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Investment and risk appraisal in Energy Storage Systems: a real options approach

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Abstract

The increasing penetration of variable renewable energy is becoming a key challenge for the management of the electrical grid. Electrical Energy Storage Systems (ESS) are one of the most suitable solutions to increase the flexibility and resilience of the electrical system. This paper presents an innovative methodology for the appraisal of the investment in ESS. The methodology is based on the Real Option Analysis and it is able to properly consider investment risks and uncertainties as well as the options available for the investor. The paper assesses the value of the option to wait for a change in the market conditions before investing and re-evaluates the profitability of the investment after each step of the development of the ESS project. In order to exemplify relevant results, this method is applied to the UK energy market and assesses the technical and economic feasibility of investing in ESS operating price arbitrage and Short Term Operating Reserves. The results show that the implementation of the Real Option Analysis increases the economic performance of ESS. Nevertheless, ESS still requires limited incentives to be economically viable.

Keywords: Energy Storage; PHS; CAES; Economics; Investment Appraisal; Real Options Analysis

1 Introduction

Global renewable generation increased in 2013 by 240 TWh, accounting for almost 22% of total power generation, and it is expected to grow by almost +45% by 2020 [1]. The increasing penetration of variable Renewable Energy Technology (RET) is becoming a key challenge for the management of the electrical grid, as a high percentage of RET requires flexible power systems to quickly react to the variability of supply and demand, as exemplified in [2]. Nuclear power plants are also critical if required to operate in “load following mode” because their operation costs are almost fixed and the daily variation of power rate would lead to early aging [3].

Electrical Energy Storage Systems (ESS) are one of the most promising solutions to moderate the effects of intermittent renewable resources and to store electricity produced by other base-load plants (e.g. nuclear power plants) when in not needed and to provide the necessary flexibility required for future smart grids [4], [5]. ESS support the creation of a reliable stream of power throughout the day filling the gap between demand and supply.

In the power industry, several uncertainty factors affect the profitability of ESS, and literature (see section 2.3 and 2.3.2) recommends to assess the value of uncertainties through the Real Option Analysis (ROA), which is a valuable method in uncertain contexts [6]. This work is a further development of [3], and investigates the technical and economic feasibility of investing in ESS operating price arbitrage and Short Term Operating Reserves (STOR), i.e. doing “cross arbitrage” [4], [7]. Similarly to Reuter et al. [8], this paper calculates the level of incentives that would trigger the investment in ESS. In addition, the model implements three relevant real options for the investment appraisal: the option to wait to invest, the option to build and the options to wait to build. The method is applied from the investors' point of view and uses UK data because: the availability of public information, the expected increase of renewable sources [9], the remarkable interest in further nuclear development [10].

In summary, this work addresses the following research questions:

- Which ESS are technically and economically suitable for the storage of several MWh?
- Which are the risks and options of investing in ESS?
- How ROA can be implemented for an investment appraisal in ESS?
- What is the economic performance of ESS implementing ROA?

2 Literature Review

2.1 Overview of Energy Storage Systems

Energy Storage refers to a three-steps process that consists of (1) withdrawing electricity from the grid, (2) converting it into a form that can be stored, and (3) converting it back and returning it to the grid when needed [11]. This process enables the storage of energy at times of either low demand, low generation cost or from intermittent energy sources and uses it at times of high demand, high market price and or when power is needed as backup.

Akinyele and Rayudu [11] give a complete overview of ESS, updating the work of Chen et al. [12]. ESS have four main components: the charging unit, the storage medium, the discharging unit, and the control unit, and can be classified by the form of storage into four different main clusters [12]:

1) Mechanical (Pumped Hydro Systems, Compressed Air Energy Storage..);
2) Chemical (fuel cells, batteries..); this cluster is sometimes further divided into Chemical ESS and Electrochemical ESS [13];
3) Electrical (capacitor, super capacitors);
4) Thermal (low temperature and high temperature storage).

ESS can also be classified according to several other parameters, such as the quantity of energy stored, the rate at which energy can be absorbed, the efficiency of the ESS, their cycle life, their applications [14] and according to the implementation within the power grid [15]. Denholm et al. [16] list the different applications of ESS depending on the combination of discharge time, response time and benefits provided to the grid (see a description of benefits in [17].

Following the research of Locatelli et al. [3], this work focuses on large ESS operating price arbitrage and STOR. Price arbitrage is one of the most common application of large-scale ESS and refers to the practice of purchasing low-cost off-peak energy in order to sell it during periods of high prices. Off-peak prices normally incur during the night, when the energy demand is lower. STOR is one of the services provided by UK National Grid, and it provides electricity to match demand and production. The minimum requirements for a power plant willing to operate STOR are [18]:

- offer a minimum of 3MW generation;
- have a maximum Response Time for delivery of 240 minutes, although typical contracts are for 20 minutes or less;
- be able to deliver the contracted MW for a continuous period of minimum 2 hours;
- have a recovery period after provision of Reserve of not more than 1200 minutes;
- be able to deliver at least three times per week.

As in Locatelli et al. [3], price arbitrage and STOR are the most relevant for the integration of large amount of electricity, especially from wind farms. In fact, due to the large deployment of wind farms, the grid is affected by balancing problems, and reserve services are required. ESS can be used in alternative or to complement gas turbines in order to tackle the balancing problems, to generate electricity when prices are high and to store it when prices are low. However, only few technologies meet the aforementioned requirements and the most adequate ESS for price arbitrage and STOR are Pumped Hydroelectric Storage (PHS) and Compressed Air Energy Storage (CAES), as they both fulfil the above-mentioned requirements. Currently there are several PHS systems (e.g. 7.6 GW in Italy, 7.6 GW in Germany, more than 20 GW in the US..), and two CAES systems installed in the world [19].

2.2 ESS' Risk Analysis

Chapman and Ward [20] assert that: *"it is useful to define risk as an uncertain effect on project performance rather than as a cause of an (uncertain) effect on project performance*"

Moreover they point out that:

- uncertainty is related to *"the lack of certainty",* which concerns of variability and ambiguity;
- variability is related to "*performance measures like cost, duration, or quality";*
- ambiguity is associated with "*lack of clarity because of the behaviour of relevant project players, lack of data, lack of detail, lack of structure to consider issues, working and framing assumptions being used to consider the issues, known and unknown sources of bias, and ignorance about how much effort it is worth expending to clarify the situation".*

This paper discusses risks and corresponding causes, as several uncertainties affect the Net Present Value (NPV) of ESS during their life cycle. Then it uses the ROA to manage the variability of the uncertainties.

Investors look for investments with the highest return at the lowest possible risk, so a risks' taxonomy is extremely important. As in Blythe and House [21], risks are here classified as:

1) techno-economic risks, that are related to the specific technology;
2) market risks, that are the factors that affect the electricity supply system;
3) regulation and policy risks.

Tab 1 classifies the most relevant external and internal investment risks in ESS, and their respective causes: external risks are related to market and policies concerns, while internal risks are the technology-specific. Tab 2 highlights the causes of the risks with the highest impact and highest probability to occur. In summary:

1) one of the major external risk for the NPV of ESS is the high unpredictability and volatility of electricity prices, mainly caused by the increase of renewable power plants, and wind farms in particular.
2) the introduction of incentives or the publication of long-term and stable energy policies specifically designed for ESS would have a major impact on the NPV of the ESS. For instance, the increase of intermittent renewables intensify the volatility of electricity prices during the peaks. Therefore, the increase of intermittent renewables is twofold: it favours the absolute revenues but it may decrease their relative value for power installed due to the higher price volatility. In order to overcome to this trade-off, fixed tariffs per kWh sold specifically designed for ESS would be valuable to guarantee ESS profitability.
3) natural gas has a relevant impact on the Life Cycle Cost (LCC) of a CAES, as 85-90% of the Variable Operative Costs (VOC), besides the purchase of electricity, are fuel costs, and VOC have an impact on the LCC in a range of 36%-42%, as shown in section 4;
4) the main internal risks affecting profitability of PHS and CAES are the delays in the construction and cost overrun. Both might have a very high impact on the profitability and high probability to occur. Moreover, any delay in the construction affects the profitability in two ways: firstly as a direct cause of cost overrun and secondly delaying the positive cash flow.
5) variations of the electricity price mean value do not significantly affect the investment appraisal, as price arbitrage leverages the difference between the highest and the lowest electricity prices.

Nonetheless, the aforementioned investors' risks should be analysed in the light of the technical and societal benefits that ESS provide [17].

High Impact	**INCREASE OF NATURAL GAS PRICE (ONLY for CAES)**	**VARIATION OF THE ELECTRICITY PRICE SPREAD** **UNCERTAIN LEVEL OF INCENTIVES** **DELAYS IN THE CONSTRUCTION PHASE** **COST OVERRUN**
Low Impact	**VARIATION OF THE ELECTRICITY MEAN VALUE**	**DECREASE OF THE ELECTRICITY PRICE VOLATILITY**
	Low probability	*High Probability*

Tab 1. Internal and External Risks of PHS and CAES operating Price Arbitrage and STOR

Main risks	*Causes*	*Technologies analysed*
VARIATION OF THE ELECTRICITY PRICE SPREAD	Installation of Photovoltaic increases	PHS, AACAES, H2 and CH4 [22], ESS [23]
	Installation of Natural Gas Plant increases	PHS, AACAES, H2 and CH4 [22]
	Grid interconnection increase	ESS [24] [25]
	Efficiency in control reserve increases	PHS, AACAES, H2 and CH4 [22].
	Demand response, energy efficiency, distributed generation increase	ESS [25] [26]
	Electricity demand decreases, no need of new capacity to be installed	ESS [23].
	Installation of ESS increases	PHS, AACAES, H2 and CH4 [22],
	Phase out of nuclear power plants	PHS, AACAES, H2 and CH4 [10], [22]
	CO2 Price changes	PHS, AACAES, H2 and CH4 [22], PHS and CAES [27], ESS [23].
	Installation of Wind farm increases	PHS, AACAES, H2 and CH4 [22], ESS [23]
UNCERTAIN LEVEL OF INCENTIVES	Institutional inertia and complexity in the elaboration of an efficient regulatory plan for ESS	PHS and CAES [27], ESS [23] [28], [29].
DELAYS IN THE CONSTRUCTION PHASE	Lengthening of the planning phase and/or construction phase and maturity of the technology	PHS [11] [30][12], CAES [11] [31]
COST OVERRUN	Environmental concerns	PHS [12], [32]. [33]
	Limited Experience	ESS [23]
	Construction risks	Power plants [34], not specific of ESS

Tab 2. Main External and Internal Risks of PHS and CAES operating Price Arbitrage and STOR & corresponding causes

2.3 ROA in the Power Industry

2.3.1 General Overview

In UK, the electricity market liberalization has increased the investment risk [35], and traditional techniques based on deterministic Discounted Cash Flow (DCF) for the appraisal of projects are not fully adequate to evaluate the arisen uncertainties and the investor's flexibility to deal with them. Conversely, ROA is a valuable set of tool to assess investments in uncertain context [36].

Fernandes et al. [37] list studies applying ROA on energy sector from 1987 till 2011, where the focus was mainly on the oil&gas industry, power generation and policy studies. Lee [38]presents an overview of ROA applied to RET. Tab 10, in appendix, is a holistic review of ROA applied to the Power Industry, and shows the increasing interest in the application of ROA in the Power Industry.

2.3.2 ROA applied to EES

Only few papers apply ROA to evaluate investments in ESS. The most relevant are discussed in this section and in Tab 11 in the appendix.

Kroniger and Madlener [39] evaluate the investment in a hydrogen storage system to store the excess of electricity produced by wind farms. The risks are assessed through Monte Carlo (MC) simulations, and ROA is used to assess the investor's flexibility with respect to the choice of the investment timing. Reuter, Fuss et al. [8] use the ROA for the investment appraisal of PHS connected to a wind farm in the German and Norwegian scenario. ROA takes into account the variability of the electricity price, the possibility to benefit from incentives, and the intermittency of wind power.

Results show that the electricity premium price to trigger the investment of the PHS is very high (70% for Germany and 75% for Norway), and that the subsidy that would make up the difference between this needed premium and a more realistic premium is 35% for Germany and 50% for Norway. Muche [40] applies the ROA to the investment appraisal of PHS in Germany. Compared to the ROA, the deterministic NPV undervalues the investment because it doesn't consider the uncertainty and the flexibility associated the investment.

2.3.3 Conclusions about ROA

In conclusion, the current review shows that:

1) there is an increasing interest in the application of ROA in the power industry, as the ROA supports a more accurate appraisal of the project's value, assessing the investors' flexibility;
2) the ROA can be applied at different stages of a project;
3) the ROA can evaluate the uncertainties such as the variability of electricity price, possible changes in regulations, potential increase of the natural gas price, and unexpected increase in capital costs;
4) ROA can help to assess the risks related to investments in RET and ESS, that are affected by variability of their sources and uncertainties related to the regulatory environment.

3 Model

Traditional methods for projects' financial evaluation are based on the DCF analysis, where cash flows are discounted to the current value and the NPV is the sum of the sum of the DCF over the project as in Eq **1**, where WACC stands for Weighted Average Cost of Capital:

$$\boldsymbol{NPV = \Sigma_{t=0}^{T} \frac{CF_t}{(1+WACC)^t}} \qquad \textbf{Eq 1}$$

A common investment rule is to proceed if the NPV is greater than zero or, in case of a choice between two or more projects of comparable size, the priority will be given to the one with the higher NPV [41]. DCF analysis is easy to implement, but has some flaws [42], that can be reduced using different techniques, such as the sensitivity analysis or the scenario analysis. However, these two techniques are deterministic, as they do not consider the stochastic nature of the parameters that affect the analysis.

A more powerful tool is the MC simulation, in which the values of the independent variables ***x*** are extracted from their assumed stochastic processes, generating the approximated probability distributions of the dependent variables ***F(x).*** For every simulation, a defined number of paths is generated, sampling the values of the stochastic variables, to create the NPV distribution. These NPV distributions are characterized by a mean value μ(NPV) (also called expected value E[NPV]), a standard deviation σ(NPV), and many other parameters supporting the investors in their decisions. As in Locatelli et.al [43], the current analysis implements the MC simulation to model the stochastic nature of the main risks concerning ESS.

In order to model the ROA, four sequential steps are considered, as explained in the following sections, as shown in Fig 1.

The ROA considers calculates the value of three real options:

1) the option to wait to invest;
2) the option to build;
3) the option to wait to build.

The first option considers the investors' option not to invest immediately after the concept screening, but to wait that some relevant parameters (i.e. capital costs) decrease to a certain value that would trigger the investment. The second option considers the investors' option to decide whether to build or not after the detailed design phase. The third option models the investors' option to further postpone the decision to build the ESS system, waiting for a further capital costs reduction. Fig 2 shows the logical flow chart to develop the ROA analysis. The parameter called **CC*** in Fig 2 is the capital costs value that triggers the investment, as explained in step 3.

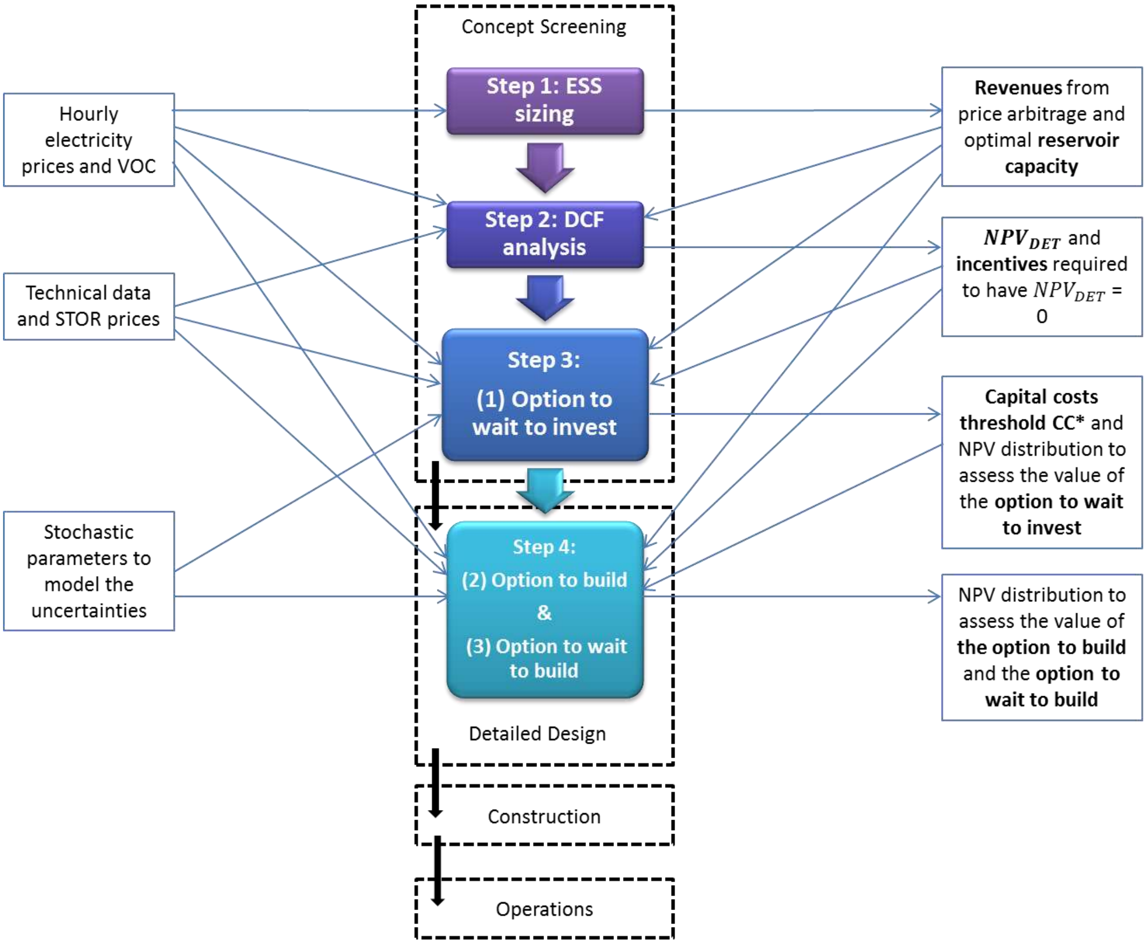

Fig 1. The four-steps model and the three real options implemented

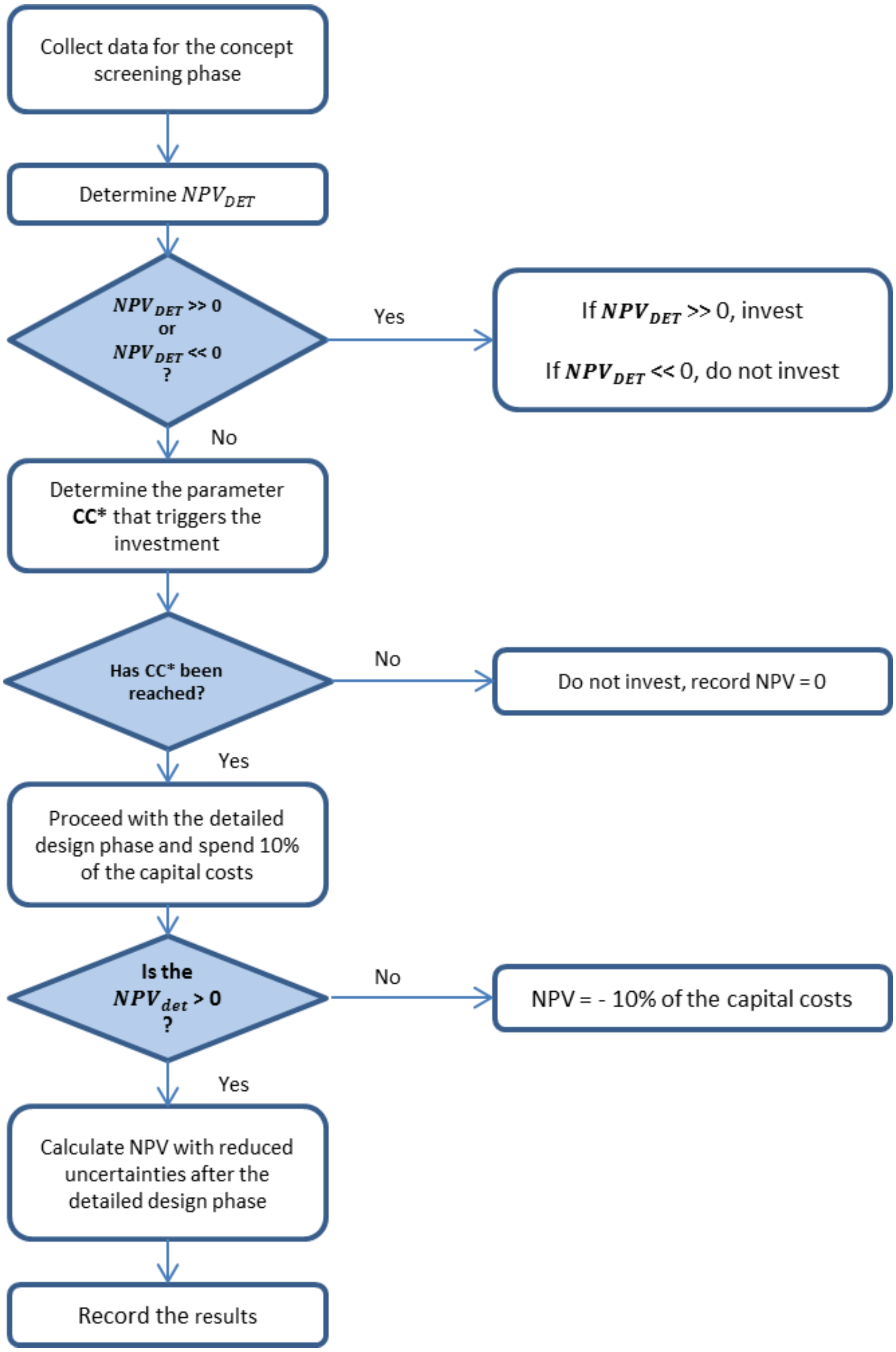

Fig 2. Logical flow chart

3.1 Inputs

The inputs of the four steps are summarized in Tab 3 and they are classified into Historical data (H), Deterministic data (D) and Stochastic ones (S). Tab 4 lists the technical data for PHS and CAES systems. STOR revenues are added to the average yearly revenues from price arbitrage, as the UK National Grid allows the utility to provide different services, as long as price arbitrage operations do not interfere with the provision of STOR [44]. Stochastic inputs are evaluated in Step 3 and Step 4.

Input	Value	1	2	3	4	Source
Hourly electricity prices [£/MWh]	N2EX Day Ahead Auction Prices	H				[45]
Revenues from Price Arbitrage CAES [£/MW]	15,656 £/MW		D	S	S	Average Revenues 2010-2014 [45]
Revenues from Price Arbitrage PHS [£/MW]	32,758 £/MW		D	S	S	Average Revenues 2010-2014 [45]
Storage Capacity installed CAES [hours]	4 h		D	D	D	Output of Step 1
Storage Capacity installed PHS [hours]	6 h		D	D	D	Output of Step 1
STOR average availability payments [£/MWh]	2.45 £/MWh		H	H	H	[46]
STOR average utilization payments [£/MWh]	155 £/MWh		H	H	H	[46]
STOR average availability hours [hours]	3,864 h		H	S	S	[46]
STOR average utilization hours [hours]	78 h		H	S	S	[46]
Capital Costs [£/MW]	Tab 4		D	S	S	[47]
Fixed Operating Costs [£/MWh]	Tab 4		D	D	D	[47]
Variable Operating Costs [£/MWh]	Tab 4	D	D	D	D	[47]
Round Trip Efficiency_PHS [kWh_{out}/kWh_{in}]	0,8		H	H	H	[11], [13]
Energy Ratio_CAES [kWh_{in}/kWh_{out}]	0,75		H	H	H	[11], [13]
Heat Rate_CAES [kj_fuel/kWh_out]	1,17		H	H	H	[48]
Planning time [years]	3		H	H	H	[19] [47] [33]
Construction time [years]	3; 4; 5;		H	H	H	[19] [47] [33]
Service life [years]	40 years		H	H	H	[47]
Natural Gas Price [£/MWh]	22.17 £/MWh		H	S	S	[49]
WACC [%]	5%; 7.5%; 10%;		D	D	D	[50] [51]
Conversion Rate (£/$)	0,65 £/$	H	H	H	H	[52]
Incentives [£/kWh]	0; 10; 25; 40; 55			D	D	Output of Step 2
Capital Costs Threshold [£/MW]	Tab 8				D	Output of Step 3

Tab 3. Inputs of the four Steps: H = Historical data, D = Deterministic data, S = Stochastic data

ESS	CAES				PHS	
	50 MW	236 MW	322 MW	441 MW	280 MW	1300 MW
Installed Capacity [MW]	50	236	322	441	280	1,300
Power Costs [$/kW]	1,078	867	636	524	1,550	1,550
Energy Costs [£/kWh]	17	16	17	17	156	103
Fixed O&M Costs [$/kW]	25.5	25.5	25.5	25.5	13.81	11.2
Variable O&M Costs [$/kWh]	0.003	0.003	0.003	0.003	0.00029	0.003

Tab 4. Technical data of CAES and PHS [47]

3.2 The four steps model

Step 1 – Optimal Storage Capacity to operate Price Arbitrage and STOR

The first step of this work relies on the same hypothesis and method detailed in [3] and calculates the optimal size capacity of the storage reservoir of the PHS and the CAES system analysed.

Step 2 – DCF analysis

The second step is the deterministic DCF analysis over the plant lifecycle. The DCF analysis provides:

1) the investment NPV, IRR and PBT;
2) the ratios between capital costs or operating costs considering the entire LCC. These ratios are particularly relevant for the CAES system, in order to assess the impact of Natural Gas Cost on the LCC. The ratio between VOC and LCC for a CAES lays in the range 36%-43%;
3) the required incentives to guarantee NPV = 0 for PHS and CAES operating price arbitrage and STOR, that for a CAES lays in the range 34 £/MWh – 47 £/MWh, while for a PHS they are 22 £/MWh – 25£/MWh.

Step 3 – Option to wait to invest

The NPV calculated in step 2 uses as deterministic inputs:

1) the expected values of capital costs [£/MW];
2) the current value of natural gas cost [£/MWh];
3) the current values of the electricity price [£/MWh].

Since the capital costs overrun is the most relevant risk jeopardizing the investment in ESS, it is fundamental to assess its impact. Step 3 evaluates the expected capital costs threshold **CC*** that triggers the investment in ESS. **CC*** is the threshold that guarantees the maximum E[NPV], taking into account the probability to reach such value. Capital costs equal to zero would surely guarantee the maximum NPV, but there is a probability equal to zero that this could happen. So step 3 considers the trade-off of a costs reduction (and increment) in combination with the probability that it will occur.

Step 3 starts with the DCF analysis, where the major risks that affect investments in PHS and CAES presented previously are modelled as explained in Tab 5. The impact of all the stochastic inputs is taken into account in the DCF - MC simulation. Step 3 deals with five scenarios with different levels of incentives per MWh of electricity sold (0, 10, 25, 40 and 55 £/MWh) because:

1) even if there are no incentives dedicated to ESS at the moment, incentives for ESS are a debated topic [27], [50];
2) the level of incentives introduced is uncertain;
3) the E[NPV] without incentives would be so low that the ROA would add only a very little value to the analysis, and there would be no capital costs threshold **CC*** that would trigger the investment.

Major risks	Impact	Evaluation tool	Ref
Electricity Price Spread increases/decreases	Price Arbitrage revenues increase/decrease	Geometric Brownian Motion	[39], [53]–[55]
Volatility increases/decreases	STOR revenues increase/decrease	β-Pert distribution	[30], [43], [51], [56]–[58]
Incentives are allocated	Revenues increase	Scenario analysis	[41]
Natural Gas costs increases/decreases	CAES VOC increases/decreases	Geometric Brownian Motion	[53], [54], [59]–[62]
Cost Overrun occurs: Capital Costs increase/decrease	Expected Costs increase/decrease	β-Pert distribution	[30], [43], [51], [56]–[58]

Tab 5. Tools used to model the major risks that affect PHS and CAES

Being the capital costs overrun the most risky parameter, the model focuses on it. The β-Pert distribution is suitable to model uncertainties related to capital costs, as it emphasizes the "most likely" value, which in this model is equal to the expected capital costs, as well as the lower and the upper limits. The β-Pert distribution related to the concept screening phase has a lower value of 0.5 and an upper value of 2 to emphasize the high uncertainty related to capital costs during this phase [58]. The β-Pert distribution related to the detailed design phase has a lower value of 0.9 and an upper value of 1.6 to highlight the fact that, after the detailed design, the uncertainties about capital costs have reduced, but there is still the possibility that costs will rise significantly [58].

Fig 3 represents the NPV distribution of the concept screening phase of a CAES system with a rated capacity of 50 MW, 40 £/MWh of incentives and WACC = 7.5%, that corresponds to a scenario of high capital costs uncertainty [58]. The mean of the NPV distribution is slightly positive, so the standard DCF approach would suggest to invest. However, implementing the option to wait to invest, it is possible to take a more careful decision, as the decision to invest will be exercised only in some scenarios, i.e. when the value of the capital costs is lower than the capital cost threshold **CC***. These scenarios are represented through iterations of the MC simulation.

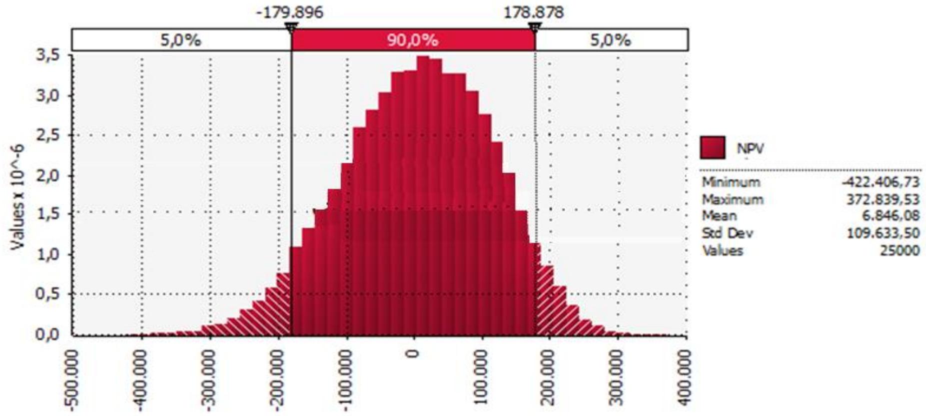

Fig 3. Stochastic NPV distribution CAES 50 MW, 40£/MWh of incentives, WACC=7.5%

Fig 4 shows the impact of capital costs on the E[NPV] and it refers to the 50 MW CAES with 40 £/MWh of incentives and WACC = 7.5%. In summary:

1) the E[NPV] corresponding to very low capital costs (in the region of 400 – 600 k£/MW) is close to zero, because the probability to reach so low capital costs is negligible;
2) the E[NPV] corresponding to very high capital costs is equal to the NPV without considering the threshold **CC*,** i.e. where the investment is triggered 100% of times (E[NPV]>0). Regarding the 50 MW CAES system, E[NPV] = 6.846 k£/MW;
3) between these two extremes, the E[NPV] has a maximum value: the capital costs that correspond to the maximum expected NPV is the capital cost threshold **CC*.** In ROA, the maximum E[NPV] is called expanded NPV [53]. Regarding the 50 MW CAES system the expanded NPV is 39.330 k£/MW;
4) At **P** the NPV is equal to the NPV without considering the threshold **CC*.** For capital costs lower than **P**, the E[NPV] is lower than the one found with the MC simulation of the concept screening phase. Regarding the CAES system of Fig 4, P corresponds to capital costs equal to 505.196 k£/MW.
5) Additionally, the σ[NPV] decreases with the reduction of capital costs, resulting, when combined with the E[NPV] of Fig 4, in Fig 5.

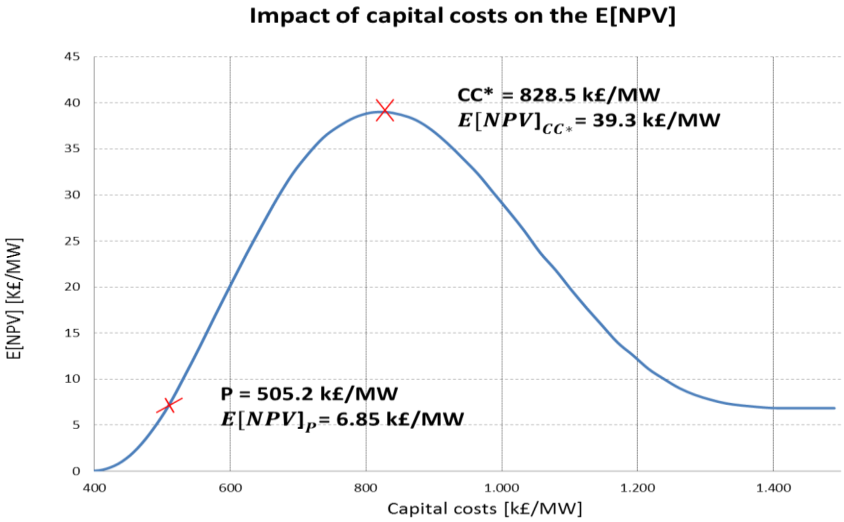

Fig 4. Impact of Capital Costs on the E[NPV]

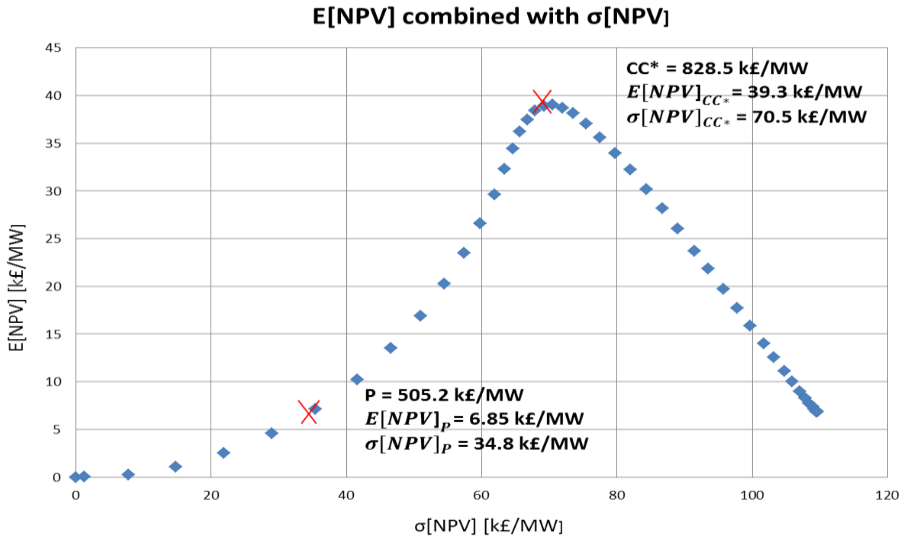

Fig 5. E [NPV] combined with σ[NPV]

Fig 5 shows that:

1) investing now is less profitable and more risky than wait for the capital cost threshold **CC*,** that optimizes the mean of the NPV distribution;
2) the distribution obtained from waiting the threshold **CC*** has the highest E[NPV]. NPV distributions with capital costs lower than **CC*** have lower standard deviation, but also their E[NPV] is lower;
3) the Pareto front is defined as a set of non-dominated solutions, so all the points corresponding to capital costs from 0 to CC* are on a Pareto front. Indeed, each point of the Pareto front in Fig 5 does not have a corresponding point with both higher E[NPV] and lower standard deviation.

4) there is an optimal capital costs range in which is convenient to invest. This range lays between **P** and **CC***: between these two values the investment reaches the highest NPV, and the utility can decide to invest, according to its risk aversion. For the CAES system of 50 MW displayed above, the range of capital costs lies between capital costs equal to **P** = 505,196 £/MW and capital costs equal to the threshold **CC*** = 828,511 £/MW.

The results of this study also indicate that not every scenario presents capital cost threshold **CC***. In some scenarios the NPV is already so high that it is useless to wait for a reduction of capital costs; in other scenarios the NPV is so low that even a dramatic reduction in capital costs would not cause a positive NPV. For instance, a PHS system with a rated power of 280 MW, in a scenario with 40 £/MWh of incentives and a WACC of 7.5 % has an E[NPV] of the concept screening phase equal to 582,573 £/MW. In this case there is no need to wait for a reduction of the capital costs, as the investment would be profitable anyway. As shown in Fig 6, the curve reductions with the reduction of capital costs, because the probability that capital costs decrease substantially is low, which has a negative impact on the E[NPV].

Conversely, a CAES system with a rated power of 50 MW, in a scenario with 25 £/MWh of incentives and a WACC of 7.5 % has a very low NPV, and waiting for a capital costs' reduction would be pointless. As shown in Fig 6, the expected NPV is equal to -164,992 £/MW, and even if capital costs decrease considerably, the NPV remains ≤ 0. Even with a cost of capital equal to zero the operation cost would be greater than revenue, with a net loss every year. Fig 6 shows consistency with the literature about ROA: if the NPV is very high or very low, ROA is useless. For this reasons, step 4 focuses only on the scenarios where the assessment of the value of uncertainties of capital costs is relevant, i.e. where there is a capital cost threshold **CC*.**

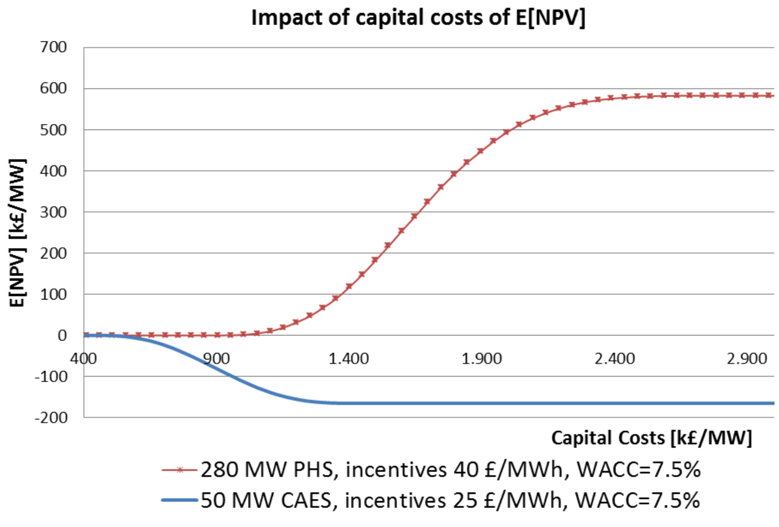

Fig 6. Impact of capital costs on E[NPV]

Step 4 – Option to build & Option to wait to build

ROA's main assumption is that some uncertainties decrease over time [36]. The algorithm of Fig 7 assesses the value of the investor's option to decide to build or not after the detailed design (i.e. after the uncertainties related to capital costs have reduced). The detailed design allows the execution of the project to proceed without major changes [63]. After the detailed design phase, the algorithm assigns a new β-Pert distribution to the capital costs, with lower and upper limit closer to the capital costs' expected value, to model the reduction of the capital costs' uncertainty.

The NPV distribution of the MC simulation with low uncertainties records the number of times that the detailed design has not been done (that corresponds to null NPV), and the number of times where the project was abandoned after the concept screening, as shown in Fig 8. This analysis causes a remarkable increase in the E[NPV] as the project has been aborted several times before the detailed design phase, as the peak in Fig 8 shows.

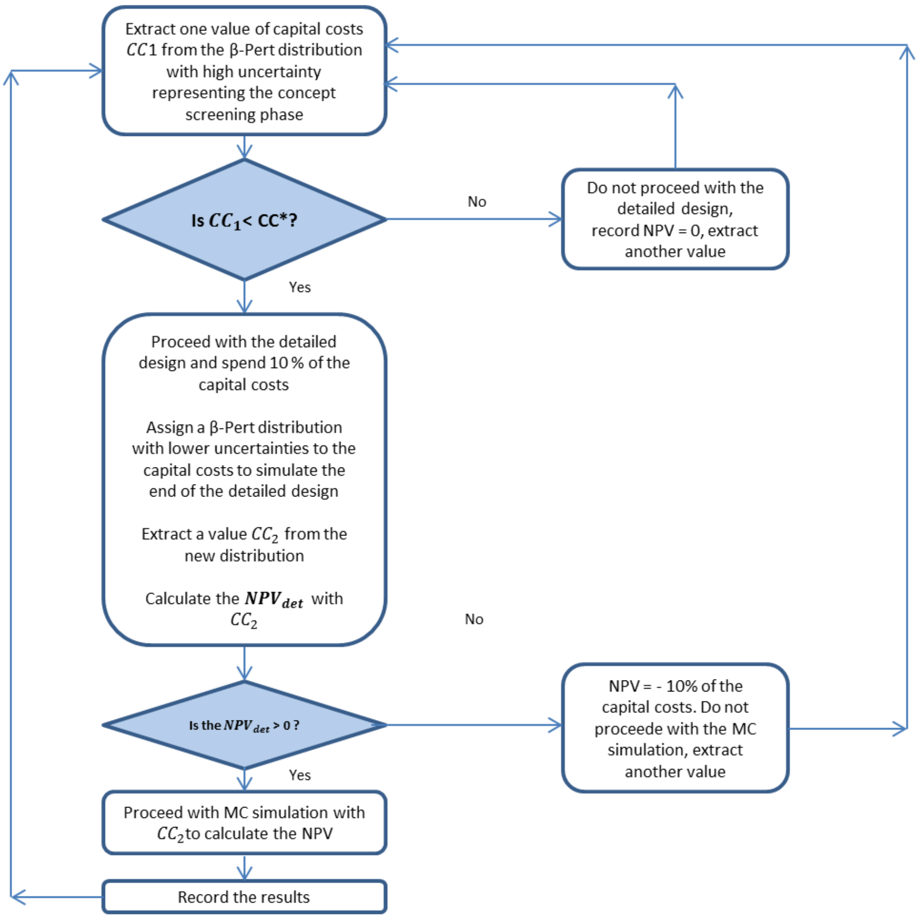

Fig 7. Algorithm of Step 4

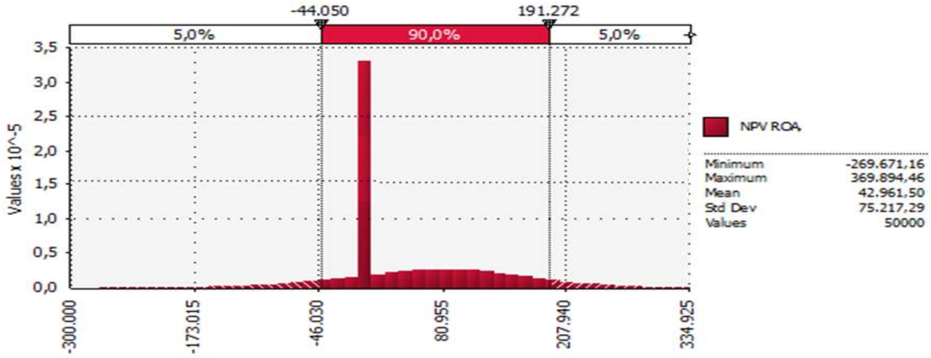

Fig 8. ROA's NPV distribution CAES 50 MW, 40£/MWh of incentives, WACC=7.5%

Compared to the stochastic DCF analysis, ROA captures (1) the added value that investors gain from the option to wait for a reduction in capital costs, and (2) the added value of postponing the decision to build or not the ESS after the detailed design. The option to wait to invest (step 3) causes a remarkable increase in the E[NPV], and in some scenarios it even causes an adjustment of the NPV from negative to positive. The option to build after the detailed design further increases the E[NPV] and lowers the number of times that negative NPV occurs.

For example, regarding the CAES system with a rated capacity of 50 MW, 40 £/MWh of incentives and WACC = 7.5% of Fig 3 and Fig 8:

1) the results of the stochastic DCF analysis are:
   - E[NPV] = 6,846 £/MW
   - probability of negative P(NPV<0) = 46.07 %
2) the option to wait that the capital cost threshold **CC*** is reached provides:
   - E[NPV] = 39,339 £/MW
   - probability of negative P(NPV<0) = 11.26 %
3) as shown in Fig 8, the option to invest in the detailed design and to postpone the decision to build causes:
   - E[NPV] = 42,961 £/MW
   - probability of negative P(NPV>0) = 10.4 %

Step 4 models the investors' behaviour that, after the detailed design, has to decide whether to build or not. However, investors might find convenient to postpone the decision and to wait for a further reduction of the capital costs caused by external exogenous factors. Indeed, factors such as technology breakthrough, mass production, industrial learning or currency issues, can have a remarkable impact on the ESS' economics, especially on the long term.

To mathematically model the additional flexibility of the option to wait to build, a reduction of capital costs has been simulated through a reduction of the parameters of the corresponding β-Pert distribution. Results are presented in section 4.

4 Results

Results of Step 1

The optimal storage capacity for PHS systems and CAES systems is respectively 6 hours and 4 hours, that shows consistency with Ref [3]. Due to the market conditions a bigger storage capacity would be detrimental, as the cost to build it would be higher than the revenues provided by a bigger reservoir. The results regarding the optimization of the size of the reservoir are consistent with the literature, i.e. with the analysis that deal with the same ESS in the UK market [3] and with the analysis that deal with other countries (i.e. Germany and Norway in [8]). In both cases results are comparable.

Results of Step 2

The DCF analysis of step 2 provides several outputs. Tab 6 lists the deterministic NPV of the ESS systems of the different scenarios under evaluation and it highlights in *italics* the scenarios with very high NPV (blue cells), or very low NPV (white cells). The scenarios are called "very high" or "very low" because it is irrelevant to proceed with step 3 and step 4, as the ROA would not generate additional value. The investment is profitable or unprofitable regardless the modelled uncertainties. In **bold** are highlighted the scenarios where the ROA generates relevant additional value (purple cells), and the assessment of the value of uncertainties can change the investment decision from not investing (E[NPV] <0) to investing (E[NPV]>0).

Incentives	WACC	CAES				PHS	
		50 MW	236 MW	322 MW	441 MW	280 MW	1300 MW
0 £/MWh	5%	*-475*	*-429*	*-36*	*-322*	**-82**	**-103**
	7.50%	*-421*	*-372*	*-302*	*-269*	*-264*	*-269*
	10%	*-384*	*-334*	*-268*	*-234*	*-363*	*-356*
10 £/MWh	5%	*-308*	*-269*	*-195*	*-170*	*246*	*210*
	7.50%	*-306*	*-266*	*-195*	*-170*	**-39**	**-61**
	10%	*-301*	*-259*	*-192*	*-170*	*-201*	*-208*
25 £/MWh	5%	**-56**	**-30**	**44**	**58**	*738*	*678*
	7.50%	*-134*	*-106*	**-36**	**-21**	*297*	*252*
	10%	*-177*	*-146*	*-79*	*-62*	**43**	**14**
40 £/MWh	5%	*195*	*210*	*283*	*286*	*1,230*	*1,146*
	7.50%	**37**	**54**	*1240*	*128*	*633*	*565*
	10%	**-52**	**-33**	**34**	**40**	*287,*	*235*
55 £/MWh	5%	*446*	*449*	*523*	*514*	*1,722*	*1,615*
	7.50%	*209*	*214*	*284*	*277*	*970,*	*879*
	10%	**72**	*81*	*148*	*143*	*531*	*457*

Tab 6. Deterministic NPV [k£/MW] with different level of incentives

A remarkable finding from Tab 6, is that in the scenarios with 10 £/MWh of incentives a very small variation of the WACC causes remarkable changes in the E[NPV] of the PHS system analysed, that varies form a very high value (NPV > 200,000 £/MW) to a very low value (NPV < -200,000 £/MW). This is because the capital costs of PHS systems are more than 85% of the LCC, and even a small variation of WACC has a large impact on their E[NPV]. Indeed, compared to the capital costs of CAES systems, the capital costs of PHS system are more than double. This result highlights the relevance of the WACC since a variation of only 2.5% provokes a significant change in the investment appraisal and in the adequacy of the ROA. ROA does not provide any additional value when WACC is equal to 5% or 10%, as the correspondent NPV is either already very high or very low.

As shown in Tab 7, CAES's deterministic NPV is lower than PHS's deterministic NPV, which causes a higher incentives. In particular the CAES systems analysed require incentives that lays between 34.4 £/MWh and 46.4 £/MWh, while PHS systems need incentives that vary from 22.4 £/MWh and 24.8 £/MWh. These results are consistent with [8], and slightly differ from the conclusion of [3], due to changes in the UK market conditions [46]. In accordance to the results of Tab 7, it is useful to analyse five scenarios with different level of incentives for each MWh of electricity sold: 0, 10, 25, 40 and 55 £/MWh.

ESS	CAES				PHS	
	50 MW	236 MW	322 MW	441 MW	280 MW	1300 MW
Capital Costs/LCC	43%	42 %	35%	34%	89%	87%
FOC/LCC	21%	21%	24%	24%	11%	8%
VOC/LCC	36%	37%	42%	42%	1%	5%
Incentives [£/MWh]	46.4	44.8	36.0	34.4	22.4	24.8

Tab 7. Capital Costs and Operating Costs compared to LCC and incentive that guarantee NPV=0

Results of Step 3

Results of step 3 consist of:

1) the NPV distributions of the concept screening phase;
2) the capital costs thresholds **CC*.**

The NPV distributions of step 3 are particularly relevant when compared with the ones of step 4. Therefore the main parameters (E[NPV], σ[NPV] and the probability of having negative NPV) of the aforementioned distributions are listed in the following paragraph as a comparison with the results of step 4.

Tab 8 lists the capital cost threshold **CC*** of the scenarios where NPV is neither very high nor very low. The scenarios with NPV >> 0 or NPV << 0 are not further analysed, as there are no capital cost threshold CC*. The comparison between the values of **CC*** of Tab 8 and the current expected capital costs is also relevant, as (1) in some scenarios, the expected capital costs are close to the capital cost thresholds CC*, and (2) in some others the expected capital costs are already lower than the threshold CC*, as the distributions assigned to the capital costs have a negative skew.

Incentives	WACC	CAES				PHS	
		50 MW	236 MW	322 MW	441 MW	280 MW	1300 MW
	5.0%	*NPV<<0*	*NPV<<0*	*NPV<<0*	*NPV<<0*	**1,451**	**1,222**
0 £/MWh	7.5%	*NPV<<0*	*NPV<<0*	*NPV<<0*	*NPV<<0*	*NPV<<0*	*NPV<<0*
	10.0%	*NPV<<0*	*NPV<<0*	*NPV<<0*	*NPV<<0*	*NPV<<0*	*NPV<<0*
	5.0%	*NPV<<0*	*NPV<<0*	*NPV<<0*	*NPV<<0*	*NPV>>0*	*NPV>>0*
10£/MWh	7.5%	*NPV<<0*	*NPV<<0*	*NPV<<0*	*NPV<<0*	**1,550**	**1,309**
	10.0%	*NPV<<0*	*NPV<<0*	*NPV<<0*	*NPV<<0*	*NPV<<0*	*NPV<<0*
	5%	**632**	**525**	**537**	**487**	*NPV>>0*	*NPV>>0*
25 £/MWh	7.5%	*NPV<<0*	*NPV<<0*	**369**	**334**	*NPV>>0*	*NPV>>0*
	10%	*NPV<<0*	*NPV<<0*	*NPV<<0*	*NPV<<0*	**1,748**	**1,438**
	5%	*NPV>>0*	*NPV>>0*	*NPV>>0*	*NPV>>0*	*NPV>>0*	*NPV>>0*
40 £/MWh	7.5%	**829**	**710**	*NPV>>0*	*NPV>>0*	*NPV>>0*	*NPV>>0*
	10%	**623**	**525**	**537**	**463**	*NPV>>0*	*NPV>>0*
	5%	*NPV>>0*	*NPV>>0*	*NPV>>0*	*NPV>>0*	*NPV>>0*	*NPV>>0*
55 £/MWh	7.5%	*NPV>>0*	*NPV>>0*	*NPV>>0*	*NPV>>0*	*NPV>>0*	*NPV>>0*
	10%	**920**	*NPV>>0*	*NPV>>0*	*NPV>>0*	*NPV>>0*	*NPV>>0*

Tab 8. Capital Costs Thresholds CC* [k£/MW]

Results of Step 4

The algorithm presented in Fig 7 provides the following outputs:

1) how many times the investment in the detailed design is done, i.e. the times that the capital cost was lower than the threshold **CC*;**
2) how many times the deterministic NPV is lower than zero and the project does not proceed after the detailed design phase;
3) how many times the deterministic NPV is higher than zero and the analysis proceeds with the MC simulation with low uncertainty;
4) the NPV distribution after the implementation of the option to build.

The results of step 4 are presented in Tab 9 highlighting the comparison between the main parameters of the NPV distribution regarding:

1) the stochastic DCF analysis in the concept screening phase;
2) the scenario with capital costs equal to **CC*,** i.e. the implementation of the option to wait to invest;
3) the implementation of the option to build after the detailed design phase;
4) the implementation of the option to wait to build after the detailed design phase.

ESS	Incentives	WACC	Concept screening phase: Stochastic DCF analysis		NPV distributions corresponding to the capital cost threshold CC*		Detailed Design Phase: Option to build		Detailed Design Phase: Option to wait to build	
			E[NPV]	NPV<0	E[NPV]	NPV<0	E[NPV]	NPV<0	E[NPV]	NPV<0
	£/MWh	%	£/MW	%	£/MW	%	£/MW	%	£/MW	%
PHS 280 MW	0	5	-127,662	74.69%	14,937	5.83%	17,324	5.05%	19,891	4.31%
PHS 1300 MW	0	5	-145,597	77.43%	10,427	5.69%	13,671	5.00%	13,416	4.74%
PHS 280 MW	10	7.5	-90,486	70.15%	21,943	6.30%	27,075	5.78%	30,754	3.13%
PHS 1300 MW	10	7.5	-107,878	73.71%	16,895	6.43%	21,175	5.24%	22,395	3.89%
CAES 50 MW	25	5	-90,753	72.56%	5,878	5.57%	6,184	7.96%	7,518	7.44%
CAES 236 MW	25	5	-60,958	65.28%	9,158	7.86%	10,637	9.20%	10,743	7.38%
CAES 322 MW	25	5	19,114	42.01%	35,058	20.24%	38,189	19.33%	40,819	18.44%
CAES 441 MW	25	5	34,795	37.14%	43,102	22.61%	46,567	22.23%	48,582	21.10%
CAES 322 MW	25	7.5	-56,857	73.00%	3,235	6.73%	3,670	4.98%	3,910	4.68%
CAES 441 MW	25	7.5	-39,858	67.85%	4,772	7.54%	5,362	7.34%	5,658	7.13%
PHS 280 MW	25	10	-9,381	50.88%	51,766	6.25%	59,719	7.28%	71,264	0.84%
PHS 1300 MW	25	10	-34,790	57.18%	39,396	4.04%	45,160	5.50%	49,792	1.01%
CAES 50 MW	40	7.5	6,846	46.04%	39,330	11.26%	42,961	10.40%	48,270	8.19%
CAES 236 MW	40	7.5	26,781	38.52%	46,346	11.87%	50,718	11.42%	53,994	9.35%
CAES 50 MW	40	10	-80,504	78.80%	6,040	5.05%	7,212	4.74%	7,905	3.85%
CAES 236 MW	40	10	-57,405	73.78%	7,318	5.60%	8,460	5.47%	8,999	4.49%
CAES 322 MW	40	10	15,300	40.07%	30,480	10.24%	33,520	11.40%	36,453	8.88%
CAES 441 MW	40	10	23,705	34.18%	32,822	13.35%	35,727	11.37%	24,951	1.38%
CAES 50 MW	55	10	44,030	31.84%	61,258	7,95%	66,899	7.79%	74,575	3.51%

Tab 9. Summary of the results

5 Conclusions

The increasing amount of variable power production from RET is becoming a key challenge for the management of the electrical grid. ESS are one of the most promising solutions to provide the flexibility required for future smart grids, as they can store energy and deliver it on demand. In particular, the most suitable ESS for the storage of several MWh are PHS and CAES. Being investments in these technologies intrinsically risky a careful appraisal is envisaged. The risks that mainly affect the profitability of PHS and CAES systems are (1) the reduction of the electricity price spread and its volatility, (2) the increase of natural gas prices, (3) the value of incentives, (4) delays in construction and (5) costs overrun. Within these, costs overrun is the major challenge, as the capital costs of PHS weights 87%-89% of its LCC and the capital costs of CAES weights 33% - 43% of its LCC.

This paper proposes and applies an innovative method, based on the ROA, to evaluate the ESS' investment profitability and support the decision maker strategy. Its key contribution is the monetary quantification of the investors' risks and flexibility during the decision-making process, through the implementation of three options. The first option appraises the value of waiting for a reduction of the capital costs; the second option calculates the value of postponing the decision of building the ESS after the detailed design; the third option assesses the value of waiting to build after the detailed design. The model is congruent with the ROA theory, as it shows that, in the presence of investment uncertainty, the ROA can evaluate more positively the profitability of the project compared to what it is obtained with a classic DCF analysis.

As shown in section 4, the implementation of the first option provides a remarkable increase of the E[NPV] and a reduction of the probability to incur in a negative NPV. In all the scenarios with negative E[NPV] the option to wait for a reduction of the capital costs till the threshold **CC*** causes the change from the negative E[NPV] to a positive E[NPV]. Similarly to the first option, the implementation of the second option further increases the E[NPV] and reduces the probability to incur in a negative NPV. Conversely, the implementation of the third option shows that, unless a halving of the capital costs occurs, no additional value is provided from the decision of waiting to build after the detailed design.

This paper paves the way to a number of further researches. Among them the most relevant are:

1) To assess the profitability of other ESS technologies for different storage applications, such as providers of fast reserve or integrate nuclear power;
2) To investigate other European and extra-European scenarios, assessing the relative risks to compare the results with the UK market;
3) To implement other real options, e.g. investments in small-medium CAES or batteries can profit for the implementation of the option to expand;

4) To analyse economical and technical risks and benefits of building ESS from the point of view of the society;
5) To model the grid behaviour, including transmission limits and failure in the generation units.

Appendix

Scenario	Focus of the ROA	Assumptions & main simplification of the model	Real Option	Main achieved results
-Location not specified -Small hydro power plant (500 kW) [35]	-Volatility of electricity prices -Regulatory change: given the current economic crisis, the government believes that the support given to electricity generation from renewable sources is no longer a priority	-No technology changes, no environmental policies, and no fuel costs are considered -No spot market prices are included as they may be strongly influenced by short-term factors. -Mini-hydro plant is not implemented in phases	-Option to postpone the investment (also called option to defer)	-The project value after ROA has higher NPV when compared with the NPV of the traditional DCF analysis. The option value is the difference between static NPV and expanded NPV, and it has a positive value. It is convenient for the investor to wait for more information in order to lower project uncertainty, and will invest when electricity price are sufficiently high
-France -Small Modular Reactors [43]	-Analysis of the economic viability of building an algae-biofuel plant or a desalinisation plant coupled to an SMR	-Numerical assumptions regarding technical data	-Option to build -Option to switch	-The main economic result is that the desalination plant can be a viable investment in several scenarios -The option to switch is able to add an extra worth to the investment project given by the operation flexibility. The advantage given by the possibility to switch between two alternative output products strongly depends on the combination of relative prices of water and electricity
-UK market [64] -Domestic photovoltaic system	-Improvement in efficiency and cost reduction in the photovoltaic (PV) modules increase the value of the option to defer the investment	-Hypothesis of the domestic consumers do not apply to every analysis. -Simplified assumptions about the FITs can have significant impacts on economic attractivness on PV systems in UK. - The model employs a quadranomial lattice to address uncertainty in the life cycle cost of PV systems due to the greenhouse gas emissions trading market.	-Option to postpone the investment	-The results suggest that PV technologies can be introduced in the next 4 years if cost reductions and tradable permits value increases are realized. A relevant result is that delaying investment in a system designed with wafer-based multi-crystalline is not convenient, but delaying investment in a system with emerging organic-based thin film cells is highly convenient.
-China [65] -Nuclear power	-Fluctuations of input costs -Regulatory actions might cause a forced termination of the construction -The potential that a reactor may not be re-licensed is considered -Risk of mismanagement is considered	-Not explicit: numerical assumptions regarding technical data	-Option to abandon	-The goal of this analysis is to assess the loss of value in a nuclear project, taken the listed risks into account. Once investor's heterogeneity and the potential for market based climate policy are taken into account, it appears that new nuclear may be a viable investment at current rates of subsidy.
-Germany [66] -Several renewables technologies	-Price of electricity -Public incentives: feed-in tariffs, investment subsidies, tax credits, portfolio requirements, certificate systems -Impact of large companies on prices in the market & uncertainties emanating from market and environment	-No alternative ideas to stabilize profits from renewable energy carriers, such as PHS, were explored	-Option to invest into new power generation capacity and choose the most convenient type of technology	-Environmental uncertainties such as the variability of renewable loads need to be modelled explicitly, due to their high impact -Feed-in tariff are an effective means of promoting renewable investment
-Nordic region: [67] -Renewables, focus on wind farms	-Price uncertainty -Public incentives: feed-in tariffs and renewable energy certificate trading.	-Independence between production and price. -Annual production is a function of the capacity installed, and this function is increasing and concave -No depreciation on renewable investment. -No correlation between capital cost and steel spot prices and no correlation between electricity future price and subsidy payments.	-Option to postpone the investment, under different support schemes. -Option to choose the plant scale	-In the Nordic case study, feed-in tariff encourages earlier investment. Nevertheless, as in investment has been undertaken, renewable energy certificate trading create incentives for larger projects
-Generic [68] -Hydro power	-Price of electricity -RET's sources	-Siting -Characteristic of the hydro power plant -Storage dimension	-Option to wait -Option to wait and adjust design parameter	-Flexible investment timing and flexible projects' designs is assessed together implementing a method called "Advanced ROA". This method is illustrated through an hydropower case study
-Spanish market [69] -Wind power generation	-Volatility, strength of reversion and long-term trend of the NPV are inserted into a trinomial investment option valuation tree. -The energy produced and the price of the electricity sold are the two stochastic processes analysed	-Not explicit: technical data regarding the six case studies analysed	-Option to invest now, to wait and or to abandon are considered	-Aa real options model is built upon a trinomial tree that evaluates numerically the probabilities of the alternatives of investing now, waiting or abandoning the project Among other results, it is interesting to notice that the variation of the option price is found to be almost linear with respect to the risk aversion and that the volatility of the spot price does not affect results significantly
-Taiwan [38] Wind technology	Main option parameters are -Underlying price (estimated NRE costs) -Exercise price (estimated RE costs) -Time to maturity -Risk-free rate -Volatility (historic percentage of price movements)	-The model incorporates internal factors as firm decision-making actions and external factors such as oil price fluctuations and other changes in the investment environment -The reliability and accuracy of the data has to be reviewed, in order to further improving the proposed model.	-Option to wait is considered in order to reduce uncertainty in policy planning	-Analytical results indicate that ROA is a highly effective means of quantifying how investment planning and managerial flexibility influence RE development. This study shows the relationship between the value of developing RE and underlying price, exercise price, time to maturity, risk-free rate, and volatility

-Taiwan, 2011 [70] -Renewable technology, and wind farms	-Fluctuation in the price of traditional fossil-fuel generated power is taken into account, as it affects RE. -Development in the policies are discussed	-Not explicit: technical data regarding the case study of wind energy technology analysed	-The government has the following five options: to grow, abandon, contract, expand, switch	-The binomial RO pricing approach is adopted to explain the effect of fluctuations in the cost of fossil fuel-generated power. The model accounts for reductions in the cost of RE generation as well and it is used to draft development policies for the upcoming year. The proposed PET model can help reduce policy implementation costs, enhance policy performance, and facilitate an estimation of substantial benefits brought by specific policies
-United States [71] -Oil & Gas	-Oil price volatility: As the level of oil price uncertainty increases, the option value of waiting to invest increases and the incentive to invest declines.	-These models assume risk neutrality, perfect competition, and constant returns to scale technology	-Option to wait -Option to grow	-Results provide a very strong evidence for a U shaped relationship between firm level investment and oil price volatility. Once the inflection point is reached, investment increases as the strategic growth option value dominates
-Eastern Kentucky [72] -Oil & Gas, focus on gas production	-Natural gas price	-A deterministic model has been used. -Data of a specific well have been used. -A strategic model that starts at the pre-drilling phase could be considered in further researches.	-Option to scale the production level -Option to scale the extraction rate by pausing the production	-The use of ROA increases the value of the well. It is notable that the option value of the portfolio that includes all the three scaling options exceed the sum of the values of individual options -Option to produce, abandon, pause, invest/disinvest are also considered
-China [73] Oil & Gas, overseas investment	-Three major uncertainties: oil prices, investment environment and exchange rate.	-First: the model has not considered the potential reward form the acquisition of future development options. Second, this research has assumed the oil price, exchange rate and investment environment to follow geometric Brownian motion which is a simplification. Third, the tax rate, interest rate and oil-production cost are constant in this model, and the impact of resource taxation on oil investment has not been considered	-Option to abandon the project at an early stage.	-It is a broad model that can be used by every oil investor country to value overseas oil resources. Using the model to evaluate the critical value per unit of oil reserves in different countries, it is possible to compare their oil investment risk by ranking their values of the Option Value Index. The investor can compare different countries' oil-investment risk by ranking their OVI to find which countries or areas are more proper to invest.
-Europe and North America [74] -Oil & Gas: Liquefied Natural Gas	-Natural Gas price volatility and convergence. -The effect of the variation of initial market prices for MC simulations, of mean reversion, of extra maritime transportation costs, of the number of alternative markets	-Constant volatility and yearly average prices	-Option to switch, i.e. to choose which international market is more convenient for the delivery of liquid natural gas.	-The value of free destination is substantially reduced if we have high price convergence and low price volatility in the alternative market. Under these circumstances the parameters determining the price dynamics in the EU base market, mean reversion and price volatility in the base market, would gain importance in determining the value of free destination.
-Norwegian context [75] -Hydropower plant	-Volatility of electricity prices (that is linked to aspect like demand, international fuel prices, transmission constraints, climate, introduction of CO_2 allowances..)	-It is possible to construct a dynamic portfolio of assets	-Option to invest	-The option value is calculated as a function of average forward price.

Tab 10. Review of ROA applied to the Energy Sector

	This work	G. Locatelli et al 2015 - [3]	D. Kroniger and R. Madlener 2014 - [39]	W. H. Reuter et al 2012 [8]	T. Muche 2009 [40]
Country Considered	United Kingdom	United Kingdom	Germany	Germany and Norway	Germany
Topic analyses	Investment appraisal of ESS operating Price Arbitrage + STOR combined, adopting the investors' point of view, through the DCF analysis and the ROA. The DCF analysis includes the optimization of the Storage Reservoir. The ROA considers the degree of freedom of the investors.	Investment appraisal of ESS operating Price Arbitrage and Price Arbitrage + STOR combined, adopting the investors' point of view, only through the DCF analysis. The DCF analysis includes the optimization of the Storage Reservoir.	Investment appraisal of hydrogen storage for excess electricity produced with wind farms.	Investment appraisal of a PHS connected to a wind farm vs. the wind farm alone	Investment appraisal of a PHS plant
Applications	Electricity sold for Price Arbitrage + STOR combined	Electricity sold for Price Arbitrage alone & electricity sold for Price Arbitrage + STOR combined	Hydrogen produced for electricity storage purposes or produced and sold as a commodity	Correlation between price arbitrage and the incentives required to have a profitable investment	Electricity sold on the wholesale market and on reserve market
ESS evaluated	PHS and CAES	PHS and CAES	Hydrogen Storage	PHS connected to a WPP	PHS
Method used	DCF and ROA to 1) find the optimal storage capacity 2) find the incentives that guarantees NPV = 0 3) calculating the the capital cost threshold that would guarantee the maximum NPV and the value of the real option to wait to invest 4) calculating the value of the real option to build and to wait to build	DCF to maximize the ESS's profit or the minimisation of the incentives	ROA to maximize the profit of ESS	ROA to maximize the expected profit during the planning period	ROA to quantify the unit commitment planning that corresponds to future scope of actions. The difference between the contribution margins is the value of the future scope of actions.
Real Options implemented	Option to wait to invest; option to build; option to wait to build.	none	Option to switch between different strategies (not explicit); Option to wait (not explicit).	Option to wait to invest (not explicit)	Option to switch operation mode (not explicit)
Results obtained from the investors perspective	PHS and CAES are technologically suitable to balance renewables, but economically risky: currently investing is not recommended. ROA can help to evaluate risky investments as it evaluates more positively the profitability of the investment. However the development in the scenario has to be monitored, as results show that under specific conditions the investment in ESS would be profitable (NPV > 0).	PHS and CAES are technologically suitable to balance renewables. However their NPV remains negative, unless specific incentives are introduced. The DCF model calculates the amount of incentives to have NPV = 0	In the first scenario fuel cell cannot operate cost-effectively under the three operating modes considered, under current German market condition. The second scenario can offer only minute reserve, but avoiding the initial cost of fuel cell can cause a positive cash inflow, namely for hydrogen prices of more than 0.36 €/m^3. ROA recommends this solution as the project value is twice the investment cost of the ESS.	The necessary price premium so that the investment in ESS is profitable and the necessary subsidy to reach a more realistic price premium. In particular the premium price that triggers the investment of a ESS is 70% for Germany and 75% for Norway, and that the subsidy that should make up the difference between this needed premium and a more realistic premium, in the range 10% - 30%, reaches 35% for Germany and 50% for Norway.	The comparison between the Real Option values and the traditional NPV approach shows that the traditional NPV has lower contribution margins that would lead to misevaluation of the investment.
Further development recommended and/or main hypothesis adopted that suggest further development	Modelling the grid behaviour including transmission limits and failure in the generation units	Modelling the investors behaviour to offset the investors risks that consider an investment in ESS	The hydrogen price is limited; Reserve capacity market development might have an impact on the analysis; Cost of technical progress are neglected, only a rise in efficiency is taken into account.	Further research should also try and include factors that have not been considered explicitly in this analysis: grids, economies of scale and – in the case of Norway – the planned green certificate system.	Reserve market is not considered;. day-ahead market serves as a forecasting basis for the intra-day market; Power output is fully and immediately available; No power networks constraints; Water usage is not constraint to any other usage.

Tab 11. Benchmarking table with the literature concerning ROA and ESS

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