Valuing the option to prototype:
A case study with Generation Integrated Energy Storage

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Abstract

New energy generation and storage systems are continuously being developed due to climate change, resource scarcity, and environmental laws. Some systems are incremental innovations of existing systems while others are radical innovations. Radical innovation systems are risky investments due to their relevant technical and economic uncertainties. Prototyping can hedge these risks by spending a fraction of the cost of a full-scale system and in return receiving economic and technical information regarding the system. In economic terms, prototyping is an option to hedge risk coming at a cost that needs to be properly assessed. Real options analysis is the project appraisal approach for these assessments. This paper aims to introduce and test an algorithm based on real options analysis to quantitatively assess the "option to prototype" in the energy sector. First, the interrelated research areas of prototyping, energy systems, and real options analysis are reviewed. Then, a novel algorithm is presented and applied to an innovative Generation Integrated Energy Storage system: Wind-driven Thermal Pumping to demonstrate the effectiveness of option to prototype and the main parameters influencing this decision. The paper shows that the cost of the prototype and the market size (number of identical systems to build) are key parameters.

Keywords: prototyping, real options analysis, generation integrated energy storage, energy infrastructure, investment risk

Highlights

- Prototyping in the energy sector is crucial for testing radical innovation systems
- Prototyping is a cost to be evaluated against the value of information received
- Introducing an algorithm to evaluate the option to prototype
- Algorithm applied to Generation Integrated Energy Storage (Wind-driven Thermal Pumping)
- The prototype costs and market size are key parameters in valuing the option

Nomenclature

Abbreviations

AACE	Association for the Advancement of Cost Engineering
CCS	Carbon Capture and Storage
DCF	Discounted Cash Flow
GIES	Generation Integrated Energy Storage system
PTES	Pumped Thermal Energy Storage
NPV	Net Present Value
O&M	Operation and Maintenance
PDF	Probability Density Function
RO	Real Option
ROA	Real Options Analysis
STOR	Short Term Operating Reserve
TES	Thermal Energy Storage
Wind-TP	Wind-driven Thermal Pumping system

Symbols

α	Cost for prototyping [%]
$b, c,$ and d	Three parameters for the PERT distribution
μ	Expected value for the PERT distribution
$\mathrm{Cost}_{\mathrm{Most-likely}}$	The most likely value for the generator capital cost of the system [£/kW]
$\mathrm{Cost}_{\mathrm{Original}}$	The original generator capital cost of the system [£/kW]
$\mathrm{Cost}_{\mathrm{Systemreduced}}$	Generator capital cost of the system with reduced uncertainty [£/kW]
K	Number of systems
$\mathrm{NPV}_{\mathrm{System}}$	NPV of the system [M£]
$\mathrm{NPV}_{\mathrm{Afterprototype}}$	The system NPV after prototyping [M£]
$\mathrm{NPV}_{\mathrm{Max}}$	Maximum NPV threshold (determine to proceed with the project if above) [M£]
$\mathrm{NPV}_{\mathrm{Min}}$	Minimum NPV threshold (determine to abandon the project if below) [M£]
$\mathrm{NPV}_{\mathrm{Static}}$	Static NPV assuming no option is available [M£]

1 Introduction

Driven by the need for a low-carbon society, innovative energy systems are needed to reduce global warming and environmental pollutions [1, 2]. In the energy sector, novel low-carbon energy systems are proposed across different domains, including solar photovoltaic [3] wind turbines [4], nuclear reactors [5]. System innovation in the energy sector is not limited to power systems since accommodating the low-carbon energy generation, and decarbonising energy consumption requires several other novel systems, including energy storage systems [6], transmission lines [7] and power conversion systems [8]. Therefore, several innovative energy systems are continuously developed and proposed.

While some novel systems are incremental innovation or marginal improvement of existing ones, others are more of radical innovation [9]. Following [10], we define radical innovation as the propensity of a firm to introduce new systems that incorporate substantially different technology from existing systems and can fulfil key customer needs better than existing systems. Although radical innovations bring attractive business opportunities, they are risky due to relevant technical and economic uncertainties [11]. Examples of technical uncertainties are related to efficiency (real vs expected), time performance (e.g., start-up time), and reliability (e.g., unexpected outage). Examples of economic uncertainties are construction and operating cost.

Prototyping is a common approach aiming to reduce the investment risk of radical innovations. A prototype is a system developed to test a design idea empirically [12]. It is possible to study the aspects of the system of interest with a prototype and to gain additional insights [12]. Prototyping is an essential stage for research and development. It allows spending a fraction of the actual system cost and, in return, receiving valuable information (e.g., economic and technical). This information can reduce uncertainties and thus, risks in building the actual system. In other words, investors have the option to invest some money in a prototype in exchange for valuable information for reducing investment risks. The trade-off between “the money invested in developing the prototype” and “value of the information obtained” needs to be evaluated. The Real Options Analysis (ROA) is the method to evaluate this trade-off.

ROA is an appraisal approach for capital budgeting decisions. A Real Option (RO) itself is the right, but not the obligation, to exercise specific business opportunities (or options) based on the technological, market, or economic conditions [13]. In the energy sector, several ROs are available, including the options to [14]:

- Defer the possibility of waiting to make some irreversible decisions (e.g., building the system).

- Abandon the possibility to abandon current operations permanently if market conditions become extremely unfavourable or if the detailed design reveals lower than expected profitability.
- Expand, contract, or extend the life of a facility: the possibility to increase capacity if it is profitable (e.g., adding further capacity to an existing system).
- Switch: the possibility to change systems, processes or inputs.
- Prototype: as discussed in this paper.

Despite the relevance, there is a paucity of studies in the literature about the "option to prototype". From a search query in a scientific database[1] only 6 documents were found [15-20]. However, none of the documents was about minimising the investment risk for an energy system by building a prototype or valuing prototyping against its cost. Given the gap in knowledge and the relevance of the problem; this work presents a novel ROA algorithm for the "option to prototype." This algorithm is relevant for stakeholders interested in prototyping to reduce the investment risk and increase the bankability of radical innovations for energy systems.

To test the algorithm, this work employs the "Generation Integrated Energy Storage" system (GIES) as a relevant and timely case study. GIES is an innovative and unique class of integrated energy system, composed of a generator and energy storage. GIES *"stores energy at some point along with the transformation between the primary energy form and electricity"* and is potentially competitive for storing several MWh [4]. GIESs are usually non-electrochemical and could be thermal energy storage, compressed air energy storage, etc. [21, 22]. The idea is converting the primary energy into an energy form that is easier to store than electricity [23, 24]. The GIES system considered in this work is a Wind-driven Thermal Pumping system (Wind-TP) located in the UK [1].

This paper aims to introduce and test an algorithm based on ROA to quantitatively assess the "option to prototype" in the energy sector. Section 2 presents a literature review on interrelated research areas of prototyping, energy systems, and ROA. Section 3 presents the discounted cash flow model for the real options analysis and the option to prototype algorithm. Section 4 applies the algorithm to Wind-TP and discusses the results. Section 5 concludes the

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[1] The scientific database considered is Scopus (www.scopus.com). The exact query is TITLE-ABS-KEY ("Real option" AND prototyp* AND energy). Last checked 01-October-2020

paper.

2 Literature review

The economic and financial appraisal of energy systems is performed with a Discounted Cash Flow (DCF) model [25, 26]. DCF model calculates the key financial indicators, e.g., Net Present Value (NPV) and internal rate of return, by forecasting and discounting future cash flows. The key weakness of the DCF model is the inability to properly evaluate the degrees of freedom available to the investors to hedge the investment risks [27].

In reality, uncertainties exist for energy systems because of technological (e.g., efficiency and lifetime) and economic (e.g., capital cost and operating cost) factors. ROA can support capital budgeting decisions when there are relevant uncertainties, like in the development of innovative energy systems.

As depicted in Fig. 1, this research concerns three research areas, namely: Energy, ROA, and prototyping.

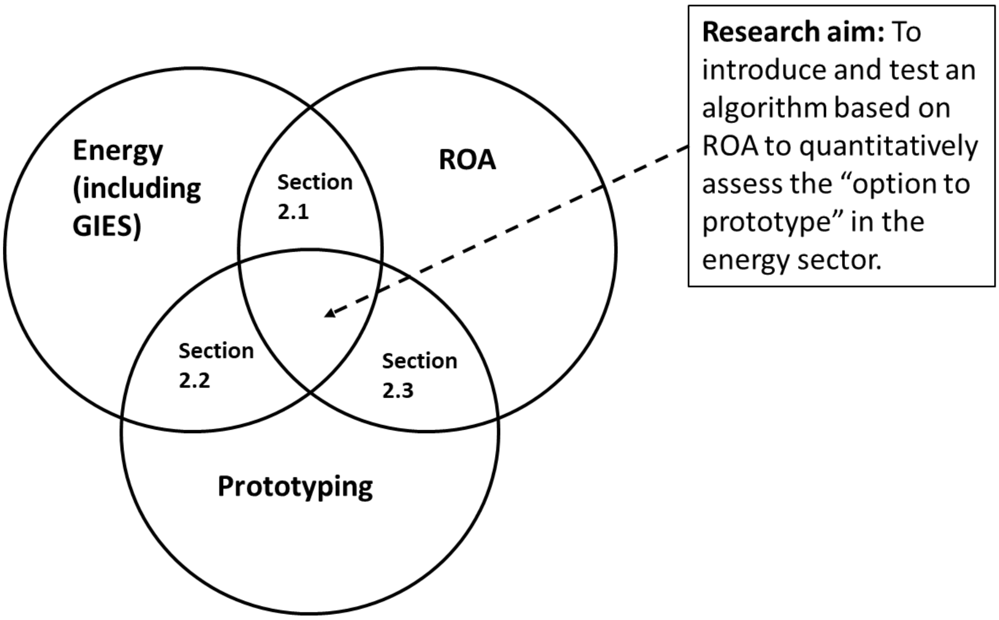

Fig. 1. Research areas and aim.

As this work focuses on RO with prototyping and using GIES as a case study, Table A.1 (in Appendix A) summarises the results of a Scopus[2] search for real options analysis for energy storage. 35 documents were identified and the table summarises the key research outputs. As

[2] The exact query is TITLE-ABS-KEY ("energy storage" AND "real options"). Last checked 02-October-2020

this paper is a research article and not a review article, the authors select the most recent and representative works, i.e., covering a wide range of ROA.

2.1 ROA in the energy field

ROs can increase project value and minimise investors' risk. ROA is meaningless if there is no uncertainty in the project; in such cases, the traditional DCF is appropriated [13]. Kodukula and Papudesu [14] details the differences between DCF and ROA and their implementations. Fleten et al. [28] investigated the actual (observed) behaviour and concluded that ROA is a suitable descriptor of the observed investment behaviour in the renewable energy sector.

There are several approaches for the ROA. The choice of method depends on the nature of the problem, including the complexity and the available computational resources [14, 29]. ROA can be divided into three classes, known as partial differential equations (e.g., Black and Scholes model), simulations, and lattice. As computers are getting more powerful, approaches based on simulations are becoming increasingly common [27]. Horn et al. [30] developed questionnaires and asked decision-makers in various companies which valuation techniques they use and find that real options methods are used particularly in the energy sector. When ROA is not used, key reasons are lack familiarity with the ROA or the complexity of the mathematical frameworks.

Kozlova [31] reviewed the academic literature on renewable energy project valuation with ROs. The most common type of ROs is the option to build (or invest), which is in the planning stage and no longer available once the investment decision has been made.

ROA has been applied in the energy field, particularly for the following applications:

Novel low-carbon power generating systems: Zhang et al. [32] proposed an ROs model to determine the best investment strategy for hydrothermal geothermal heating projects. Various technological, geological, and political uncertainties are considered. MacDougall [17] applied ROA to an investment in a 10 MW array of in-stream tidal energy conversion devices. There is value in the option to delay. Locatelli et al. [33] presented a novel investment appraisal method for small modular reactors based on ROs with 1) The modelling of the time to market effect and 2) The investment in a particular power system considering the utility portfolio.

Energy storage: Moon [34] proposed a ROA model to determine the optimal investment time for energy storage in a price arbitrage trade application under uncertain future profits. ROA provides additional financial value compared to the traditional DCF approach. Locatelli et al. [13] presented a ROA methodology to properly consider investment risks and uncertainties as well as the options available for the investor in energy storage. Similar to [34], ROA increases the economic performance of energy storage. However, energy storage requires incentives to be economically viable.

Carbon Capture and Storage (CCS): Wang and Du [35] proposed a lattice-based quadrinomial ROA model to evaluate the investment in retrofitting existing coal-fired power systems with CCS. The uncertainties considered are fossil fuel price, carbon price, government subsidy, and investment cost. They show that government subsidy is crucial to reduce the critical carbon price for CCS investments. Similarly, Elias et al. [36] used ROA with a backward iterative induction approach to examine the retrofitted natural gas-fired baseload power system with CCS. Sensitivity analyses on various prices, costs, and volatility parameters are conducted to gain insights into which CCS system to use.

The above review shows that ROA is a robust capital budgeting decision technique for energy projects. The energy sector often requires large capital investments with relevant uncertainties; therefore, valuing the option to prototype is relevant in the energy sector.

2.2 Prototyping for energy system

Widely used in engineering, a prototype is a model developed to test and verify a design idea [37]. The prototype emphases on the system properties that need additional insight [12]. Prototyping is a critical activity in the system development process, and it can be described as the "*activity of engaging with the product-to-be, instantiating the design process*" [38]. However, prototyping is one of the least explored areas of design practice [39].

Prototyping encourages learning in the design process and provides decision variables helping designers answer specific design questions while also giving rise to new ones [38, 39].

Ullman [40] defined four types of prototyping as follows:

Proof-of-Concept develops the system function for customers' requirements or engineering specifications comparison. This prototype acts as a learning tool, and details (e.g., materials and manufacturing process) are unimportant (e.g., a prototype could be built from any material or part available).

Proof-of-Product is constructed to aid refining the assemblies and components. This prototyping examines the details and the performance of the system. The prototyping time and cost can be optimised with rapid/desktop prototyping, using stereolithography, 3D printing, or computer-aided design.

Proof-of-Process verifies the design details. The precise manufacturing processes and materials are employed to manufacture system samples for functional testing.

Proof-of-Production verifies the whole production process. This prototype is the outcome of a preproduction run.

Since *Proof-of-Concept* is at an early stage of system development, the option to prototype can be used in the stages of *Proof-of-Product, Proof-of-Process,* and *Proof-of-Production* to probe the investment viability.

The eight purposes of prototyping and applicable to innovative energy systems are [39-43]:

Active learning: To secure novel knowledge about the design. Designers see failure as an opportunity to learn and enhance a sense of progress. Physical prototyping could help to determine differences between a concept and a real system. Active learning with prototypes focuses on the student's education, and students are encouraged to learn with prototyping.

Communication: The process of distributing information to stakeholders (e.g., customers) about the design and functionality of the design. Prototypes are essential for communicating concepts within the design team, including in the education environment [44], and allow stakeholders to interact with the design or the potential system. Prototypes can aid sales presentation and pitch, consequently, increase the success probability and amount of sales.

Demonstration: Also known as "milestones," the demonstration is related to the design process planning. Prototypes set design objectives and ascertain that the system has reached a level of its anticipated functionality or impose deadlines that should be met during system development.

Integration: To verify that all individual parts of a system can fit and work together as envisioned. Several prototypes can be created for sub-systems, and each sub-system may have reached its anticipated function. However, all of the already tested sub-systems must be compatible as a system.

Refinement: The process of improving design and is a significant benefit of prototyping. It determines critical design concerns, validates requirements, minimises errors, to determine performance-enhancing design variations, and design feature optimisation.

Exploration: To seek out for new design concepts. It can be classified into "divergence" and "convergence". "Divergence" denotes collecting information and creating new concepts. "Convergence" denotes creating a set of refined concepts by selecting available concepts. Designers use physical prototypes to assist in exploration (concept generation process).

Requirement elicitation: To define the requirements for a specific system or process. It also comprises the prioritising of them and the identification of the stakeholder's participation. Requirement elicitation is challenging in engineering design because of the high uncertainty and the volatile factors involved, known as "unknown unknowns." Thus, it is essential to understand the information developed during the prototyping process [40].

Workforce morale enhancement: Gerber et al. [45] studied the psychological experience of prototyping with an ethnographic study of a high-tech firm. By breaking huge tasks into modest size tasks, designers produce visible results that are both self-validating and validated by others. Consequently, designers gain motivation and confidence to develop the system. Designers acknowledge success to prototyping with each modest accomplishment and continue committed to the design process, despite the outcome's uncertainty.

According to the above purposes, *active learning* is the prerequisite for the option to prototype.

With the emergence of data-driven design, additive manufacturing, and big data, prototyping can be more productive and less costly. Prototyping is gaining popularity for energy systems development. Some of the emerging prototyping techniques include [43]:

- Virtual reality and augmented reality allow immersive and high-quality simulations. Also, open-source software repositories and machine learning reduce simulation cost.
- Internet of things allows data-intensive prototyping, with extensive data sources (e.g., video) and continuous wireless monitoring of real-time data.
- Reconfigurable electronic hardware (e.g., Raspberry Pi) and additive manufacturing (e.g., 3D printing) enable a drastic cost reduction in hardware prototyping. These systems enable additional levels of complexity with advanced capabilities (e.g., direct texture printing with multi-material 3D printing).

2.3 GIES systems and prototyping

Garvey et al. [4] presented the concept and terminology of "GIES". GIES reduces the need for energy transformation by storing the energy in primary form (e.g., heat or kinetic). The energy transformation (to electricity) will occur when electricity is required. This is different from non-GIES, where energy is stored as electricity via electro-chemical energy storage (e.g., batteries). Currently, battery systems (especially Lithium-ion and redox flow batteries) are one of the most mature grid-scale energy systems [46]. A review of GIES systems is presented in [21].

Relevant examples of GIES include:

Wind power and Pumped-Thermal/heat Energy Storage (PTES) [47-49]. PTES uses a reversible heat engine or heat pump and two Thermal Energy Storage (TES) vessels. Howes

[50] presented the early conceptualisation of a reversible heat/work conversion system based on the heat engine cycle used for utility-scale thermal energy storage. Three prototypes were developed for PTES by Isentropic Ltd. The first prototype was an air-cycle heat pump, devised to reduce heat transfer and valve pressure losses during compression and expansion. The prototype was able to process a high mass flow for a reciprocating machine. The second prototype was designed with several objectives, including maximum valve open area and maximum physical separation of hot elements from cold. The third prototype claimed to be ongoing work with 150 kW capacity. Wind-TP is an integrated wind power generator and PTES system [51], with a liquid thermocline and a packed bed as the cold store [24]. The research on Wind-TP is currently led by the University of Nottingham, UK, and funded by the Engineering Physical Science Research Council. It is expected that a 60 kW prototype (using an electric motor to replicate the wind turbine rotor input) will be developed and examined [23].

Concentrating solar power system with TES [52-55]. This system generates solar power with lenses or mirrors, by concentrating a significant area of sunlight onto a receiver. Concentrating solar power system converts water into steam with solar thermal energy, and the steam spins a turbine to create electricity. In GIES, the thermal energy can be stored by TES. TES can be classified as sensible TES, latent TES, and thermochemical TES [56]. Molten salts and thermic oils are established TES heat transfer fluids. Thermochemical TES has a reduced charging temperature, volume requirement, and heat loss, compared to latent TES and sensible TES [55, 57]. Thermochemical TES is developing and can bring ten times the energy storage density compared to sensible TES. Paskevicius et al. [58] designed and constructed a prototype for examining the viability of hydrogen storage materials for concentrating solar power systems. The prototype proves that solar TES based on metal hydrides is feasible, and future work consists of geometries and design optimisations. Zipf et al. [59] presented a novel latent TES by using a screw heat exchanger for heat transfer. The prototype is developed to learn the dynamics of the phase change and the heat transfer characteristics in the screw heat exchange.

In this work, the option to prototype has been applied to Wind-TP; a type of GIES system. Wind-TP is a novel system and currently in the research and development stage [23, 24]. Wind-TP consists of a wind power generator and PTES. The synchronous generator produces electricity from mechanical power resulting from the slowly-rotating shaft of a large wind turbine rotor via the high-pressure gas circulation running in a closed circuit. In the basic operating mode, power is injected into the gas circuit through specialised low-speed nearly-adiabatic compressors with very high isentropic efficiency [1]. The power is extracted with an expander that is also nearly-adiabatic with great isentropic efficiency. In other operating modes, the variation in gas temperature following adiabatic compression/expansion allows the power transmission to store or recover Energy from storage. For an ideal gas, the power extracted from an adiabatic compressor is proportional to the intake volume flow rate. The power released by an adiabatic expander is proportional to its intake volume flow rate. In a steady-state condition, the mass flow rate of gas around a closed circuit is constant at all points in the circuit. The intake volume flow rates are proportional to temperatures. The system can store Energy by cooling the gas after compression (i.e., storing the heat) following by removing and storing coolth (coldness) from the gas after the expander. The temperature variations make the compressor to draw greater work than the expander delivers. The system can recover energy from energy storage by including additional heat to the gas following the compression process and by adding coolth to the gas following the expansion. The expander gives greater power than the compressor draws. For the DCF model, the input data for Wind-TP can be found in Tables B.1, B.2, B.3, and B.4 in Appendix B.

Table 1 presents the ROs to minimise risks and uncertainties for GIES. There is no single RO that can hedge all investment risks in the economic, technical, and financing dimensions. The option to prototype hedges risks similar to the option to build, but further reduces the investment risk by learning more about the system instead of building the actual system, which requires a more substantial investment.

In summary, prototyping is a crucial stage in engineering design. Current GIES prototypes focus on exploratory and requirement elicitation. The types of prototyping for GIES are proof-of-concept or proof-of-product. Soon, Wind-TP and its developers will use prototypes to seek additional funds. The next section examines the research areas of prototyping and the use in ROA.

Table 1 Real options and risk hedging approaches to minimise risks and uncertainties for GIES.

Type of option		Build		Wait	Switch	Contract	Abandon	Expand
		System	Prototype					
Risk hedging approach		Build small systems in increments	Active learning: invest more on the engineering - upfront	Others to develop the system and/or market change	As stated above	As stated above	As stated above	As stated above
Economic	Capital cost overrun [M£]	✓	✓	✓	✓	✓	✓	✗
	GIES capital cost [£/kWh or £/kW]	✓	✓	✓	✗	✗	✗	✓
	STOR average availability hours price [$/hr]	✗	✗	✓	✗	✗	✗	✗
	STOR average utilisation hours price [$/kWh]	✗	✗	✓	✗	✗	✗	✗
Technical	Storage efficiency [%]	✓	✓	✓	✗	✗	✗	✗
	Operating lifetime [years]	✓	✓	✓	✗	✗	✗	✗
	Construction time [years]	✓	✓	✓	✗	✗	✗	✗
	Energy storage degradation [%]	✓	✓	✓	✗	✗	✗	✗
	Transmission efficiency [%]	✓	✓	✓	✗	✗	✗	✗

2.4 ROA and prototyping

Twenty-nine documents were found according to an enquiry on Scopus[3]. Erdogmus [60] demonstrated the application of ROA for software development considering the two consecutive stages: 1) a mandatory prototyping stage and 2) an optional full-development stage. The full-development proceeds if the prototype is successful and the market outlook is relatively positive at the end of the prototyping stage. The project's staged design expands the project value. The effect of prototyping cost and value of building multiple systems after prototyping were not examined.

Benaroch [61] presented a RO approach to establish the option for optimal information technology investment, with internet sales channel as a case study. The author discussed the

[3] The exact query is TITLE-ABS-KEY ("Real option" AND prototyp*). Last checked 02-October-2020

option to explore/prototype by building a pilot or prototype system. The advantages of the option to explore/prototype include examining risks without making the full-scale investment, disposing of a prototype brings no reputation, competitive, or regulatory consequences, and prototype can be created with existing resources at a fraction of the full-scale investment cost. The case study only considers options to abandonment, defer, contract, expand, and switch-use, where the option to prototype is not explored.

Schäfer and Sorensen [62] proposed a novel ROA model for set-based concurrent engineering (i.e., by broadly considering sets of possible solutions and gradually narrowing the set of possibilities to converge on a final solution). Prototyping is essential for automobile design and the option to switch between design alternatives were considered.

Chevalier-Roignant et al. [63] examined the option value of a firm with a compound option (the option to enter a new market considering uncertain demand), consisting of developing a prototype and entering the market under oligopoly competition. The market entry is not viable if a firm fails to develop the prototype (follows a Bernoulli trial). If a prototype is viable, a firm can decide whether or not to commercialise the innovation and launch the new product. The market-entry decision will depend on the state of future demand, including how many rivals succeed at developing competing viable prototypes. The RO model generalises the Black-Scholes-Merton formula considering firm development success probabilities and heterogenous market-entries for developing a system or determining economies of scale in production.

Based on the above review, there is no work examining the value of prototyping against its cost and decide to whether proceed with a prototype or not. To address this gap in knowledge, the next section presents a new option to prototype an algorithm to minimise the investment risk of energy systems.

3 An algorithm for the option to prototype

This paper aims to introduce and test an algorithm based on ROA to quantitatively assess the “option to prototype” in the energy sector. This section details the algorithm.

3.1 Definitions, inputs, and hypothesis

ROA models are an enhanced version of the DCF model. The details of the underlying DCF model complete with all the inputs are in [1], where the authors identified that the generator capital cost is the most influential factor in the GIES system’s economics and exhibits great uncertainty. This section details the ROA model expanding the aforementioned DCF model. The key elements of the RO model are:

Static NPV: This is calculated by the traditional DCF method, as documented in [1] without considering ROs.

Expanded NPV: The resulting NPV created by considering the value introduced by one or more options [64, 65].

The option value can be calculated with Equation (1) [64, 65]:

$$\text{Option value} = \text{Expanded NPV} - \text{Static NPV} \tag{1}$$

State variable: As aforementioned, GIES systems are capital intensive investments, and the most influential state variable is the generator capital cost. The cost estimate guidelines from the Association for the Advancement of Cost Engineering (AACE) describe reasonable cost uncertainties classified in five classes of estimates according to the project stage [66], as described in Table 2. Specifically, the higher the class number is, the greater the cost uncertainty (i.e., variance) will be. Class 5 is the highest class and Class 1 is the lowest class.

Following the approach presented in [66], Fig. 2 shows the Probability Density Functions (PDFs) with PERT distribution for five classes of estimate, for the capital cost considering a “most likely value” for a generator capital cost of 1280 £/MW as suggested in [1, 4].

Table 2. AACE cost estimate classification [66].

Estimate class	**Level of maturity for project definition deliverables (% of completeness)**	**Reason for estimate**	**Typical estimating method**	**Expected accuracy range, lower and upper range [%]**
1	65 to 100	Check estimate or bid/tender	Detailed unit cost	-10 and +15
2	30 to 75	Control or bid/tender		-15 and +20
3	10 to 40	Budget authorization or control	Semi-detailed unit costs	-20 and +30
4	1 to 15	Study of feasibility	Equipment or parametric model	-30 and +50
5	0 to 2	Concept screening	Parametric model, judgement or analogy	-50 and +100

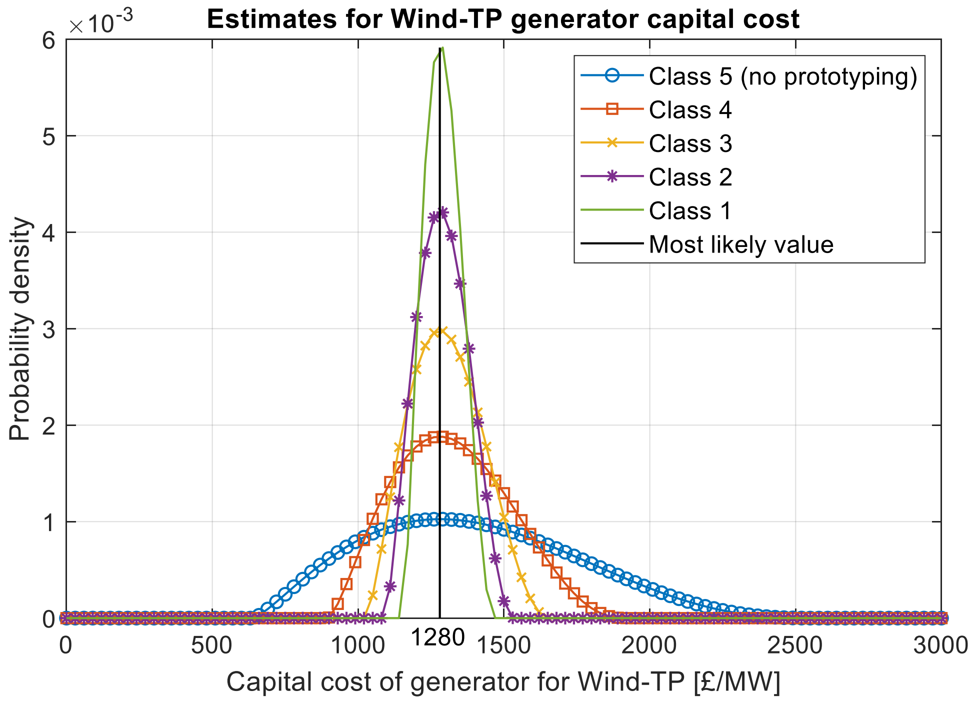

Fig. 2. Five cost estimates for generator capital cost of Wind-TP with AACE. For illustration purposes, the most likely value is the same for all cost estimates.

Table 3 presents the key inputs for the algorithm to value the option to prototype. α is the cost for prototyping and calculated as the percentage of the actual system; the full list of inputs for the DCF model is in Appendix B. NPV_{Max} [M£] is the maximum NPV threshold (determine to directly proceed with the project if above), and NPV_{Min} [M£] is the minimum NPV threshold (determine to abandon the project if below) [13]. K is the number of systems to build (market size).

Table 3. Model inputs for the option to prototype algorithm.

Input	Type of distribution	Min. value	Most likely value	Max. value
Original uncertainty (Class 5)	PERT distribution	640 [£/MW]	1280 [£/MW] [1, 4]	2560 [£/MW]
Uncertainty after prototyping (Class 4)	PERT distribution	Most likely value (Class 4) * 70% [£/MW]	Generate from class 5 distribution [£/MW]	Most likely value (Class 4) * 150% [£/MW]
α **[%]**	Not applicable	10		
Number of systems to be built (*K*)	Not applicable	1		
$\mathbf{NPV_{Max}}$ **[M£]**	Not applicable	+20		
$\mathbf{NPV_{Min}}$ **[M£]**	Not applicable	-40		

In developing the option to prototype algorithm, the hypotheses (HP) are:

HP1. The variance of the state variable will be reduced from Class 5 to Class 4 after prototyping (Table 2), as a result of obtaining more information about the system as shown in Fig. 2. A Class 5 cost estimate assumes that the system is at a “Concept screening” phase. The construction and testing of a prototype allow to overcome this phase and achieve at least a Class 4 uncertainty, i.e., “Study of feasibility” phase.

HP2. The uncertainty of the “state variable” for building one system or more (*K*) systems does not change. This is a conservative hypothesis because the uncertainty will reduce with more systems built due to the accumulating of knowledge. However, since the prototype is assessed even before the first unit is built, the uncertainty, at this point of time, of all the K units, is the same.

HP3. The cost spent on prototyping is a percentage of the actual system, denoted α (Fig. 4).

HP4. The most likely value for Class 4 estimate is generated from the PERT distribution of Class 5. In probability and statistics, the PERT distribution is a family of continuous probability distributions defined by the minimum, most likely, and maximum values denoted by $b, c,$ and $d,$ respectively [67]. Its expected value is given in Equation (2).

$$\mu = \frac{b + 4c + d}{6} \tag{2}$$

Having presented the definitions, model inputs, and hypothesis, the next section presents the option to prototype algorithm.

3.2 The discounted cash flow model

This section describes the DCF model for the ROA. Fig. 3 presents the DCF model adapted from [1] for the techno-economic and financial analyses of GIES and non-GIES (i.e., wind power generator with battery) systems. The model accounts for three categories of inputs (technical, economic and financial) and compute the free cash flow to firm and free cash flow to equity. In this work, the free cash flow to equity is examined as more relevant to the equity holders.

3.2.1 Costs

For the power generator and energy storage, capital costs are the upfront cost comprising of both “hard costs” (e.g., components such as wind turbine) and “soft costs” (e.g., licensing fees) [68, 69]. Operation and Maintenance (O&M) costs comprise labour, regular servicing, repair, and electricity purchasing (energy storage charging cost) [68]. For a wind power generator, the construction cost mainly comprises of the upfront capital cost for the wind turbine [70]. Table B.3 presents the cost adapted from [1].

3.2.2 Revenue sources

Revenues sources depend on the national electricity market. Because of public data availability and the effort in decarbonisation this paper uses the UK as context. In the UK, the most relevant revenues for GIES systems are:

Wholesale market/ spot price: Nord Pool AS provides the hourly wholesale market price [71]. Table B.4 presents the market prices adapted from [1].

Short Term Operating Reserve (STOR): STOR is a balancing service subject to contract. The provider delivers a contracted level of power once ordered by the National Grid Electricity System Operator to fulfil energy reserve requirements [72]. Tables B.2 and B.4 summarise the key values for STOR adapted from [1].

Fast Reserve: Fast Reserve provides rapid active power by increasing the generation or minimising the demand, as ordered by an electronic dispatch instruction from the National Grid Electricity System Operator [73], by being involved in controlling frequency variations. Tables B.2 and B.4 present the key values for Fast Reserve adapted from [1].

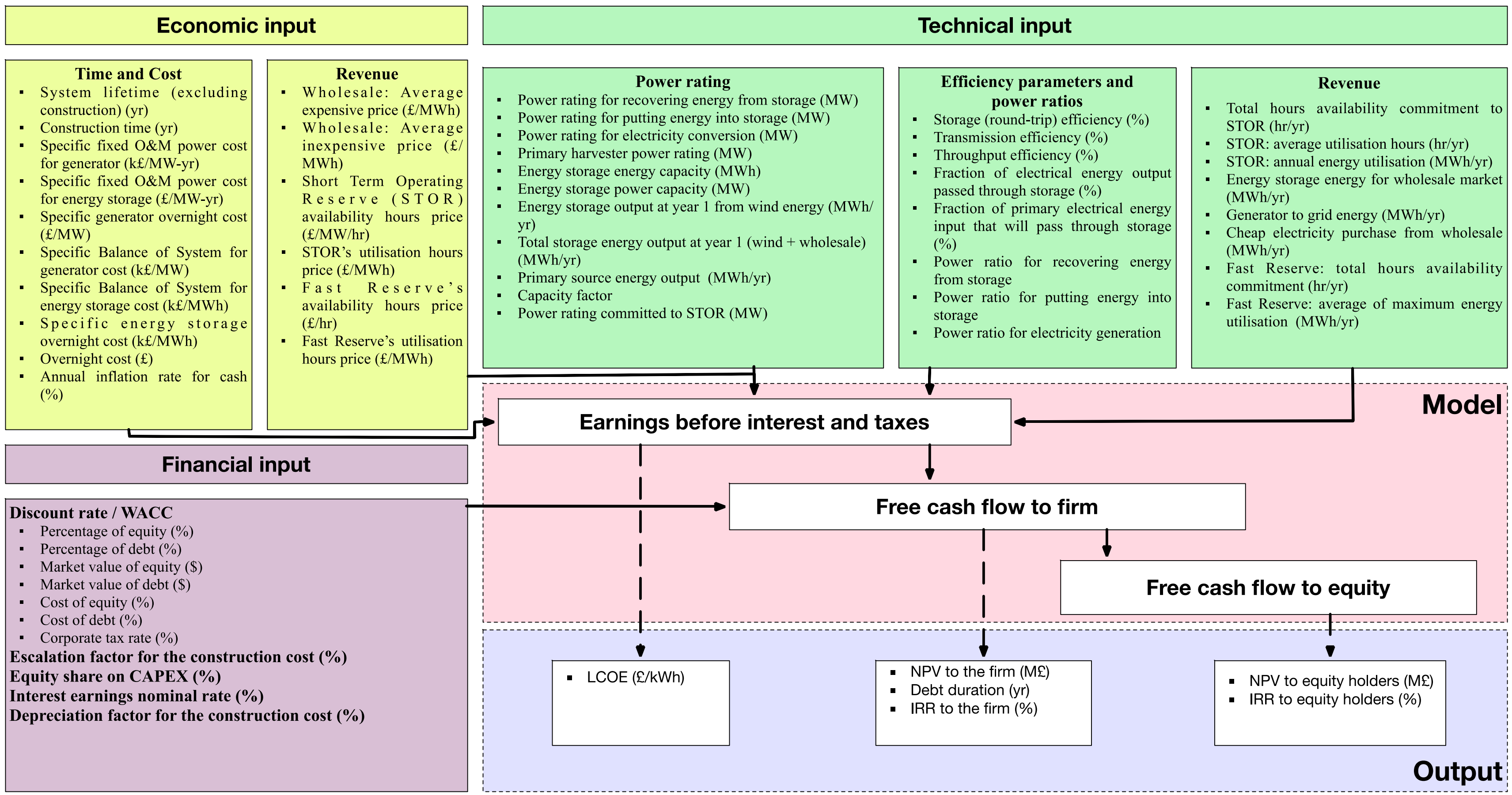

Fig. 3. Discounted cash flow model adapted from [1] .

3.3 Algorithm

Fig. 3 shows the algorithm for the option to prototype. The algorithm consists of two stages: 1) traditional DCF and 2) the option to prototype. If the NPV for the system is already attractive or clearly not bankable, then the decision to proceed or abandon with the system is clear and there is no need to prototype. However, if the situation is uncertain, i.e., the NPV is close to zero (positive or negative), the option to prototype allows us to obtain valuable information regarding the system.

Specifically, the algorithm requires the calculation of three NPVs as follows (Fig. 4):

① NPV_{Static}: The traditional DCF calculated assuming that the option to prototype does not exist.

② $NPV_{Afterprototype}$: The expected NPV calculated after building the prototype.

③ NPV_{System}: The NPV of the actual K system(s) minus the cost for one prototype (expanded NPV).

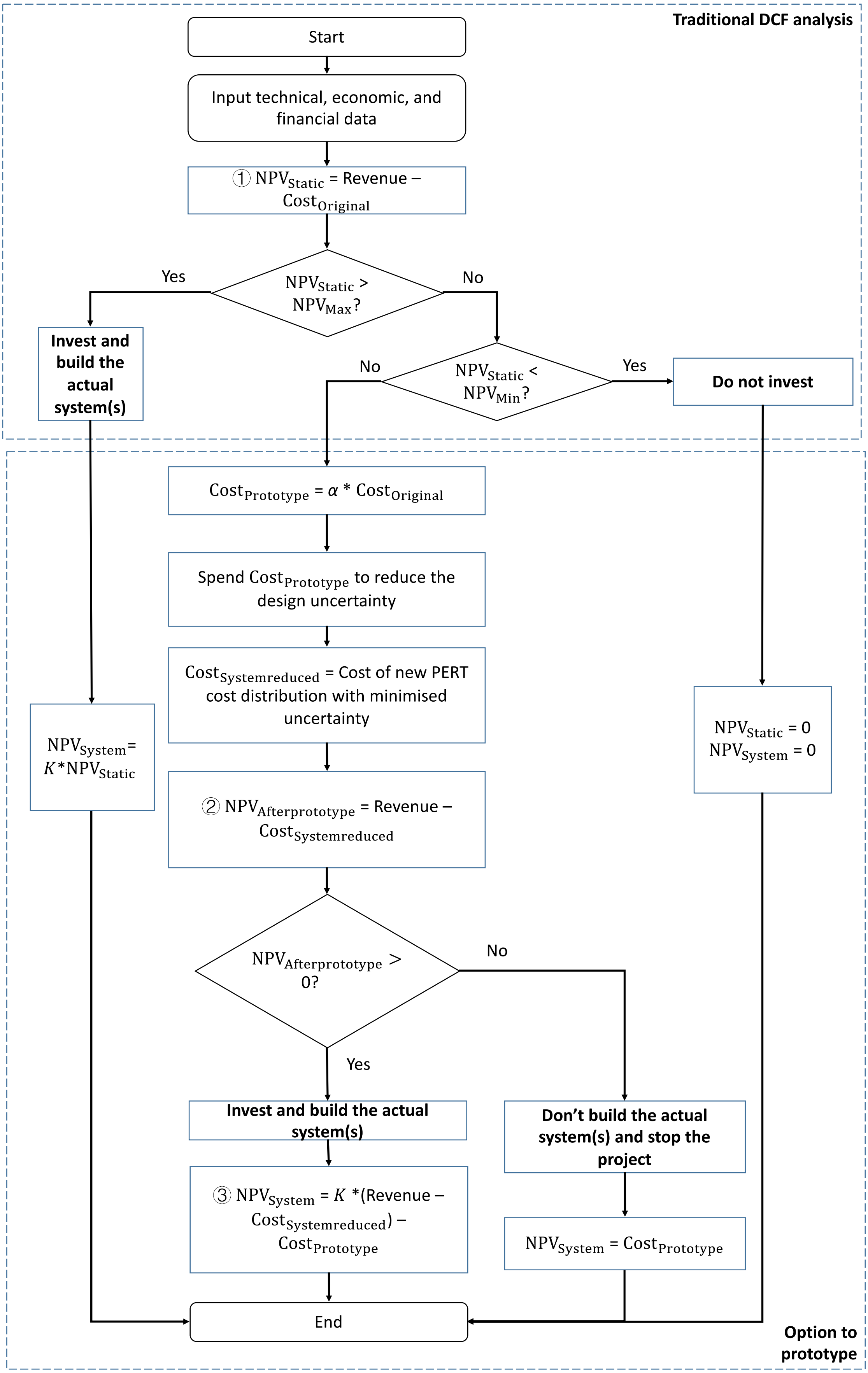

Fig. 4. ROA algorithm for the option to prototype.

4 Results and discussion

4.1 Option to prototype considering a single system

It is important to recognise the need for a ROA and prototyping by examining the PDF of the NPV with the traditional DCF. Fig. 5 depicts the system NPV for the GIES system considered (a Wind-TP) with no real option applied. This distribution across the NPV = 0 shows that the investment is very risky. This confirms that the ROA is ideal for this case study.

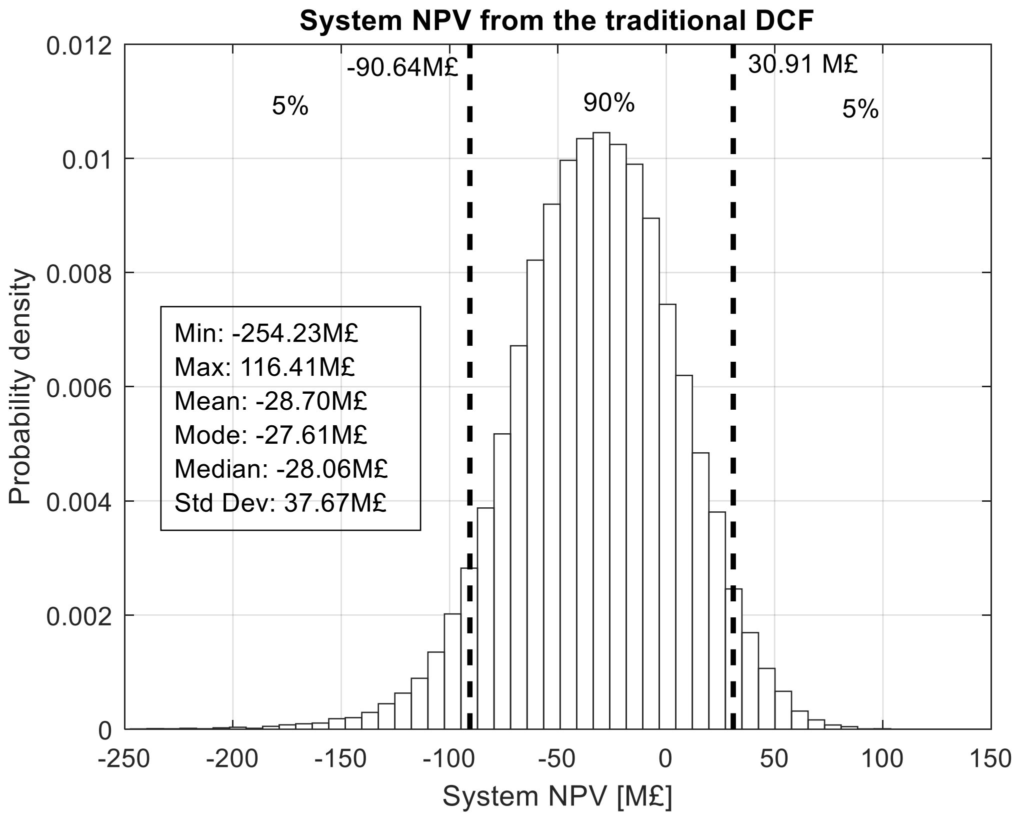

Fig. 5. System NPV from the traditional DCF.

Fig. 6 presents the PDF of the system NPV for Wind-TP with the option to prototype and build one system. The negative values in the system NPV are mainly contributed by the prototyping cost. The PDF has a strong mode for NPV = 0 M£, i.e., when the system is abandoned as $NPV_{Static} < NPV_{Min}$. This means that in 38.0% of the cases, it is not worth building a prototype of the technology but just terminating the development process. This number is reasonable considering that, in real life, often the development of a new technology terminated before building a prototype.

The option to prototype provides a mean system NPV of -4.61 M£ and a mean option value of 24.09 M£ (i.e., -4.61-(-28.70)) for building one system, assuming a prototype cost equals to 10% of the system.

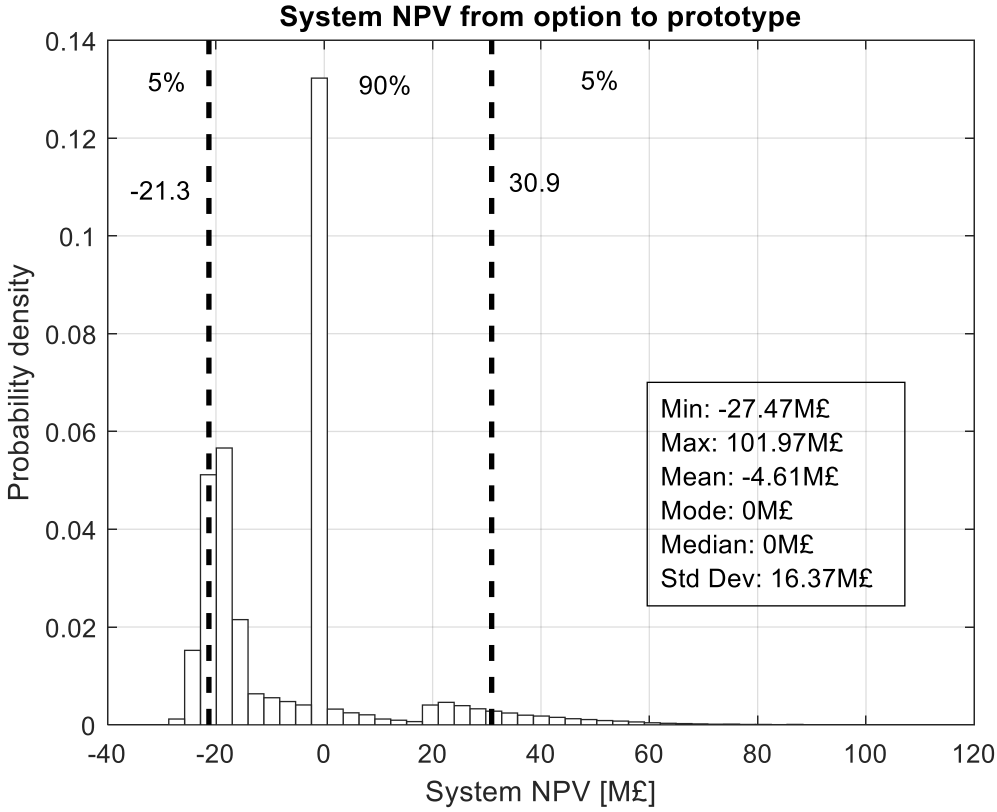

Fig. 6. System NPV from option to prototype and building one system.

To gain a more holistic perspective, Fig. 7 illustrates the negative, positive, and zero expanded NPVs for the different stages of the option to prototype. The results are obtained from the algorithm presented in Fig. 4. Fig. 7 shows that there is a value in the option to prototype as the probability reduced from 77.2% with the traditional DCF to 48.9% with the option to prototype.

Remarkably the option to prototype also reduced the percentage of positive NPV; this justified considering that cost of a prototype can be higher in the NPV of the "actual system" (called $NPV_{Afterprototype}$ in Fig. 4) leading to a final negative NPV. This is particularly relevant in the case of K=1. If K is more than 1 the cost of the prototype is spread over more "actual systems" and therefore the NPV increases (as shown in Table 4). With regard to the zero NPV, this is an important factor that reduces the percentage of negative NPV. The high frequency of "zero NPV" is due to the decision to abandon the system when the DCF analysis shows that the system will give an unacceptably low NPV. For the standard DCF analysis, the percentage of zero NPV is small, giving the decision-maker no option to abandon the system.

Investing in the building of just "one prototype and one system" is an extreme and mostly unreasonable situation. In the energy sector, novel systems (e.g., GIES) are designed to be built more than once and spreading upfront costs (e.g., design, licensing, prototyping) over several nearly identical systems. Reasonably, if the investor is expecting to build more systems (i.e., a larger market size), then the investor will be more willing to spend money upfront, including building a prototype. We quantitatively explore this aspect in the next section.

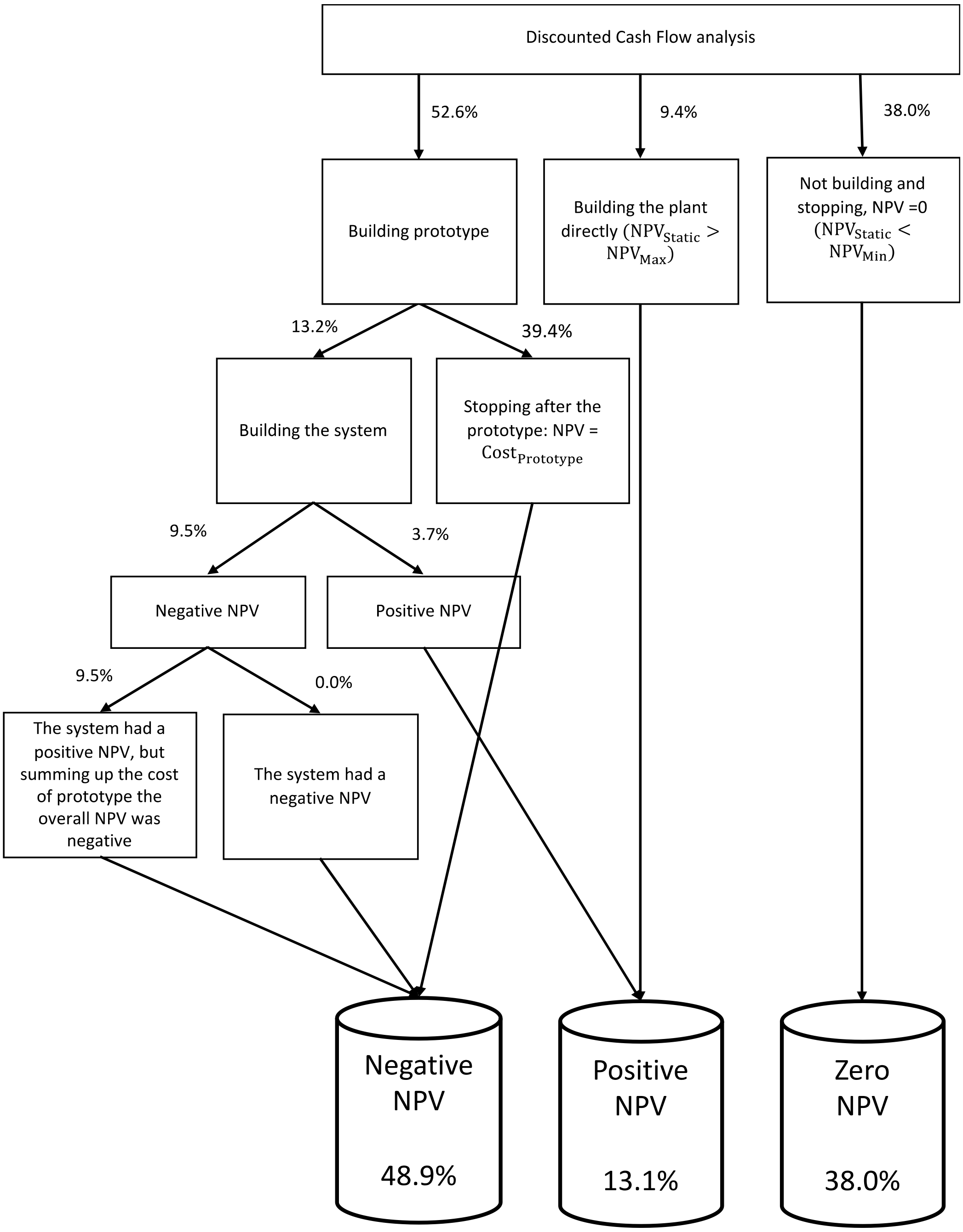

Fig. 7. Illustration of the option to prototype with 1 system and 10% prototype cost.

4.2 Option to prototype considering multiple systems

Remarkably, energy systems are very seldom built “one-off,” i.e., when a company develops an energy system (e.g., Wind-TP considered in this paper), the expectation is to build several units. Therefore, the willingness and value of building a prototype depend on two key parameters:

1) The cost of the prototype itself (the input α of this model): other factors being equal, higher the cost of the prototype, less is the incentive to build, and vice-versa.

2) The number of units to be built (the input K of this model): higher the number of units to be built, higher the justification to build a prototype (and vice-versa). In this situation, the upfront cost of the prototype is paid only once, but costs, revenues and therefore, profits for the full-scale system are multiplied by the value K.

These observations trigger a research question: “How many systems are required to be built to justify the cost of prototyping?” This question can be answered by a sensitivity analysis of the parameters α and K of the algorithm in Fig. 4. To this end, Table 4 shows the mean system NPV for different percentages of prototyping cost and the number of systems to be built after prototyping. The mean expanded NPV increases as the prototyping cost reduces. When $\alpha = 10\%$ (as examined in Section 4.1), the mean expanded NPV is positive when at least two systems are built. The mean expanded NPV turns negative when the prototyping cost increases. This indicates that if the prototyping cost is too high and not enough systems are built, then the system is no longer bankable. Reasonably, when several systems are built (i.e., 100), the mean NPV becomes positive even at high prototyping cost. Table 4 can be developed by companies investing in the innovative energy system to support their decision making regarding identifying the percentage of prototyping cost and the number of systems to be built.

Table 4. Mean system NPV [M£] for the different number of systems concerning prototyping cost.

		Number of systems to be built after prototyping (K)										
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**100**
α [%]	**10**	-5	1	5	10	15	20	25	30	36	41	481
	20	-15	-10	-5	1	6	11	17	22	27	31	475
	30	-24	-19	-16	-9	-5	1	7	12	18	24	470
	40	-36	-29	-24	-18	-14	-9	-5	4	6	15	450
	50	-45	-38	-35	-29	-23	-18	-14	-10	-4	2	439
	60	-55	-48	-43	-37	-34	-29	-23	-18	-14	-9	432
	70	-64	-59	-55	-48	-46	-37	-31	-30	-23	-18	425
	80	-72	-70	-64	-60	-56	-48	-42	-41	-35	-30	418
	90	-86	-79	-75	-66	-62	-57	-51	-52	-43	-40	411
	100	-96	-89	-84	-79	-71	-68	-60	-62	-54	-49	401

5 Conclusions

Radical innovations to develop new systems in the energy sector are needed to address climate change and improve living standards in developing countries. Inherently, new systems present investment risks due to relevant technical and economic uncertainties. Investors are reluctant to finance radical innovations if the investment risk is excessive. A common approach to hedge investment risks is by prototyping, i.e., spending a fraction of the cost of a full-scale system and, in return, receiving economic and technical information regarding the system. A prototype is a "real option" coming at a cost that needs to be justified. This paper provides two key research contributions:

1. It provides an algorithm for evaluating the "option to prototype" in the energy sector. The algorithm can be used for capital budgeting decision appraisal for a new energy system.
2. It applies the algorithm to the relevant case of Generation Integrated Energy Systems (GIES). The authors examine the option to prototype for Wind-TP.

GIES including Wind-TP, are radical innovations that aim to reduce the cost of energy storage for large-scale (MW) low carbon power generation. This paper has examined critical inputs of the algorithm, including the prototyping cost as a percentage of the actual system. For Wind-TP with an overnight cost at 181 M£/system, the option to prototype can give an expanded NPV of up to 41 M£ when 10 systems are built. The results show that the option to prototype can increase the NPV of the system, but if the prototyping cost is too high, then the system could no longer be bankable.

If the prototype cost is comparable to the cost of the actual system, it may be better to construct the system directly as: 1. the prototype cannot be used for commercial purposes; therefore no revenue can be generated; 2. the prototype cost is an "extra cost" for the business, and the greater the extra cost, more functioning units are needed to break-even. By building multiple systems (i.e., expanding the market), the expanded NPV would be positive under different prototyping costs (even if the prototyping cost equals to the cost of an actual system). Therefore, the expanded NPV is mostly dependent on the cost of prototyping and the number of systems to be built.

This paper paves the way to several streams of research that can either overcome the current limitations or expand the scope; here, the most meaningful ones are as follows:

- Regarding inputs and data availability, it is important to remember that the economic, technical, and financial data employed to conduct the real options analysis can greatly impact on the results. In particular, data availability for revenue sources (i.e., STOR and FR) from organisations such as National Grid is often very limited and, in some countries, might not be publicly available. Subsequently, it might also be difficult to estimate the probability density functions for inputs where historical data are scarce.
- Regarding the algorithm itself, the hypotheses including its assumptions can be improved. For instance, a hypothesis that the uncertainty of the "state variable" does not depend on the number of units. Actually, each further unit is an "option to build" that will be exercised with more information considered. An enhanced RO model will consider how the construction of additional systems will further reduce the risk and increase the expanded NPV.
- Another improvement in the model is considering other financial indicators. The NPV is not a specific measure; for instance, 1 M£ NPV can be "high" or "low" depending on the money invested to achieve this NPV. In investment appraisal, more indicators should be considered and included in the algorithm, among the other, the most relevant might be: internal rate of return, payback time, return on investment.
- Regarding the results, we showed prototyping is essential to develop new systems which could address climate change and improve living standards. However, prototyping, being a relevant cost can act as a barrier to innovation and particularly radical innovation. This has relevant policy implications for stakeholders in the energy sector and particularly governments. Governments should develop a list of key activities to support companies in developing prototypes, such as: grants to cost-match

investments, favourable tax conditions for investment in prototyping (e.g., forms of tax relief), and loans with low-interest rate. A policy-oriented research team should establish criteria and guidelines for the public support of novel energy systems.

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Appendix A

Table A.1
Review on ROA works with energy storage.

Paper	Energy storage	Risk considered	Options	Method	Findings
This work	Wind-TP (GIES)	Generator capital cost	Option to prototype	Monte Carlo	Presents a novel real option to prototype algorithm to increase the project value of radical innovation energy systems by minimising the investment risk via prototyping. The market size (number of identical systems to build) is a key parameter.
Chen et al. [74]	Not specified	Electricity demand	Option to invest	Real option game model (combines evolutionary game theory and real options)	Price subsidy for energy storage has a greater effect than the initial cost subsidy for microgrid development. Although electricity price subsidy for energy storage is important, the initial cost subsidy also ensures microgrid investment value and minimise the initial cost of energy storage.
Zeng et al. [75]	Not specified				Production tax credit mechanism, feed-in tariff mechanism and initial cost subsidy for energy storage can alleviate microgrid development. The feed-in tariff has a larger effect than the production tax credit for energy storage.
Ma et al. [76]	Battery	Electricity demand, diesel fuel price, cost of photovoltaic and battery	Compound option (option to defer and option to expand)	Least square Monte Carlo	Running the compound options at the optimal timing enhances the investment value.
Locatelli et al. [13]	Pumped hydro storage and compressed air energy storage	Revenues from price arbitrage, STOR average utilisation payments, STOR average availability hours, capital costs, and natural gas price	Option to build, option to wait to build, and option to wait to invest	Monte Carlo	ROA improves the economic performance of energy storage. However, energy storage needs incentives to be economically viable.
Muche et al. [77]	Pumped hydro storage	Intra-day hour prices	Option to switch (operation)	Proposed a valuation model to value a future price-based unit commitment planning	As the static NPV cannot examine the scope of actions, it can suggest wrong investment decisions.
Reuter et al. [78]	Pumped hydro storage	Electricity price, new generation capacity, wind intermittency, policy investment subsidy	Option to switch (operation) and option to wait	Monte Carlo with dynamic programming	The system is unprofitable without substantial public support. Investments should be made on research and development on the system, rather than supporting investments with incentives.
Kroniger and Madlener [79]	Hydrogen storage	Wind speed, spot market electricity prices, and call of minute reserve capacity	Option to switch the operation mode	Monte Carlo and Black and Scholes	The ROA recommends investment in a storage device without re-electrification unit beyond an expected project value (approximately two times the investment cost of the storage device).

Bakke et al. [80]	Lithium-ion battery	Spot price and balancing price	Exotic option (Bermundan call option)	Dynamic programming	When energy storage participates only in the spot market, the revenues are not sufficient to overcome the initial investment cost. The RO value is higher than the static NPV suggesting there is the value of flexible investment timing (when both investment cost and revenues are uncertain).
Xiu and Li [81]	Lithium-ion storage, redox flow, and sodium sulphur batteries	Asset value	Option to build	Binary tree options pricing model	Investment in Li-ion battery is better than the vanadium redox flow battery and sodium sulphur battery.
Kitapbayev et al. [82]	Thermal storage	gas price, electricity price	Option to switch (operation)	Monte Carlo and dynamic programming	Thermal storage can be an important system to provide flexibility in district energy systems.
Matthias et al. [83]	Compressed air energy storage, carbazole storage, and hydrogen storage	Investment cost, hydrogen price, hydrogen storage cost	Option to build and option to abandon	Monte Carlo and Black and Scholes	For new systems, ROA can help to further analyse the results gained by a basic NPV calculation and to calculate the value represented by managerial flexibilities.
Martínez-Ceseña and Mutale [84]	Pumped hydro storage	Discount rate, electricity price, average water flows	Option to wait, option to switch, and option to contract	Tao Wang's Methodology (A ROA model based on a two-stage integrated process with stochastic mixed-integer programming) and proposed ROA method with Monte Carlo simulation	The advanced RO methodology can give higher expected profits for the project.
Hedman and Sheblé [85]	Pumped hydro storage	Wind turbine output power	Option to build	Monte Carlo simulation with Black and Scholes	Options purchasing and building the pumped hydro storage for the wind farm are both financially competitive to hedge the wind energy risk.
Detert and Kotani [86]	Not declared	Coal price	Option to switch	Monte Carlo with dynamic programming	There is a potential for huge welfare losses in the value of coal-based system operations, except the government inflates electricity prices or switch to renewable generation.
Chen et al. [74]	Not declared	Power demand	Option to invest (build)	Real option (binomial) evolutionary game model	The energy storage electricity price and capital cost subsidies are crucial for the investment value of microgrids.
Coronel et al. [87]	Redox flow battery	Electricity market	Suggested to use ROA	N/A	Based on DCF, at present, the capital cost for flow battery should decrease around 75% to be considered profitable.
Hammann et al. [88]	Compressed air energy storage	Demand rate for minute reserve, electricity and natural gas spot prices	Option to defer	Binomial lattice model	Diabatic compressed air energy storage used for load-levelling is determined to be the most economical option.
Ceseña et al. [89]	Thermal storage	Electricity and heat demand, electricity and gas prices	Option to wait	Stochastic programming model	ROA minimises both expected cost and risk and enhances the business case of flexible distributed multi-energy generation systems.
Risthaus and Madlener [90]	Integrated pumped-heat-electricity storage	Fuel price, solar power	Option to invest (build)	Black and Scholes with stochastic dynamic programming	NPV and real options analysis yield the same result due to the high cost of heat pumps.

Kienzle and Andersson [91]	Not declared	Electricity and heat price	Option to build	Monte Carlo	ROA can properly evaluate the value of distributed generation units with storage devices in changing prices.

Appendix B: Data and materials

Table B.1
Project time, power rating, and efficiency parameters of Wind-TP (technical specification) in DCF model (adapted from [1]).

Category	Input	Min.	Most likely	Max.
Project time	Construction time [yr]	2	3	4
	System life (excluding construction) [yr]	22	25	27
Power rating	Power rating for recovering energy from storage ($P_{\eta_{B4}}$) [MW]	$P_{Har}.\eta_{B4}$		
	Power rating for putting energy into storage ($P_{\eta_{B3}}$) [MW]	$P_{Har}.\eta_{B3}$		
	Power rating for electricity conversion ($P_{\eta_{B2}}$) [MW]	$P_{Har}.\eta_{B2}$		
	Primary harvester power rating (P_{Har}) [MW]	100		
	Energy storage energy capacity ($E_{energystorage}$) [MWh]	100		
	Energy storage power capacity ($P_{energystorage}$) [MW]	50		
	Energy storage energy output at year 1 from wind energy ($E_{energystorage-Har}$) [MWh/yr]	$E_{Har}.\eta_X.\beta_{SO}$		
	Total energy storage energy output at year 1 (wind + wholesale) ($E_{energystorage-Output}$) [MWh/yr]	$E_{STOR-Util} + E_{Sell-Wholesale} + E_{Grid} + E_{FastReserve-Util}$		
	Primary source energy output (E_{Har}) [MWh/yr]	$P_{Har} * CF * 365 * 24$		
	Capacity factor (CF) [%]	30		
	Power rating committed to STOR (P_{STOR}) [MW]	20		
Efficiency parameters	Storage (round-trip) efficiency (η_S) [%]	84.1	88.5	89
	Transmission efficiency (η_T) [%]	82.2	86.5	87
	Throughput efficiency (η_X) [%]	$\frac{\eta_T.\eta_S}{\eta_S+(1-\eta_S).\beta_{SO}}$		

Table B.2
Power ratios and revenue of Wind-TP (technical specification) in the DCF model (adapted from [1]).

Category	Input	Min.	Most likely	Max.
Power ratios	Fraction of electrical energy output from generator passed through energy storage (β_{SO}) [%]		17	
	Fraction of primary electrical energy input that will pass through energy storage (β_{SI}) [%]		$\frac{\beta_{SO}}{\eta_S + (\beta_{SO}.(1-\eta_S))}$	
	Power ratio for recovering energy from storage (η_{B4})		1	
	Power ratio for putting energy into storage (η_{B3})		1	
	Power ratio for electricity generation (η_{B2})		*CF*	
Revenue	Total hours availability commitment to STOR ($H_{STOR-Avail}$) [Hr/yr]		3867	
	STOR: average utilisation hours ($H_{STOR-Util}$) [Hr/yr]		39.42	
	STOR: annual energy utilisation ($E_{STOR-Util}$) [MWh/yr]		$H_{STOR-Util}.P_{STOR}$	
	Energy storage energy for wholesale market ($E_{Sell-Wholesale}$) [MWh/yr]		$\eta_S.\left(E_{energystorage-Har} + E_{Buy-Wholesale}\right) - E_{STOR-Util} - E_{FastReserve-Util}$	
	Generator to grid energy (E_{Grid}) [MWh/yr]		$(E_{Har} - E_{energystorage-Har}).\eta_T$	
	Cheap electricity purchase from wholesale ($E_{Buy-Wholesale}$) [MWh/yr]		$\frac{E_{energystorage} * 365 - E_{energystorage-Har}}{\eta_S}$	
	Fast Reserve: total hours availability commitment ($H_{FastReserve-Avail}$) [Hr/yr]	448	2957.5	5040
	Fast Reserve: maximum energy utilisation ($E_{FastReserve-Util}$) [MWh/yr]	0	422.5	1200

Table B.3

Economic and financing specifications of Wind-TP in the DCF model (adapted from [1]).

Category	Input	Min.	Most likely	Max.
Economics	Specific fixed O&M power cost for generator ($C_{\mathrm{O\&M-Gen}}$) [k£/MW-yr] [a]	22.4	45	89.6
	Specific fixed O&M power cost for energy storage ($C_{\mathrm{O\&M-energystorage}}$) [£/MW-yr]	$1.43 * 10^{-6}$	$2.2 * 10^{-6}$	$4.44 * 10^{-6}$
	Specific generator overnight cost (C_{Har}) [£/MW]	640	1280	2560
	Specific Balance of System for generator cost ($C_{\mathrm{BOP-Har}}$) [k£/MW] [b]	249	384	633
	Specific Balance of System for energy storage cost ($C_{\mathrm{BOP-energystorage}}$) [k£/MWh] [c]	0.83	2.80	4.77
	Specific energy storage overnight cost ($C_{\mathrm{energystorage}}$) [k£/MWh]	5.5	18.65	31.8
	Overnight cost ($C_{\mathrm{Overnight}}$) [k£]	$E_{\mathrm{energystorage}}.(C_{\mathrm{BOP-energystorage}} + C_{\mathrm{energystorage}}) + P_{\mathrm{Har}}.C_{\mathrm{Har}} + (\max(P_{\eta \mathrm{B3}}, P_{\eta \mathrm{B4}}) + P_{\eta \mathrm{B2}}).C_{\mathrm{BOP-Har}}$		
		181000		
	Annual inflation rate for cash (O&M and revenue) from 1998 to 2018 [%]	2.8		
Financing	Cost of debt (K_{D}) [%]	4	5	6
	Cost of equity (K_{E}) [%]	5	6	8
	Weighted average capital cost [%]	$K_{\mathrm{E}}.\theta_{\mathrm{CAPEX}} + K_{\mathrm{D}}.(1 - \theta_{\mathrm{CAPEX}}).(1 - \theta_{\mathrm{Tax}})$		
	Escalation factor for construction costs [%]	0		
	Depreciation factor for capital cost [%]	5		
	Equity share on CAPEX (θ_{CAPEX}) [%]	30		
	Effective tax rate (θ_{Tax}) [%]	11		
	Interest earnings nominal rate [%]	0.7		

[a] based on 3.5% of the specific generator overnight cost for GIES [1]; [b] based on 30% of the specific generator overnight cost as described in [1]; [c] based on 15% of the specific energy storage overnight cost for GIES as described in [1].

Table B.4
Economic specifications for revenue sources in the DCF model (adapted from [1]).

Service	Input	Min.	Most likely	Max.
Wholesale market	Average daily expensive price [£/MWh]	62.00	71.77	83.15
	Average daily inexpensive price [£/MWh]	20.00	35.73	40.91
STOR	Average availability hours price [£/MW/hr]	4.25		
	Average utilisation hours price [£/MWh]	150.57		
Fast Reserve	Availability hours price [£/hr]	160.00	277.75	504.00
	Utilization hours price [£/MWh]	84.00	97.875	106.00