifespan [23]. Therefore, the goal of LCOE is to identify the unit cost of energy (COE) over the life of a project, dividing all costs generated by the energy system by the amount of energy produced by that system [25]. Furthermore, the way of calculating LCOE is simplified into the equations depicted below (Eq. (6) to Eq. (7)), expressed in €/MWh or €/kWh.

$$LCOE = \frac{LifecycleCost}{LifetimeEnergyProduction} \tag{6}$$

or,

$$LCOE = \frac{(CAPEX + OPEX)}{TotalEnergyProduction} \tag{7}$$

The lower the LCOE of an energy project, the more competitive the project is, especially if compared with the LCOE of other energy technologies. Thus, when the cost of generating a kWh of energy is equal to or below the cost of an alternative energy source, it can be said that the technology in question is cost-competitive [23].

To perform an MCS is necessary the selection of input variables that can cause some change in the output parameters [26]. Thus, variables such as the cavern volume, the output power, the electricity production, the electricity prices, the natural gas (NG) prices, the NG heat rate, the capital expenditure (CAPEX), the operation expenditure (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. In addition, a PERT distribution was assumed for most input variables, where the minimum, the most likely, and the maximum values were defined and given to the system. According to [27], this distribution was chosen because values between the most likely and the extremes (minimum and maximum) are more likely to occur, meaning that the extremes are not as emphasized. The only exception is the distribution for the electricity prices used for arbitrage, where a uniform distribution was chosen given the minimum and

Table 2

Energy prices (electricity and NG) on the spot market for 2020; minimum, average, and maximum prices for the whole year [30 32]; and NG Heat Rate (HR) [24].

	Electricity Spot Market Price	**Gas Spot Market Price**	**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

maximum values, with all having an equal chance of occurring.

2.1. Case studies

According to [13] the two best reservoir case studies were selected considering economic-social-environmental concerns and were assessed among several potential reservoirs. The first case study concerns Monte Real/Carriço, and the second case study is Sines (Fig. 4). For those case studies, six scenarios were established, four for Monte Real and two for Sines (Table 1).

The first case study is the Monte Real salt dome and Carriço salt caverns, where six salt caverns are already being used for NG storage by REN Armazenagem. Thus, the assessment of this case study establishes the first scenario assumption as a reference case, using one of those pre-existing salt caverns (if they were to be reconverted to storing compressed air instead of NG). Otherwise, a new salt cavern can be explicitly built for CAES instead.

The second case study is the Sines Liquefied Petroleum Gas (LPG) cavern located in the Sines sub-volcanic massif. It is assumed as a reference case (the first scenario of the Sines case study or the fifth scenario), considering the possibility that when the pre-existing cavern is no longer used for LPG, it could be reconverted to compressed air storage. Thus, the LPG cavern is used to simulate different scenarios for the Sines LPG case study.

The scenarios assumed in Table 1 are distinguished by the CAES technology and cavern, considering a D-CAES or AA-CAES and utilizing a pre-existing underground cavern or a newly built cavern.

Finally, two business models were evaluated for all the scenarios. The first is a CAES RES business model 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. The second is a CAES arbitrage business model, which 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.

2.2. CAES economic model

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

The CAES plant's useful lifetime is assumed to be forty years starting at year one of production, based on Huntorf's CAES plant lifetime, running since 1978 [27], and McIntosh CAES facility running since 1991 [1]. The assumed number of days per year in operation is 350 days or cycles, considering a facility stop of around 15 days per year for O&M purposes. The number of hours per cycle is 12 h since it was determined that CAES could better fit the load variations and the demand needs with a twelve-hour daily cycle, especially considering RES such as wind and solar daily electricity load diagrams for Portugal ([28,29]. The annual plant production degradation is equal for all the scenarios and is 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 fuel used in D-CAES is natural gas (NG) and its consumption is given by the average heat rate (HR) value, which is assumed to be around 4330 KJ/KWh (Table 2) based on the CAES McIntosh value [24].

The CAPEX and OPEX are estimated inputs and differ according to the case study, the scenario, and the CAES technology type, which is why they are detailed in the results section. The CAPEX values are composed of underground investment costs and surface facility equipment and machinery costs (Eq. (8)). CAPEX is accounted for all at once (for calculation purposes) as if it was released in one full tranche at the beginning of the first year of production.

$$CAPEX = CAPEX(undergroundfacilities) + CAPEX(surfacefacilities) \tag{8}$$

In the OPEX, the costs are divided into fixed and variable (Eq. (9)) from the underground and surface facilities.

$$OPEX = OPEX(Fixed) + OPEX(Variable) \tag{9}$$

However, fixed costs are related to the equipment and machinery O&M costs, considered in the underground and surface facilities. In contrast, the variable costs are only considered for the surface facilities. They are related to energy expenses such as electricity used to run the machinery and fuel (NG) used to heat the compressed air in the expansion process. The variable costs (Eq. (10)) comprehend input electricity costs (Eq. (11)) and input fuel costs (Eq. (12)). Therefore, it is necessary to consider the input of electricity and fuel (NG) costs and the plant's energy efficiency to calculate the variable OPEX for D-CAES surface facilities. The surface variable OPEX costs are given in Eqs. (10), (11), and (12).

$$OPEX(variable) = inputelectricitycosts + inputfuelcosts \tag{10}$$

where:

$$Inputelectricitycosts = EnergyProduction(MWh)*Electricityconsumed(MWh)*Numberelectricalequipments*electricityprice(€/MWh) \tag{11}$$

And

$$Inputfuelcosts = EnergyProduction(MWh)*fuelprice(€/MWh)*fuelheatrate \tag{12}$$

For energy prices assumptions, electricity and natural gas prices were assessed for the whole year of 2020 in order to obtain a period broad enough to cover the variations of these high-volatility energy markets. Therefore, the electricity prices [29,30] and the NG prices [31 32] 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.

Several financial assumptions were 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

Table 3
Cavern volume, output power [27,38], electricity production (Eq. 13), and cost of capital/equity [35] 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 %

estimated at 40 years (CAES's project lifecycle duration); however, the loan period is estimated at 15 years. The annual average interest rate on loans (>1 million €) to companies at the end of 2019 was 1.85 %, according to [33]. Thus, this was the adopted interest rate for 2020 plus the Euribor rate at 12 months (usually used for companies) of −0.442 % in October 2020 [34].

The capital cost on equity is the most uncertain value that depends on the type of investor, the company situation, the market, or the business model. Still, typical values can vary between a minimum of 3.5 %, a maximum of 11 %, and a most likely value of 8 % [35,36].

Although the inflation rate is difficult to forecast, an average inflation rate of 2 % was assumed for 40 years.

The Portuguese corporate tax (IRC) is around 21 % [37], plus the municipal tax for companies estimated for 40 years at 4 %, which adds up to 25 % of taxes.

Finally, the equipment depreciation rate varies depending on the type of facility or equipment and can be 2 %, 2.5 %, and 10 %.

2.2.1. Monte Real / Carriço case study

The Monte Real /Carriço case study is a salt formation with salt caverns used to store NG reserves for Portugal. Therefore, the assumed uncertainty inputs of this case study are the cavern volume, which directly influences inputs such as output power and electricity production (Table 3). The cavern volume and the output power are estimated inputs based on previous CAES facilities and projects [27,38]. In addition, the estimated values of the cost of capital (Table 3) are based on Goedhart [35] and uncertain, so they are simulated by MCS techniques. Finally, the electricity production is given in Eq. (13).

$$Ep = D_c * Y_c * P_{out} \tag{13}$$

where Ep is the electricity production, Dc is the number of hours per daily cycle, Yc is the number of cycles or working days per year and P_{out} is the estimated output power capacity of the facility.

The CAPEX and OPEX (fixed costs) are also considered uncertainty values for the MCS, varying around 10 % down and 15 % up [39]. 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. There were several sources on which the CAPEX and OPEX values estimations were based, such as the total investments of the McIntosh and Huntorf plants [40,41], the REN Armazenagem salt caverns values (Personal Communication, July 2020), the values for CAES equipment kindly shared by Techsalt under confidentiality (Personal Communication, December 2018).

Finally, the total CAPEX values for all four Monte Real/Carriço scenarios are capitalized using the uncertain capital costs inputs. This capitalization involves multiplying the total costs for each scenario presented in Table 4 and the capital cost uncertain inputs from Table 3, obtaining the capitalized CAPEX values depicted in Table 5. In addition, the total CAPEX corresponds to the initial investment plus the automation components that should be replaced every ten years for a total of forty years of service.

Table 4
Table showing the CAPEX and OPEX values without capitalization (based on [40,41]) 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 (500 000 m3) 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
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 (500 000 m3) 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 of 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
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 (500 000 m3) 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 of 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
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 (500 000 m3) 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 of 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
Heat exchangers	3 400 000	0	40
Motor and generator	16 000 000	120 000	40
Total Costs	**119 400 000**	**691 000**	

Table 5
Capitalized CAPEX with the total costs for each scenario from Table 4, the cost of capital uncertain inputs from Table 3, and average Total CAPEX conditions (inputs and sampled) for the MCS of the four Monte Real / Carriço CAES case study scenarios.

CAPEX			
	Inputs	*Sampled*	*Total CAPEX*
Scenario 1			
Minimum (-10 %)	66 330 900		
Most likely	73 701 000	74 315 175	83 007 008
Maximum (+15 %)	84 756 150		
Scenario 2			
Minimum (-10 %)	100 272 150		
Most likely	111 413 500	112 341 946	121 033 779
Maximum (+15 %)	128 125 525		
Scenario 3			
Minimum (-10 %)	81 816 525		
Most likely	90 907 250	91 664 810	100 356 644
Maximum (+15 %)	104 543 338		
Scenario 4			
Minimum (-10 %)	115 757 775		
Most likely	128 619 750	129 691 581	138 383 415
Maximum (+15 %)	147 912 713		

Table 6
Cavern volume, output power [27,38,42], electricity production using Eq. 13, and cost of capital/equity inputs [35] 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 %

2.2.2. *Sines LPG case study*

The Sines LPG case study is a host rock cavern that stores LPG in the Sines sub-volcanic massif. Its uncertainty inputs are similar to the previous case study; however, its values are different since the cavern volume is smaller (Table 6).

The input values for components of CAES in all Sines LPG scenarios (Table 7) are assumed as the most likely CAPEX, and OPEX fixed costs, which may vary from 10 % down to 15 % up.

The CAPEX values capitalized with the simulated cost of capital (from Table 6) for Sines LPG case study scenarios are depicted in Table 8. Likewise, in the previous case study, the total CAPEX also corresponds to the initial investment plus the automation components (to be replaced every ten years for a forty-year useful life of the CAES facilities).

2.2.3. *Business models*

As mentioned in sub-section 2.1, two business models are considered: the CAES RES business model and the CAES Arbitrage business model.

The first 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, reducing time-shift delivery, balancing costs, and managing constraints. In this business case, buying energy to store and sell later is unnecessary, diminishing the overall OPEX variable costs and increasing the revenues.

The second business model aims to trade energy from arbitrage, meaning the CAES facility would store energy bought during a low demand period at minimum values and then sell it in a high demand peak at maximum values. Although this business case may decrease the revenues by increasing the OPEX variable costs, it is interesting to evaluate if it is economically viable for Portugal. Therefore, this business model will be named the "CAES Arbitrage Business Model.".

The big difference between this model and the previous one is the set of electricity prices considered. On the one hand, the electricity prices considered for selling the energy stored in the CAES RES business model are the ones presented in Table 2 and used as uncertainty inputs for the MCS. On the other hand, in the CAES arbitrage business model, the electricity prices are divided into two main groups: first, the electricity prices for buying it at minimum prices, and second the selling electricity prices at maximum values, as shown in Table 9.

Thus, these two business models will be applied to both CAES case studies and all the scenarios to do a proper investment assessment of CAES for the country.

Table 7
Table depicting the CAPEX and OPEX values without capitalization 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 (80 000 m3) 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
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 (80 000 m3) 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
Heat exchangers	3 400 000	0	40
Motor and generator	14 000 000	120 000	40
Total Costs	**66 400 000**	**691 000**	

Table 8
Capitalized CAPEX with the total costs for each scenario from Table 7 and the cost of capital uncertain inputs from Table 6, and average Total CAPEX conditions (inputs and sampled) for the MCS of the Sines LPG CAES case study.

CAPEX			
	Inputs	*Sampled*	*Total CAPEX*
Scenario 5			
Minimum (-10 %)	53 724 150		
Most likely	59 693 500	60 190 946	68 882 779
Maximum (+15 %)	68 647 525		
Scenario 6			
Minimum (-10 %)	64 391 400		
Most likely	71 546 000	72 142 217	80 834 050
Maximum (+15 %)	82 277 900		

Table 9
Electricity prices considered for the CAES arbitrage business model are divided into a) Buying electricity prices at minimum values and b) Selling electricity prices at maximum values [30].

Electricity Prices for Arbitrage	
Buying Electricity (at Minimum Values)	€/MWh
Minimum	1,02
Maximum	33,99
Selling Electricity (at Maximum Values)	
Minimum	33,99
Maximum	62,38

3. Results and discussion

3.1. CAES RES business model

The results obtained for the evaluated economic indicators through the MCS method for all the scenarios in the CAES RES business model are now presented. In addition, the probabilities of the full range of values for this business model are shown in Tables A1–A4 in Appendix A.

In the reference case or scenario 1 for the first case study, Monte Real/Carriço case study, where a D-CAES technology is assumed and a pre-existing salt cavern is used, the probability density functions obtained with the MCS method are shown in Fig. 5. NPV has a 95 % probability of being between 75.90 M€ and 231.91 M€ (Fig. 5A), with a standard deviation of 40.36 M€; IRR with a 95 % probability of being between 17.70 % and 33.57 % (Fig. 5B), with a standard deviation of 4.07; the investment would be recovered after six years of operation; LCOE has a 95 % probability of being between 4.33 and 5.01 €/MWh (Fig. 5C), and a standard deviation of 0.17 €/MWh.

In scenario 2 (Monte Real/Carriço case study), which is also a D-CAES scenario but with a newly built salt cavern, the NPV has a 95 % probability of being between 29.87 M€ and 185.11 M€, and a standard deviation of 39.64 M€. The IRR shows a 99 % probability of being between 10.98 % and 25.93 %, with a standard deviation of 2.26 %, and the probability of the IRR being higher than 11 % (the maximum estimated cost of capital) is around 99 %. The discounted PBP is about ten years, meaning that in the tenth year of the CAES production, the initial investment costs of the project are recovered. Finally, the LCOE has a 95 % chance of being between 5.46 and 6.39 €/MWh, with a standard deviation of 0.24 €/MWh.

As for Monte Real Scenario 3, where the technology assumed is an AA-CAES and a pre-existing salt cavern is used, NPV results are always positive (NPV > 0), having a 95 % probability of being between 55.87 M€ and 207.84 M€, with a standard deviation of 39.49 M€. Likewise, the IRR has a 95 % probability of being between 14.30 % and 25.94 %, with a standard deviation of 3.00 %, and is always higher than the cost of capital. Finally, the discounted PBP is about seven years, and the LCOE has a 95 % chance of being between 4.79 and 5.58 €/MWh and a standard deviation of 0.20 €/MWh.

In the last scenario of the Monte Real case study, scenario 4, with an AA-CAES technology and building a new salt cavern, the NPV presents a 95 % probability of being between 14.19 M€ and 170.81 M€, with a standard deviation of 39.91 M€. The IRR has a 95 % probability of being between 10.01 % and 17.17 %, with a standard deviation of 1.84 %. The discounted PBP is around twelve years, and the LCOE has a 95 % probability of being between 5.91 and 6.97 €/MWh and a standard deviation of 0.27 €/MWh.

For the second case study, Sines LPG, in scenario 5 or the reference case, which uses a pre-existing host rock cavern (the Sines LPG cavern) and D-CAES technology, there is a 99.6 % probability of the NPV being negative, with a negative mean value around −25.34 M€ (Fig. 6A) and a standard deviation of 8.61 M€. The IRR has a 95 % probability of being between 1.19 % and 5.12 % (Fig. 6B), presenting a standard deviation of 0.99 %, which means that these IRR values are mainly smaller than the average discount rate assumed. The discounted PBP is not achieved in the project's useful life, meaning that the investment done in such a CAES facility will never be recovered. Finally, the LCOE shows a 95 %

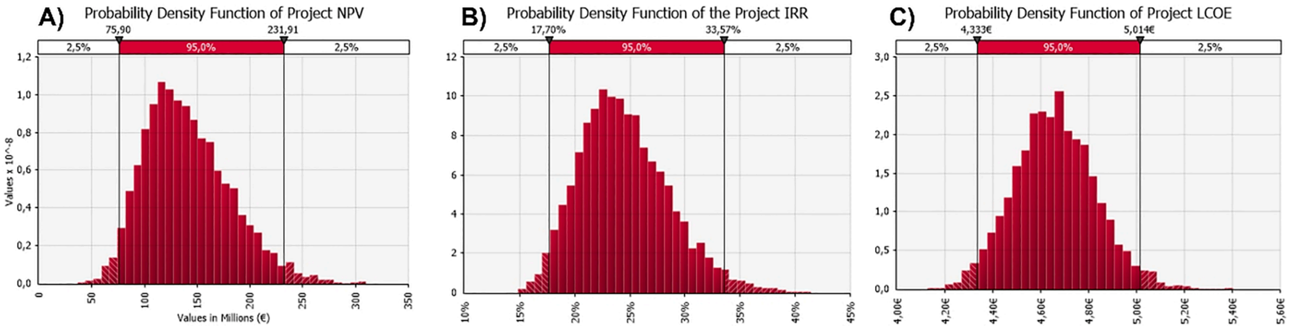

Fig. 5. Probability density functions for CAES RES business model' reference case of Monte Real/Carriço case study, scenario 1: A) NPV probability density function; B) IRR probability density function; and C) LCOE probability density function.

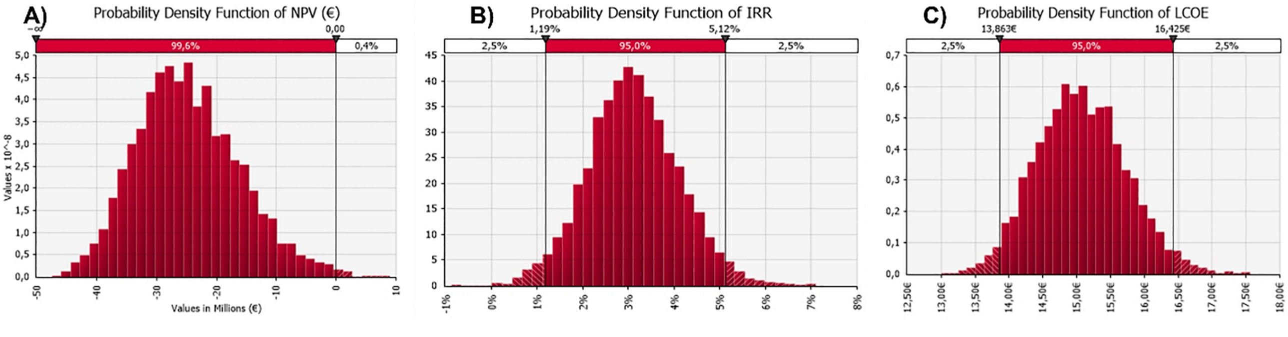

Fig. 6. Probability density functions for CAES RES business model' reference case of Sines LPG case study, scenario 5: A) NPV probability density function; B) IRR probability density function; and C) LCOE probability density function.

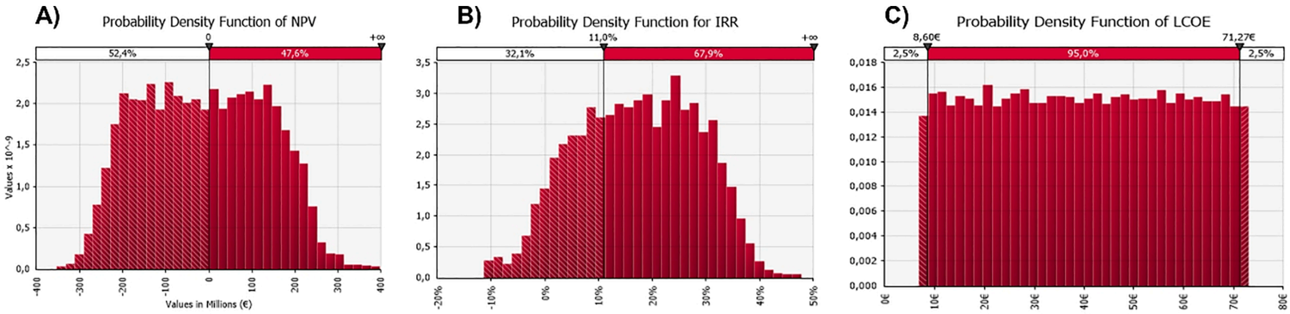

Fig. 7. Probability density functions for CAES Arbitrage business model' reference case of Monte Real/Carriço case study, scenario 1: A) NPV probability density function; B) IRR probability density function; and C) LCOE probability density function.

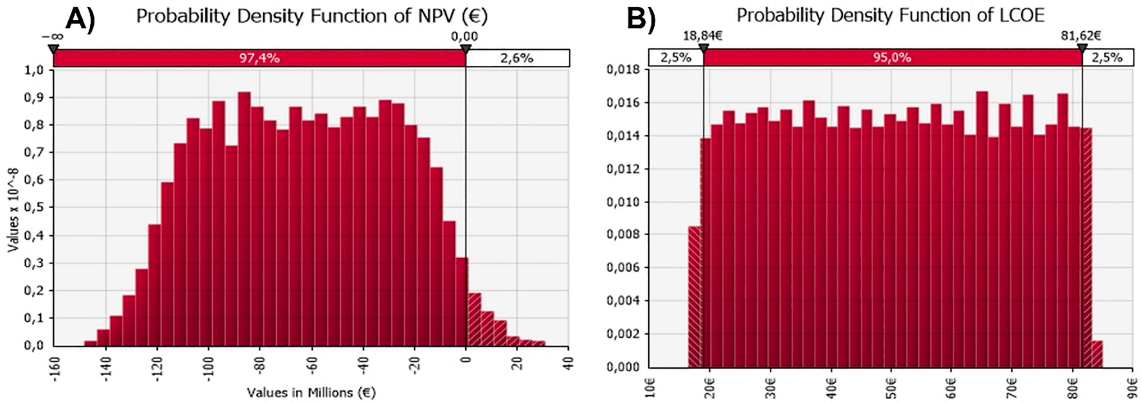

Fig. 8. Probability density functions for CAES Arbitrage business model' reference case of Sines LPG case study, scenario 5: A) NPV probability density function; B) LCOE probability density function.

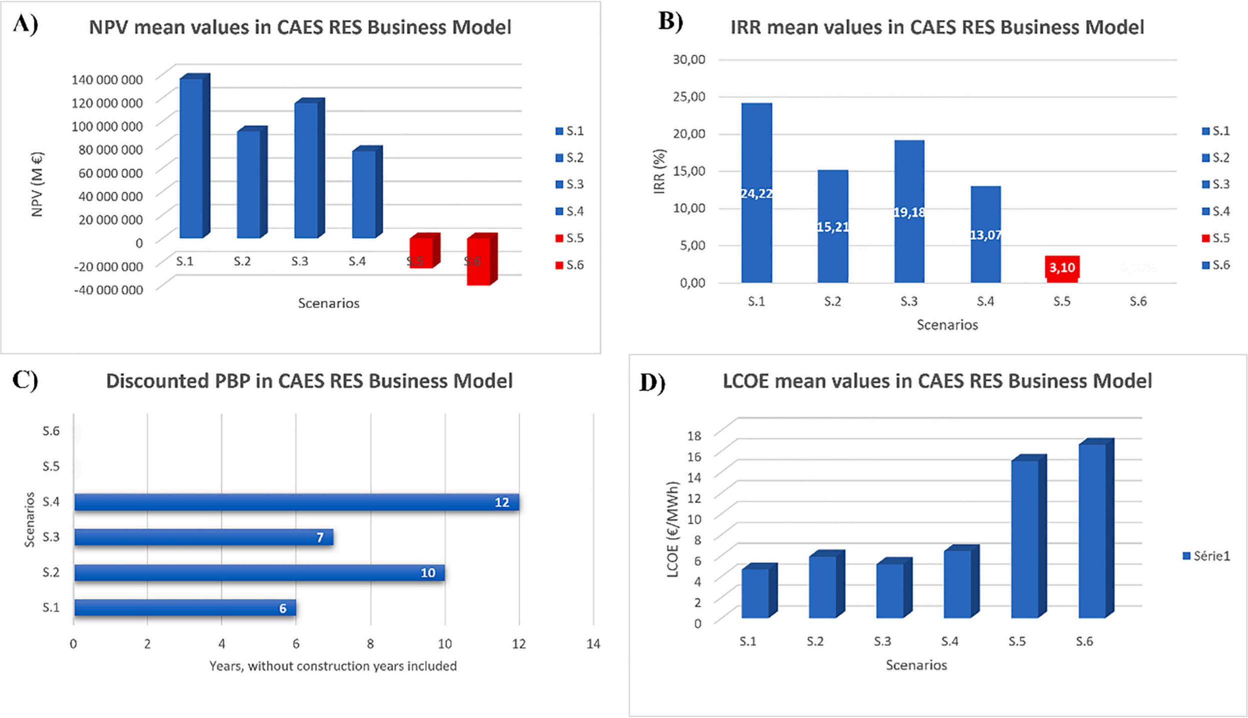

Fig. 9. Graphic representation of mean values of the economic indicator's results in CAES RES Business Model for all the six scenarios and both case studies; A) NPV; B) IRR; C) Discounted PBP; and D) LCOE. The blue color means a positive economic indicator, while the color red signifies the economic indicator is negative or if positive is not enough to be profitable. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

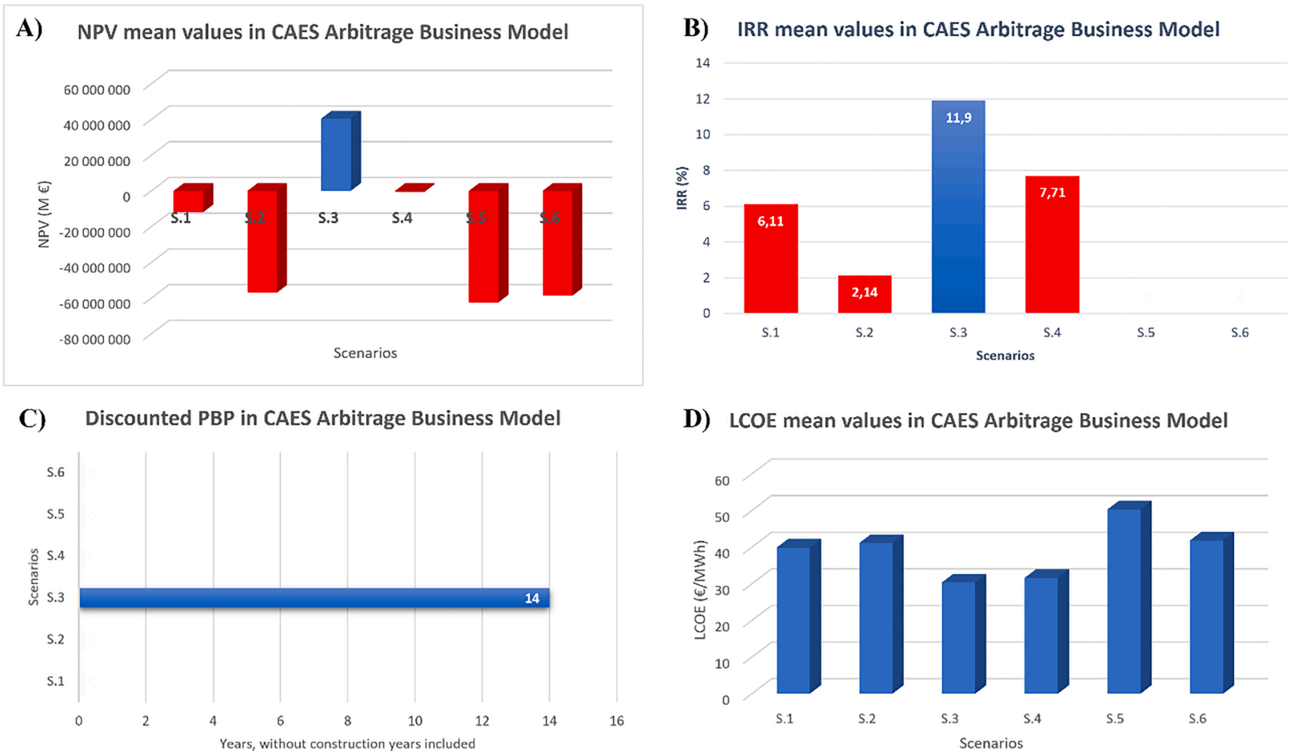

Fig. 10. Graphic representation of mean values of the economic indicator's results in CAES Arbitrage Business Model for the six scenarios and both case studies; A) NPV; B) IRR; C) Discounted PBP; and D) LCOE. The blue color means a positive economic indicator, while the red color means a negative economic indicator, or if positive is not enough to be profitable. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

probability of being between 13.86 and 16.41 €/MWh and a standard deviation of 0.66 €/MWh (Fig. 6C).

In scenario 6 of the Sines LPG case study, assuming an AA-CAES system and still using the pre-existing LPG cavern, the NPV results are always negative; its mean Value is around −39.99 M€ with a standard deviation of 8.59 M€. The IRR was not possible to be calculated since the cash flows are negative, the discounted PBP is never achieved for forty years of the project's useful life, and the LCOE has a 95 % probability of being between 15.23 and 18.19 €/MWh and a standard deviation of 0.75 €/MWh.

3.2. CAES arbitrage business model

The CAES economic model section presented the MCS conditions and inputs valid for both business models (CAES RES and CAES Arbitrage business models). However, in the arbitrage model, it is necessary to buy all the electricity at its lowest price and then sell it at its highest (Table 9).

The results obtained through the MCS method for CAES arbitrage business model scenarios are presented here. The full range values of probabilities, mean and standard deviation are shown in Tables A.5–A.8 in Appendix A. In addition, the NPV, the IRR, the discounted PBP, and the LCOE were evaluated for all the scenarios in the MCS probability function graphs.

In the first case study, the Monte Real/Carriço case study, the reference case or scenario 1 shows a 52.4 % probability of the NPV being less than zero (NPV < 0), a 47.6 % probability of the NPV being positive (NPV > 0), and a substantial standard deviation of 144.85 M€ (Fig. 7A). The IRR has a 67.9 % probability of being greater than the value of the maximum assumed cost of capital and a 32.1 % probability of being smaller than the maximum cost of capital (Fig. 7B) with a standard deviation of 11.35 %. The discounted PBP shows that investment will never be recovered within the D-CAES plant's forty years of useful life, 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 (Fig. 7C).

Scenario 2 has a 62.0 % probability of the NPV being negative (NPV < 0), a 38.0 % probability of the NPV being positive (NPV > 0), and a standard deviation of 144.85 M€. The IRR presents a 50.2 % probability of being greater than the value of the maximum cost of capital and a 49.8 % probability of being smaller than the maximum assumed cost of capital, with a standard deviation of 7.96 %. Furthermore, the discounted PBP is always unfavorable for all the forty years of CAES plant useful life, meaning the investment will never be recovered. Finally, the LCOE mean value for this second scenario is 41.14 €/MWh, having a 95 % chance of being between 9.83 % and 72.48 %, with a standard deviation of 19.04 %.

In scenario 3, the NPV results show a 38.1 % probability of being negative (NPV < 0), a 61.9 % chance of being positive (NPV > 0), and a standard deviation of 105.85 M€. The IRR has a 61.3 % probability of being>11 % and a 38.7 % probability of being less than the maximum assumed cost of capital, with a standard deviation of 9.44 %. The discounted PBP for this scenario suggests recovery of the investment after fourteen years of production, and the LCOE has a 95 % probability of being between 8.05 and 52.75 €/MWh, with a standard deviation of 13.60 €/MWh.

The fourth scenario of the Monte Real case study shows in this arbitrage model an NPV with a 50.4 % probability of being negative (NPV < 0), a 49.6 % probability of being positive (NPV > 0), and a standard deviation of 106.24 M€. The IRR probability of being greater than the value of the maximum assumed cost of capital is 42.9 %, and the probability of being smaller than the maximum cost of capital is 57.1 %, with a standard deviation of 7.29 %. The calculation of the discounted PBP for this scenario shows that the investment will never be recovered during the forty years of AA-CAES's useful life. In addition, the LCOE has a 95 % probability of being between 9.24 and 54.05 €/MWh, with a standard deviation of 13.60 /MWh.

For the second case study of Sines LPG, the reference case or scenario 5 results show a mostly negative NPV, with a 97.4 % probability of negative values and a substantial standard deviation of 36.19 M€ (Fig. 8A). The IRR was impossible to calculate for this scenario since the cash flows are negative. Furthermore, the discounted PBP result shows that the investment is never recovered during the forty years of the project's useful life. Finally, the LCOE has a 95 % probability of being between 18.84 and 81.62 €/MWh and a standard deviation of 19.04 €/MWh (Fig. 8B).

In scenario 6, the NPV has a 99.4 % probability of being negative, with a standard deviation of 26.44 M€. The IRR was also impossible to calculate since the cash flows were negative. In addition, the discounted PBP demonstrates that the investment in this scenario is never recovered during the project's useful life. Lastly, the LCOE shows a 95 % probability of being between 19.48 and 64.26 €/MWh and a standard deviation of 13.61 €/MWh.

3.3. Discussion

When analyzing the probability functions of the evaluated economic indicators for the CAES RES business model in sub-section 3.1, it can be noted 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 facility's useful lifetime, and small LCOE values (Fig. 9). However, in the Sines case study, the probability functions show that both scenarios are not feasible since most economic indicators show negative signs, mainly negative NPV values, small or even impossible to calculate IRR, discounted PBP demonstrating the investment will never be recovered during the forty years of the CAES project useful life and LCOE higher than in the first case study (Fig. 9).

Additionally, the more profitable scenarios in this business model are scenarios 1 and 3 (both in the Monte Real case study) since they show the higher NPV and higher IRR percentages, smaller discounted PBP, and smaller LCOE values (Fig. 9). In both scenarios, a pre-existing salt cavern is assumed to be used for compressed air storage, significantly decreasing investment costs.

In the CAES arbitrage business model, according to the probability functions of the MCS analysis, five scenarios of 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 lower than the cost of capital or is not even possible to calculate, 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 (Fig. 10). However, scenario 3 (an AA-CAES technology using a pre-existing salt cavern from Monte Real / Carriço case study) seems feasible for doing arbitrage of energy. It shows positive economic indicators since NPV is mainly positive, IRR is majority higher than the capital cost, it has a discounted PBP of 14 years and a lower LCOE than the other scenarios in the same business model (Fig. 10).

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 analyses show the CAES feasibility for integrating RES. Also, D-CAES seems to have better results, being more profitable than AA-CAES. These results are similar to those in the [15] study, where the CAES coupled with wind facilities is viable, and D-CAES is also more profitable than A-CAES.

At the same time, the present study uses existing underground salt caverns (in the Monte Real case study) as a possible scenario demonstrating their cost-effectiveness for CAES as bulk energy storage, like in the [18] study. These authors state that CAES is a promising technology for many countries worldwide with abundant geological resources suitable for salt-cavern-based large-scale storage [18], which is the case of Portugal, namely with the presented Monte Real salt dome case study.

[39] state that in 2012 the 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. Moreover, lower values of LCOE for CAES RES business model are in line with directly using the RES production instead of buying electricity for storage. The same authors [39] defend that variables such as cost, plant size, storage type, hours of energy production, and capacity factor can affect the LCOE results for CAES. Therefore, each case strongly depends on the assumptions made, meaning that the LCOE should be calculated and can be different for each CAES project.

Therefore, the results for all the scenarios, case studies, and business models show that CAES RES is the best 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, only one scenario seems feasible in the same six scenarios for the CAES arbitrage business model, while all the other five scenarios are not profitable.

The 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. On the one hand, in the Monte Real case study, all four scenarios are feasible for the established assumptions, irrespective of whether they consider a D-CAES or AA-CAES technology or if they use a pre-existing salt cavern or build a new cavern. On the other hand, in the Sines LPG case study, both scenarios (D-CAES and AA-CAES) using a pre-existing cavern are not feasible since most economic indicators show negative signs. These results also indicate that salt caverns may be more economically viable for storing compressed air than host rock caverns.

Several factors can explain these differences in both case studies. First, a possible explanation is the larger scale of caverns in Monte Real / Carriço compared to Sines LPG, which implies larger energy storage volumes and, respectively, greater electricity production capacity from storage in the first case. As such, despite the higher CAPEX for Monte Real / Carriço, it pays off to have the production of a CAES facility in those conditions since the energy stored comes from excess RES production and does not need to be bought.

Scenarios 1, 2, and 5 are a D-CAES technology and depend on the volatility of two energy markets (electricity and NG markets), whereas scenarios 3, 4, and 6 use an AA-CAES technology and only rely on one volatile market, the electricity market. Although noted, that difference is not significantly reflected in this CAES RES business model because the OPEX values are not high, and the stored energy comes from RES.

In general, D-CAES systems (scenarios 1, 2, and 5) show more attractive results than their equivalent AA-CAES systems (Scenarios 3, 4, and 6), at least for the CAES RES business model. This seems to indicate that in this business model, D-CAES could be more profitable than AA-CAES, despite its environmental disadvantage related to the use of NG, which could be explained because AA-CAES has higher upfront costs, mainly due to the TES costs.

However, when analyzing in detail all the scenarios, the most profitable are scenarios 1 and 3 (D-CAES and AA-CAES, respectively), which was already expected since, in both cases, a pre-existing salt cavern is assumed to be used for compressed air storage, thus significantly decreasing investment costs.

For the CAES arbitrage business model, it is necessary to buy all the energy to store underground in a CAES facility, leading to a significant increase in OPEX, which may explain the bad economic results obtained in general.

Thus, if one had to choose to invest in CAES among all the assumed scenarios, both case studies, and both business models, the best choice would be scenario 3, an AA-CAES facility using a pre-existing salt cavern from Carriço since it is the scenario that shows the best financial results in both business models. This makes scenario 3 suitable for the storage of excess RES and suitable for energy arbitrage. In addition, scenario 3 is an AA-CAES technology that does not need a fossil fuel (NG) to run, decreasing GHG emissions, having a higher efficiency (around 70 %), and presenting one of the best investment assessment results.

4. Conclusions

The CAES economic assessment of pre-selected reservoir case studies for Portugal and two business models (one to integrate RES and another for arbitrage) was conducted using stochastic analysis through an MCS risk assessment methodology considering several uncertainties of a CAES project. Although used in this case for evaluating CAES projects in mainland Portugal, this methodology can be used anywhere to determine the economic feasibility of CAES or other large-scale energy storage projects.

The results obtained pointed out a better financial performance from the CAES RES business model than the CAES arbitrage business model.

Thus, it can be said that the CAES RES business model is economically feasible in all the Monte Real /Carriço assumed scenarios but is not feasible for most Sines LPG assessed scenarios. In contrast, the CAES Arbitrage business model is not economically viable in all the assessed scenarios except in scenario 3 (Monte Real case study), where it is feasible.

In the CAES RES business model, the D-CAES assessed scenarios seem to have shown more attractive results than their equivalent AA-CAES systems, which could be explained by the higher CAPEX of AA-CAES projects. However, one of the best economic feasibility results of both business models is shown in scenario 3, which corresponds to an AA-CAES technology using a pre-existing salt cavern from the Monte Real / Carriço case study. The results of this third scenario 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, thus decreasing greenhouse gas (GHG) emissions. However, it is essential to point out that AA-CAES technology is still not fully mature and there are no large-scale operating facilities yet. Nevertheless, the AA-CAES concept is proven in small-scale CAES projects by [43].

In conclusion, it was observed that CAES is viable in specific scenarios and can be profitable for storing energy from RES. It underlines CAES's importance as a possible energy storage solution, facilitating the management of RES variability, decreasing their dependence on the weather, and helping with their integration into the grid, accelerating the energy transition process towards a more sustainable and decarbonized economy. However, CAES does not seem a good fit for grid energy arbitrage in the generality of the scenarios evaluated for both case studies (except for scenario 3, AA-CAES).

Moreover, the energy prices considered for the investment assessment performed in this study were based on 2020 prices. For that year, the maximum electricity price was 62.38 €/MWh [30] and the maximum gas price was 23.50 €/MWh [32]. However, energy markets are pretty volatile and energy prices increased sharply in 2021 and will continue this upward trend into 2022. For instance, in 2021, the electricity prices on the MIBEL market are much higher than in the previous year, having peaked at 296.78 € in October [44]. This massive increase in energy prices would certainly impact the feasibility of CAES for Portugal.

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

Funding

This work was supported by the Portuguese Foundation for Science and Technology (FCT) under the doctoral research grant SFRH/BD/117722/2016.

CRediT authorship contribution statement

Catarina R. Matos: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft, Validation, Writing – review & editing. **Patrícia Pereira da Silva:** Validation, Supervision, Writing – review & editing. **Júlio F. Carneiro:** Validation, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

Acknowledgments

Catarina R. Matos acknowledges the funding provided by the Portuguese Foundation for Science and Technology (FCT) under doctoral research grant SFRH/BD/117722/2016 and the Energy for Sustainability Initiative of the University of Coimbra.

Patrícia P. Silva acknowledges that this work has been partially funded by national funds through FCT – Fundação para a Ciência e a Tecnologia, I.P., within project grants UIDB/05037/2020 and ID/MULTI/00308/2020, and the Energy for Sustainability Initiative of the University of Coimbra.

The authors Catarina R. Matos and Júlio F. Carneiro acknowledge that this work has been co-funded by National funds through FCT - Fundação para a Ciência e Tecnologia, I.P. (projects UIDB/04683/2020 and UIDP/04683/2020).

Appendix A

Table A1
NPV probabilities, mean values, and standard deviation for all the scenarios and case studies in the CAES RES business model.

CAES RES BUSINESS MODEL					
Scenarios	**NPV (€)**				
	Probability (M€)			**Mean value (μ)**	**Standard deviation (δ)**
		Min	***Max***		
S.1	95 %	75.90	231.91	136 478 866	40 358 538
S.2	95 %	29.87	185.11	91 463 771	39 640 416
S.3	95 %	55.87	207.84	115 683 873	39 491 259
S.4	95 %	14.19	170.81	74 662 106	39 908 418
S.5	99 %	<0	<0	−25 344 566	8 605 301
S.6	100 %	<0	<0	−39 997 813	8 590 208

Table A2
IRR probability values, the mean and standard deviation for the six scenarios, and both case studies in the CAES RES business model.

CAES RES BUSINESS MODEL					
Scenarios	IRR (%)				
	Probability			Mean value (μ)	Standard deviation (δ)
		Min	*Max*		
S.1	95 %	17.70	33.57	24,22	4.07
S.2	99 %	10.98	25.93	15,21	2.26
S.3	95 %	14.30	25.94	19,18	3.00
S.4	95 %	10.01	17.17	13,07	1.84
S.5	95 %	1.19	5.12	3,10	0.99
S.6	–	–	–	–	–

Table A3
Discounted Payback Period for the six scenarios and both case studies in the CAES RES business model, where N.A. means that the investment is not recovered in the forty years of the CAES facility's useful life.

CAES RES BUSINESS MODEL		
Scenarios	Discounted Payback Period (Years)	
	(without construction years)	(with 3 construction years)
S.1	6	9
S.2	10	13
S.3	7	10
S.4	12	15
S.5	N.A.	N.A.
S.6	N.A.	N.A.

Table A4
LCOE probability values, the mean and standard deviation for the six scenarios, and both case studies in the CAES RES business model.

CAES RES BUSINESS MODEL				
Scenarios	LCOE (€/MWh)			
	95 % Probability		Mean value (μ)	Standard deviation (δ)
	Min	*Max*		
S.1	4,33	5,01	4,66	0,17
S.2	5,46	6,39	5,9	0,24
S.3	4,79	5,58	5,17	0,20
S.4	5,91	6,97	6,41	0,27
S.5	13,86	16,41	15,05	0,66
S.6	15,23	18,19	16,61	0,75

Table A5
NPV probabilities, mean values, and standard deviation for all the scenarios and case studies in the CAES Arbitrage business model.

CAES ARBITRAGE BUSINESS MODEL						
Scenarios	NPV (€)					
	Probability (M€)				Mean value (μ)	Standard deviation (δ)
	Min		*Max*			
S.1	52 %	< 0	48 %	> 0	−11 957 512	144 851 529
S.2	62 %	< 0	38 %	> 0	−56 972 607	144 849 310
S.3	38 %	< 0	62 %	> 0	40 476 180	105 852 684
S.4	50 %	< 0	50 %	> 0	−545 586	106 235 077
S.5	97 %	< 0	3 %	> 0	−62 454 141	36 196 634
S.6	99 %	< 0	1 %	> 0	−58 800 217	26 446 121

Table A6
IRR probability values, the mean and standard deviation for the six scenarios, and both case studies in the CAES Arbitrage business model.

CAES ARBITRAGE BUSINESS MODEL						
Scenarios	IRR (%)					
	Probability				Mean value (μ)	Standard deviation (δ)
	Min		*Max*			
S.1	68 %	> 11 %	32 %	< 11 %	6,11	11.35
S.2	50 %	> 11 %	49,8	< 11 %	2,14	7.96
S.3	61 %	> 11 %	39 %	< 11 %	11,9	9.44
S.4	43 %	> 11 %	57 %	< 11 %	7,71	7.29
S.5	–	–	–	–	–	–
S.6	–	–	–	–	–	–

Table A7
Discounted Payback Period for the six scenarios and both case studies in the CAES Arbitrage business model, where N.A. means that the investment is not recovered in the forty years of the CAES facility's useful life.

CAES ARBITRAGE BUSINESS MODEL		
Scenarios	Discounted Payback (years) (without construction years)	Discounted Payback (years) (with 3 construction years)
S.1	–	–
S.2	–	–
S.3	14	17
S.4	–	–
S.5	–	–
S.6	–	–

Table A8
LCOE probability values, the mean and standard deviation for the six scenarios, and both case studies in the CAES Arbitrage business model.

CAES ARBITRAGE BUSINESS MODEL				
Scenarios	LCOE (€/MWh)			
	95 % Probability		Mean value (μ)	Standard deviation (δ)
	Min	*Max*		
S.1	8.60	71.27	39,89	19,04
S.2	9.83	72.48	41,14	19,04
S.3	8.05	52.60	30,4	13,69
S.4	9.24	54.05	31,64	13,6
S.5	18.84	81.62	50,28	19,04
S.6	19.48	64.26	41,84	13,61

References

[1] Succar S, Williams R. Compressed air energy storage : theory, resources, and applications for wind power. Princeton University; 2008.

[2] Olabi AG, Wilberforce T, Ramadan M, Abdelkareem MA, Alami AH. Compressed air energy storage systems: Components and operating parameters – A review. J Energy Storage 2020::102000. https://doi.org/10.1016/j.est.2020.102000.

[3] Budt M, Wolf D, Span R, Yan J. A review on compressed air energy storage: Basic principles, past milestones and recent developments. Appl Energy 2016;170:250–68. https://doi.org/10.1016/j.apenergy.2016.02.108.

[4] Venkataramani G, Parankusam P, Ramalingam V, Wang J. A review on compressed air energy storage – A pathway for smart grid and polygeneration. Renew Sustain Energy Rev 2016;62:895–907. https://doi.org/10.1016/j.rser.2016.05.002.

[5] Matos CR, Carneiro JF, Silva PP. Overview of large-scale underground energy storage technologies for integration of renewable energies and criteria for reservoir identification. J Energy Storage 2019;21. https://doi.org/10.1016/j.est.2018.11.023.

[6] Garvey SD, Pimm A. Compressed air energy storage. In: Elsevier, editor. Storing Energy, with special reference to renewable energy sources, Elsevier Inc.; 2016, p. 87–111. https://doi.org/10.1016/B978-0-12-803440-8/00005-1.

[7] ESA. Mechanical energy storage - compressed air energy storage. accessed May 1, 2018 Energy Storage Association 2018. https://energystorage.org/why-energy-storage/technologies/mechanical-energy-storage/.

[8] Wolf D, Budt M. LTA-CAES - A low-temperature approach to adiabatic compressed air energy storage. Appl Energy 2014;125:158–64. https://doi.org/10.1016/j.apenergy.2014.03.013.

[9] Carnegie R, Douglas G, Nderitu D, Preckel Pv. Utility scale energy storage systems, benefits, applications and technologies; 2013.

[10] Gardner J, Haynes T. Overview of compressed air energy storage. Distribution 2007.

[11] APREN. Portuguese Renewable Electricity Report 2019:1–9.

[12] Carneiro JF, Matos CR, van Gessel S. Opportunities for large-scale energy storage in geological formations in mainland Portugal. Renew Sustain Energy Rev 2019:99. https://doi.org/10.1016/j.rser.2018.09.036.

[13] Matos CR, Carneiro JF, Pereira da Silva P, Henriques CO. A GIS-MCDA approach addressing economic-social-environmental concerns for selecting the most suitable compressed air energy storage reservoirs. Energies (Basel) 2021;14:6793. https://doi.org/10.3390/en14206793.

[14] Zweifel P, et al. Investment and profitability calculation. Energy Econ, Springer International Publishing; 2017. p. 37–63.

[15] Madlener R, Latz J. Economics of centralized and decentralized compressed air energy storage for enhanced grid integration of wind power. Appl Energy 2013; 101:299–309. https://doi.org/10.1016/j.apenergy.2011.09.033.

[16] Gu Y, McCalley J, Ni M, Bo R. Economic modeling of compressed air energy storage. Energies (Basel) 2013;6:2221–41. https://doi.org/10.3390/en6042221.

[17] Hammann E, Madlener R, Hilgers C. Economic feasibility of a compressed air energy storage system under market uncertainty: a real options approach. Energy Procedia 2017;105:3798–805. https://doi.org/10.1016/j.egypro.2017.03.888.

[18] He W, Dooner M, King M, Li D, Guo S, Wang J. Techno-economic analysis of bulk-scale compressed air energy storage in power system decarbonisation. Appl Energy 2021:282. https://doi.org/10.1016/j.apenergy.2020.116097.

[19] Megre L. Análise de Projectos de Investimento - uma Perspectiva Económica. 2nd Editio. Edições Sílabo; 2018.

[20] Corporate Finance Institute. Discounted Cash Flow. Https://CorporatefinanceinstituteCom/Resources/Knowledge/Valuation/Dcf-Formula-Guide/ 2021.

[21] Žižlavský O. Net present value approach: method for economic assessment of innovation projects. Procedia-Social and Behavioral Sciences 2014;156:506–12.

[22] Soares I, Moreira J, Pinho C, Couto J. Decisões de Investimento - Análise Financeira de Projetos. 3rd Editio. Lisboa: Edições Sílabo, Lda.; 2012.

[23] Eclareon. Application note - economic analysis of wind projects; 2017.

[24] Bozzolani E. Techno-economic analysis of Compressed Air Energy Storage systems; 2010.

[25] Aldersey-Williams J, Rubert T. Levelised cost of energy – A theoretical justification and critical assessment. Energy Policy 2019;124:169–79.

[26] Zaroni H, Maciel LB, Carvalho DB, de Pamplona E, O. Monte Carlo Simulation approach for economic risk analysis of an emergency energy generation system. Energy 2019;172:498–508. https://doi.org/10.1016/j.energy.2019.01.145.

[27] Crotogino F, Mohmeyer K-U, Scharf R. Huntorf CAES : More than 20 years of successful operation, 2001, p. 1–7.

[28] REN Data Hub. REN Data Hub - Electricity 2021. https://datahub.ren.pt/pt/.

[29] MIBEL. MIBEL - Iberian Electricity Market 2020. https://www.mibel.com/en/home_en/.

[30] Omie. Omie 2020. https://www.omie.es/pt.

[31] MIBGAS. MIBGAS - Mercado Ibérico del Gas 2021. https://www.mibgas.es/pt.

[32] Omip. Omip 2021. https://www.omip.pt/pt.

[33] Banco de Portugal. Taxas de juro bancárias - Empréstimos e depósitos. 2021.

[34] EuriborRates.eu. Taxa Euribor 12 meses 2020. https://www.euribor-rates.eu/pt/taxas-euribor-actuais/4/euribor-taxa-12-meses/.

[35] Goedhart, Koller, Williams. The real cost of equity. McKinsey on Finance 2002;5:11–5.

[36] McKinsey & Company. The Real Cost of Equity. Https://WwwMckinseyCom/Business-Functions/Strategy-and-Corporate-Finance/Our-Insights/the-Real-Cost-of-Equity 2020.

[37] eportugal.gov.pt. Imposto sobre o rendimento das pessoas colectivas (IRC) em Portugal 2021. https://eportugal.gov.pt/cidadaos-europeus-viajar-viver-e-fazer-negocios-em-portugal/impostos-para-atividades-economicas-em-portugal/imposto-sobre-o-rendimento-das-pessoas-coletivas-irc-em-portugal.

[38] Power south energy cooperative. McIntosh power plant. Power South Website 2017. http://www.powersouth.com/mcintosh_power_plant/compre ssed_air_energy (accessed May 2, 2020).

[39] Obi M, Jensen SM, Ferris JB, Bass RB. Calculation of levelized costs of electricity for various electrical energy storage systems. Renew Sustain Energy Rev 2017;67:908–20. https://doi.org/10.1016/j.rser.2016.09.043.

[40] 1980_NWK_The 290 MW Air Storage Gas turbine Power Plant Huntorf_english n.d.

[41] Plant MC. McIntosh (CAES) Plant 2014:0–3.

[42] APETRO. Folha de Opinião APETRO - Associação Portuguesa de Empresas Petrolíferas - APETRO 2001:6. https://doi.org/10.1017/CBO9781107415324.004.

[43] Hydrostor. Hydrostor - Our Projects. Https://WwwHydrostor.ca/Projects/ 2021. https://www.hydrostor.ca/projects/ (accessed May 1, 2022).

[44] Omie. Market Results. Https://WwwOmieEs/Pt 2021.