Department of Mechanical and Aerospace Engineering

An Early-Stage Technology Assessment of Suspended Mass Gravitational Energy Storage

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Signed: Justin Swan   Date: 23/08/2019

Abstract

The aim of this project was to evaluate the viability of utilising a suspended-mass for energy storage. To achieve this, a technology assessment procedure was developed for energy storage systems in the early stage of research and development. Specifically, the process was intended to screen new technologies prior to them receiving significant funding for proof of concept studies. The assessment procedure was then applied to the proposed method of raising and lowering a suspended mass to store and release energy. The assessment determined if the technology is likely to be commercially viable, and thus, whether it should receive funding.

To assess the suspended-mass gravitational energy storage system, a mathematical model of the physical system was created in MATLAB software. Using this model, a sensitivity analysis was carried out for various design parameters. This gave insight into how the performance of the system was affected by the aspects of the design.

Following the sensitivity analysis, the model was configured to meet a number of example applications for energy storage. The scenarios were chosen to cover a wide array of system configurations. This was done to identify applications for which the system would be suited. The modelled systems specifications were then analysed. In particular, the physical size and apparatus requirements were considered to determine applications for which the system was better suited.

Finally, an application suited to the characteristics of suspended-mass gravitational energy storage, was used to directly compare the technology to a lithium ion battery system. The comparison considered the physical aspects as well as the estimated cost of the systems.

From the assessment performed, it was determined that suspended-mass gravitational energy storage is unlikely to be viable. The systems would have to be exceptionally large per quantity of energy stored relative to other technologies. The size of the mass and the height through which it must travel would require disused mineshafts to be used. This would constrain the number of suitable locations for the systems to be implemented. Furthermore, due to its weight, the infrastructure and equipment required to suspend the mass would be excessive compared to other technologies. Additionally, these factors would likely make the cost of the technology uncompetitive against alternative options. As a consequence of these drawbacks, it is not recommended that significant funding be awarded to developing suspended-mass gravitational energy storage.

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List of Abbreviations

SMGES – Suspended mass gravitational energy storage

R&D – Research and development

T&D – Transmission and distribution

TRL – Technology readiness levels

SI – Institute of Standard Units

AC – Alternating current

MBF – Minimum breaking force

CAES – Compressed air energy storage

BOP – Balance of plant

1. Introduction

1.1 Background to the project

The United Kingdom (UK) government committed to the Climate Change Act 2008, which entails an 80% reduction in the nation's greenhouse gas emissions by 2050, relative to 1990 levels (Department for Business, Energy & Industrial Strategy, 2019). To meet these goals, the UK aims to increase the electricity generation from low carbon energy sources to 85% by 2032 (Committee on Climate Change, 2018). In comparison, the percentage of electricity generation from low carbon sources was 50% in 2017 (Department for Business, Energy & Industrial Strategy, 2018). Whether the UK will be able to reach these targets remains to be seen, however, the capacity of renewables installed will certainly increase.

Currently, the installed renewable capacity in the UK consists of 32% onshore wind, 32% solar, 17% offshore wind, 15% biofuels, and 5% from hydroelectric. With the exception of biofuel (which is contested as being a sustainable energy source) and hydroelectric, renewable energy sources are non-dispatchable. This means their power output cannot be switched on or controlled at will.

The non-dispatchability of renewables leads to issues in demand and supply matching. In times of high generation from renewables, a surplus of energy would occur. However, in order to maintain the grid voltage, renewable plants which could be producing power are switched off. Even at the current capacity of installed renewables, wind turbines are turned off in times of high generation (Constable & Moroney, 2011). This resulted in a wasted 1.7 TWh of energy that could have been generated from wind in 2018 (Renewable Energy Foundation, 2019). Without better management, as the installed capacity of renewables increases so too will the quantity of energy wasted.

Conversely, in times of low generation from renewables and peaks in demand, there is a shortfall in supply. This excess demand must therefore be met by a dispatchable power source which can be switched on at short notice. Currently the UK relies mostly on stand-by gas power plants, known as 'peaking power plants' or 'peakers', to meet fluctuating demands (350 PPM, 2019). These are plants which are switched off most of the time but are ready to switch on at short notice to reap a high wholesale energy price (350 PPM, 2019). With the increase in renewables on the grid, the capacity of balancing reserves will be required to increase significantly due to the increased variability in supply (KPMG LLP, 2016).

Energy storage offers one means by which to help balance the demand and supply. Energy storage aids the implementation of renewables as it can store surplus production that would be otherwise wasted and release it when there is shortfall. This aids in integrating renewables onto the grid (Eyer & Corey, 2010). This helps to reduce the need for conventional generation technologies (Renewable Energy Association, 2015). Hence, as the popularity of renewables has increased, so has the implementation of storage. As of June 2018, 3.3 GW of energy storage capacity were operational in the UK, with planning permission granted for a further 5.4 GW (Norris, 2018). Furthermore, IRENA estimates that 9 TWh of grid energy storage (excluding hydropower) should be available globally by 2050 (International Rnewable Energy Agency (IRENA), 2019).

Historically, the most popular form of electrical energy storage for grid applications was pumped hydro. According to the US Department of Energy, as of June 2019, pumped hydro made up 99% of the grid energy storage installed in the UK (US Department of Energy , 2019). Pumped hydro is attractive as it usually does not require significant infrastructure installation over traditional hydro plants. Pumped hydro storage offers round trip efficiencies between 70–80%, and has the ability to store vast quantities of energy (Wilson, et al., 2010). This makes pumped hydro ideally suited to storing large quantities of energy for long periods of time.

Recently, lithium-ion batteries have also gained popularity for grid energy storage. Of the 5.4 GW of energy storage with planning permission in the UK, 4.8 GW is battery storage (Norris, 2018). Lithium-ion batteries offer exceptionally high round trip efficiencies of up to 95%, rapid response times, and high energy density (Gerssen-Gondelach & Faaij, 2012). These characteristics make lithium ion fast response applications.

As the market for energy storage has increased, many storage technologies have been developed and are often presented as ground-breaking for the industry. However, the development of these technologies requires funding from government and investment bodies. Currently, the EPSRC has a £28 million grant portfolio for energy storage research (Engineering and Physical Sciences Research Council, 2019).Therefore, significant public funds could be invested in technologies which may never be viable or worthwhile. In many cases, the proposed systems can have fundamental limitations or issues in their design. As a result, there is incentive to better evaluate the performance potential of new energy storage technologies before they attract significant investment of time and resources.

One such new energy storage technology that has been proposed is a suspended-mass gravitational energy storage device (SMGES). The underlying components and ideas of the technology are not new, however, using them in the configuration suggested has only recently been proposed as a viable product (Gravitricity, 2019). In 2018, Gravitricity was awarded a £650,000 grant from Innovate UK for the further development of its concept (Cameron, 2018). At the time of writing this paper, a physical concept was yet to be built; with the proceeds from the grant aimed at being used for the development of the first prototype (Cameron, 2018).

1.2 Aim

The purpose of this project was to determine the feasibility of suspended-mass gravitational energy storage, using an early-stage technology assessment procedure. It was aimed to determine whether the fundamental characteristics of SMGES are likely to make the technology commercially viable. Hence, it was intended to suggest whether further investment should be given to the research and development of SMGES technology.

By performing this project, it was aimed to demonstrate the value of early-stage technology assessments for energy storage technologies. The process by which this project was carried out, was also intended to present a framework by which future early-stage technology assessments could be performed.

1.3 Objectives

The specific objectives to be carried out in order to achieve the aims of the project were:

- Develop a procedure to effectively assess the viability of an energy storage system.
- Assess the potential of SMGES with regards to performance characteristics, practicality, and usage scenarios.
- Compare the performance and characteristics of SMGES to energy storage technologies that it would compete against.

1.4 Scope

The case study was centred on the SMGES system proposed by Gravitricity. However, the evaluation process considered uses outside of those previously proposed by Gravitricity. This included grid and non-grid applications. A sensitivity analysis was also performed on the system parameters. For the sensitivity analysis, the parameters were varied within and beyond the levels expected with future development.

The mathematical models developed to analyse SMGES were based on the physics and engineering by which the technology is defined. Although estimated costs of the system were analysed, a full cost model of the system was not developed in this project. This was deemed beyond the scope of this project.

The process developed is aimed at technology in the basic research phase. After this stage, the costs associated with research and development tend to increase. Therefore, it was intended for the assessment framework to be applied prior to the proof of concept stage of development.

1.5 Structure of the report

A review of literature relating to new technology is presented in section 2. This includes reviews of the technology development process, the stages of technology development, and early stage assessment procedures. This is followed by a review of literature relating to energy storage in section 3.

Following the literature reviews is the Methods section, which explains the assessment procedure followed in this project. It also presents the application of the preliminary steps to the SMGES system. A description of how the mathematical models of the SMGES system were developed and verified is then shown in section 5. Following this, the procedure and results of the sensitivity analysis performed are shown in section 6.

The procedure, results, and analysis of configuring the mathematical model to meet a number of example applications for SMGES technology, are shown in section 7. This includes a comparison of the physical aspects and the costs of one SMGES system configuration with those of a comparable Lithium ion battery system.

Following this is a discussion of the procedure, results, and analysis carried out in this project. The conclusions drawn from this project are then presented in section 9, followed by recommendations and future work that could be carried out.

2. Literature Review – New Technology Development

According to Branscomb and Auersweld (2002), 'invention' refers to a commercially promising product or service idea based on new science or technology. 'Innovation' refers to a product or service idea which successfully makes it to market (Branscomb & Auersweld, 2002). Technology based innovation can be differentiated from incremental product enhancement by the extent of the novelty of the technology, hence the technological risk is greater than the market risk (Branscomb & Auersweld, 2002). As a result, technological innovations often come from companies focused on the development of a new technology rather than companies focused on the market (Branscomb & Auersweld, 2002).

The earliest stage of new product innovation has been described as the 'fuzzy front-end' (Kim & Wilemon, 2002). This phase is characterised by the lack of formality of the idea, low investment, and lack of consequence if the project is abandoned (Kim & Wilemon, 2002). Beyond this phase, formal product development begins which brings about greater repercussions in the event of product failure due to greater investment (Kim & Wilemon, 2002). Therefore, there is a strong incentive to evaluate the viability of a new technology prior to it entering the formal development phase. A schematic of the 'fuzzy front-end' idea is shown in Figure 1.

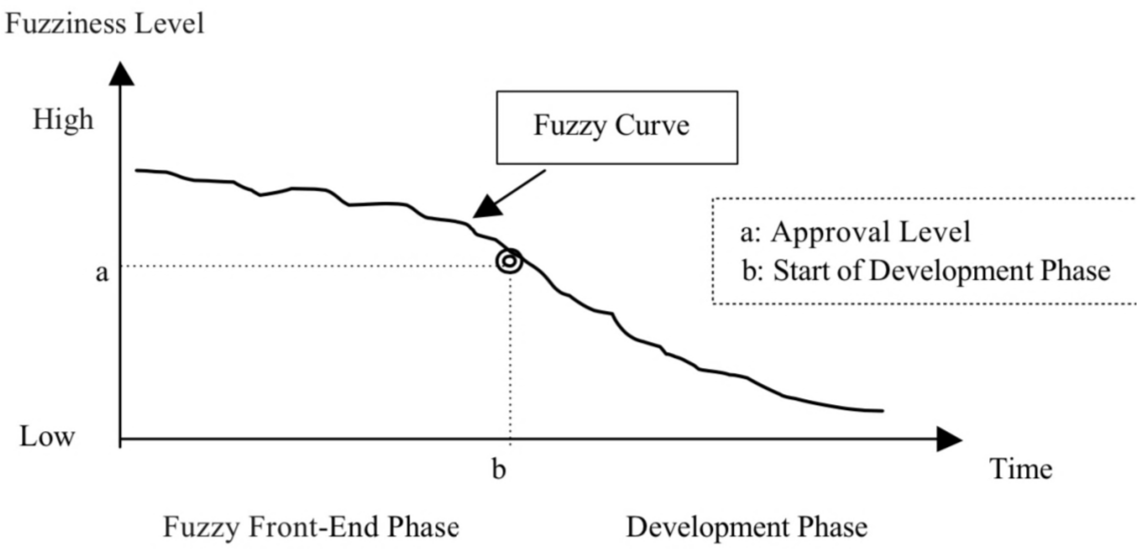

Figure 1: A visual representation of the 'fuzzy front-end' of new technology development (Kim & Wilemon, 2002).

As shown by Figure 1, the fuzziness level reduces faster once the innovation reaches the development phase as a result of greater investment in the project.

2.1 Technology development process

There are a number of different descriptions of the process through which new innovations are developed. Berkhout et al. describe four generations of research and development (R&D) management. The first generation considers scientific discoveries as the initial stage of the innovation process (Berkhout, et al., 2007). Hence, the 1st generation process is said to be of a technology push nature (Berkhout, et al., 2007). The 1st generation innovation process is shown in Figure 2.

Figure 2: Flow diagram of the 1st generation R&D model by Berkhout et al (2007).

The 2nd R&D management generation is a market-pull driven process (Berkhout, et al., 2007). In this generation, innovation is driven by market need. Therefore, the R&D is focused on market-based aspects (Berkhout, et al., 2007). The innovation process for the 2nd generation of R&D management is shown in Figure 3.

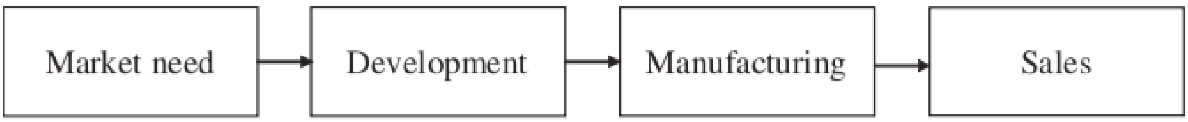

Figure 3: Flow diagram of the 2nd generation R&D model by Berkhout et al (2007).

As shown in Figure 2 and Figure 3, both the 1st and 2nd generation models of R&D management are linear processes. These models consider the new technology generation process to be carried out by individual organisations without external input during the process. Hence, early linear processes were viewed as autonomous innovation (Smits & Kuhlmann, 2004).

The 3rd generation combined the 1st and 2nd generation approaches by considering both market-pull and technology-push. However, the 3rd generation process is still product or process focussed which could hinder its effectiveness (Berkhout, et al., 2007). A representation of the 3rd generation process is shown in Figure 4.

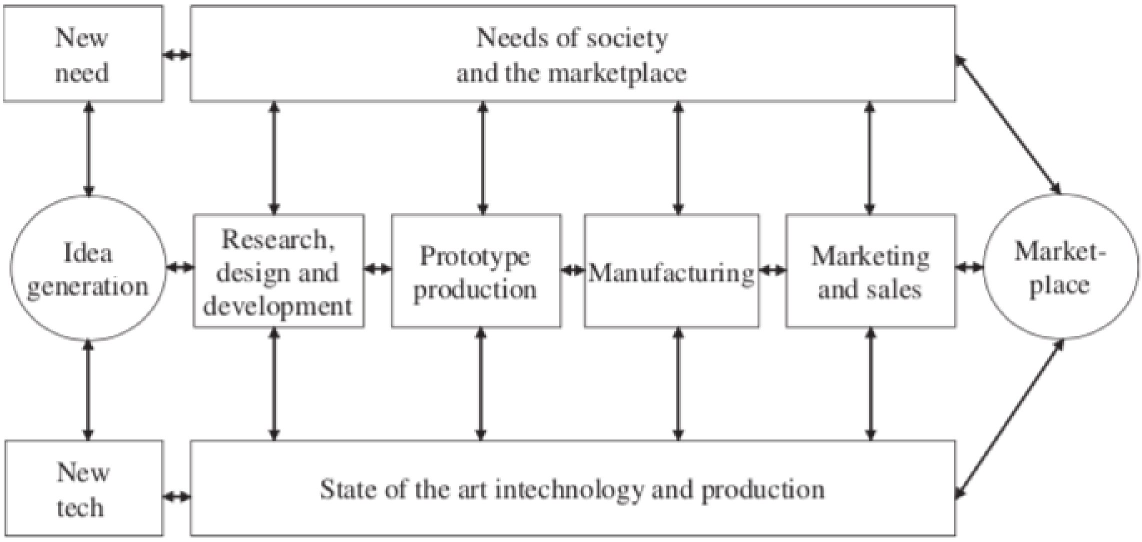

Figure 4: Flow diagram of the 3rd Generation R&D management process by Berkhout et al 2007.

In the 4th generation of R&D management, innovation projects are carried out in large networks (Berkhout, et al., 2007). The innovation process is expanded, integrating customers and suppliers directly in the process (Berkhout, et al., 2007). This leads to faster development of products due to parallel development. Zirger and Maidique (2005) proposed a similar product development process which is also market driven – this is shown in Figure 5.

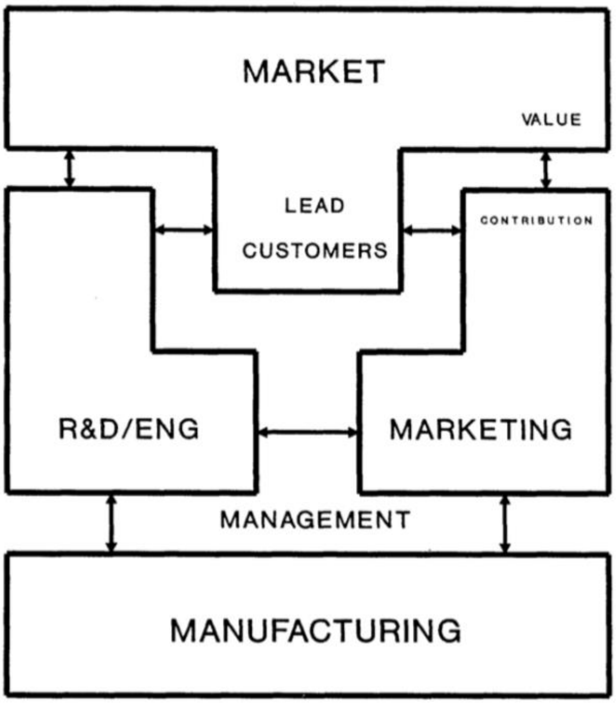

Figure 5: A schematic diagram representing the R&D process model described by Zirger and Maidique (Zirger & Maidique, 1990).

The 4th generation R&D model presented by Berkhout et Al, and the model presented by Zirger and Maidique, represent open innovation processes described by Chesbrough (2003). These are in contrast to closed innovation processes, whereby the entire innovation process is contained within the institution. In open innovation processes, the exchange of ideas both internally and externally are encouraged in order to advance the technology (Chesbrough, 2003). In open processes, ideas can still be generated and developed by the company, however, at some stage during the research and development process external bodies are consulted or involved (Chesbrough, 2003). As a result, open innovation utilises university research more than closed innovation processes. Chesbrough (2003) suggests that open research is commonplace in modern research and development. This is due to a number of factors including the rate at which new technology must be brought to market in order to be profitable (Chesbrough, 2003).

Currently, the research and development of energy storage technology often consists of open innovation processes, utilising the 4th generation process suggested by Berkhout et al., or that suggested by Zirger and Maidique. Universities and spin-off companies are frequently commissioned to carry out research on behalf of companies wishing to commercialise energy storage technologies. This is likely due to most general energy storage technologies may be more widely known. However, for some new energy storage technologies, the innovation process may be kept closed.

2.2 Stages of technological innovation

Venture economics defines the stages of new project development by three categories of financing (Branscomb & Auersweld, 2002):

1. Seed financing – this is a small investment of capital for the inventor or entrepreneur to prove a concept.
2. Start-up financing – this is capital supplied to companies for project development and initial marketing. This is usually provided to new companies who have not yet sold their product/products to the market place, but have a management structure and business plan in place.
3. First-stage financing – this provides funds to companies who have spent their initial capital and require further funding to begin manufacturing and sales.

However, it has been pointed out that the stage of funding does not necessarily accurately correspond to the stage of development of the product. Recently, significant funding has been supplied to companies with very little technology under development. (Branscomb & Auersweld, 2002)

An alternative method of defining the stage of technological development is by distinguishing between 'proof of principle' and 'reduction to practice' (Branscomb & Auersweld, 2002). 'Proof of principle' means that the ability of the technology to meet a defined challenge has been demonstrated in a research setting (Branscomb & Auersweld, 2002). A model of the product should show in a laboratory setting, that it is capable of meeting the requirements of an identified market opportunity if it were to be produced at a practical cost with suitable reliability. It presents the successful application of scientific and engineering principles to solve the given problem.

'Reduction to practice' implies that a working model of the technology has been developed to defined specifications by processes which are similar to those which would be used in scaled-up production (Branscomb & Auersweld, 2002). This essentially means, to prove that the product can be produced for a specified cost and time schedule.

The stages of R&D can also be categorised into basic research, applied research, and development. This uses the classical linear model of R&D, however, in reality the distinction between these stages can be blurred (Branscomb & Auersweld, 2002). The way in which the R&D of new technology is funded according to Branscomb and Auersweld (2002) is shown in Figure 6.

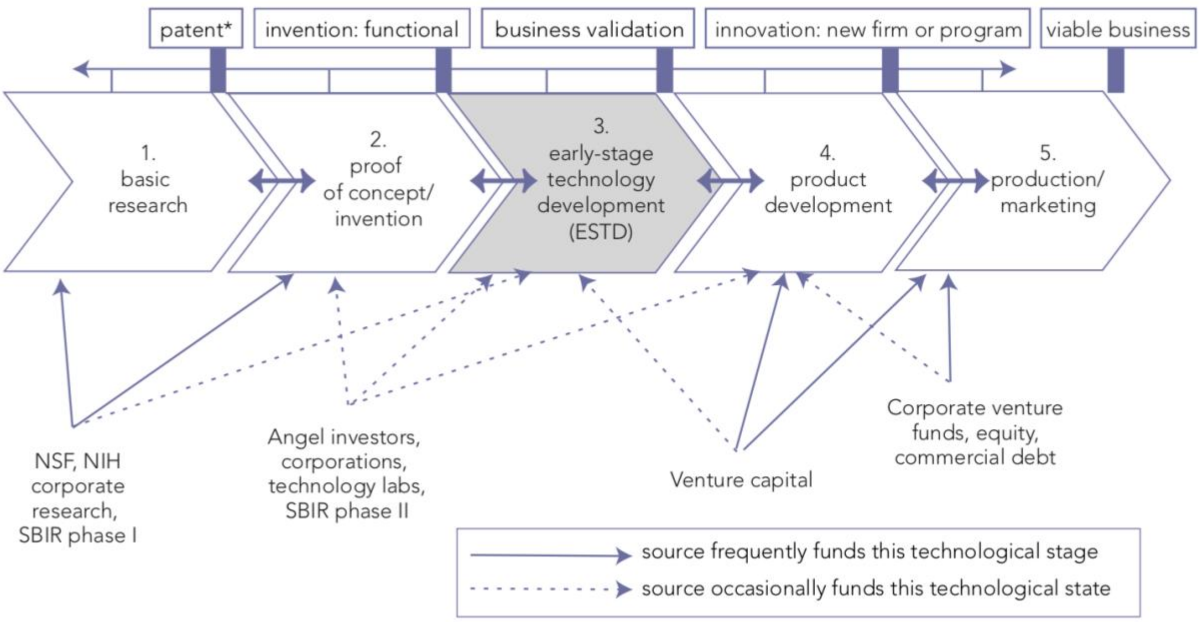

Figure 6: Schematic diagram of the stages of research and development (Branscomb & Auersweld, 2002).

A schematic showing how the risk of failure, and performance and maturity of technology varies with the stages of R&D, is shown in Figure 7.

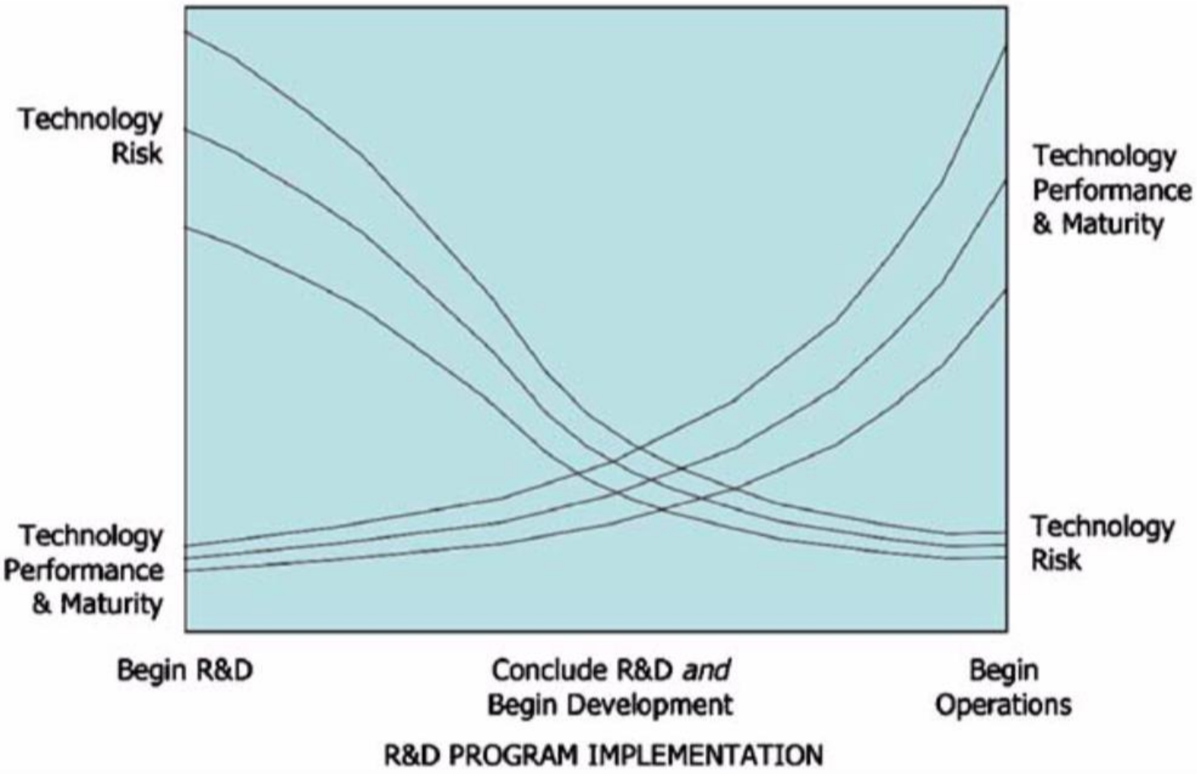

Figure 7: Diagram showing the progression of technology performance and risk with R&D (Mankins, 2009).

Figure 7 shows that as the performance and maturity of the technology increases, the risk of failure of the technology decreases. This occurs because the number of uncertainties relating to the technology are reduced as research is conducted (Mankins, 2009).

The National Aeronautics and Space Administration (NASA) developed 'technology readiness levels' (TRLs) to assist with the risk assessment process of developing new technology (Smith, 2005). TRLs provide a means to qualitatively rank the maturity of a technology in development. The nine TRL levels are shown in Table 1. Since their inception, TRLs have been widely used in other industries to measure the maturity of technology under research and development (Mankins, 2009).

Table 1: Summary of Technology Readiness Levels (Mankins, 1995).

TRL 1	Basic principles observed and reported	Transition from scientific research to applied research. Essential characteristics and behaviours of systems and architectures. Descriptive tools are mathematical formulations or algorithms.
TRL 2	Technology concept and/or application formulated	Applied research. Theory and scientific principles are focused on specific application area to define the concept. Characteristics of the application are described. Analytical tools are developed for simulation or analysis of the application.
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept	Proof of concept validation. Active Research and Development (R&D) is initiated with analytical and laboratory studies. Demonstration of technical feasibility using breadboard or brassboard implementations that are exercised with representative data.
TRL 4	Component/subsystem validation in laboratory environment	Standalone prototyping implementation and test. Integration of technology elements. Experiments with full-scale problems or data sets.
TRL 5	System/subsystem/component validation in relevant environment	Thorough testing of prototyping in representative environment. Basic technology elements integrated with reasonably realistic supporting elements. Prototyping implementations conform to target environment and interfaces.
TRL 6	System/subsystem model or prototyping demonstration in a relevant end-to-end environment	Prototyping implementations on full-scale realistic problems. Partially integrated with existing systems. Limited documentation available. Engineering feasibility fully demonstrated in actual system application.
TRL 7	System prototyping demonstration in an operational environment	System prototyping demonstration in operational environment. System is at or near scale of the operational system, with most functions available for demonstration and test. Well integrated with collateral and ancillary systems. Limited documentation available.
TRL 8	Actual system completed and "mission qualified" through test and demonstration in an operational environment	End of system development. Fully integrated with operational hardware and software systems. Most user documentation, training documentation, and maintenance documentation completed. All functionality tested in simulated and operational scenarios. Verification and Validation (V&V) completed.
TRL 9	Actual system "mission proven" through successful mission operations	Fully integrated with operational hardware/software systems. Actual system has been thoroughly demonstrated and tested in its operational environment. All documentation completed. Successful operational experience. Sustaining engineering support in place.

The costs associated with TRL 1 can vary widely, from extremely low to very high. These costs are unique to the situation and discipline (Mankins, 2009). In some cases, such as computational algorithms, the initial discovery costs may be very small. In other cases, such as aerodynamics, which requires significant infrastructure and computing power, the costs of basic research may be exceptionally high.

The costs associated with TRL 2 are typically low. This is because applications for the new technology are proposed, but no proof or detailed analysis is required to support the suggestion (Mankins, 2009). However, as with TRL 1, the costs associated with TRL 2 are unique to the field and conditions of the technology.

From TRL 3 onwards, the costs associated with successive stages of maturity increases. The costs of TRL 3 are often low to moderate followed by moderate to high for TRL 4 (Mankins, 2009). The increase in costs begins to occur at TRL 3 as this is the stage where analytical and experimental proof of concept begins. TRL 3 is often the stage at which formal funding and sponsorship begins to occur. From TRL 3 to TRL 8, the costs associated with each stage increase significantly, often by multiples of the previous stage (Mankins, 2009).

2.3 Assessment techniques for early-stage technology

Technology assessment was conceived as an analytical activity to provide decision makers with objective analysis of a proposed technology's effectiveness (Van Eijndhoven, 1997). In addition to the performance potential of a technology, a number of other aspects should also be considered in the early assessment process. These include the market need and market size, the barriers to implementation, possible uptake, as well as early cost-effectiveness estimates (Ijzerman & Steuten, 2011). A study by Cooper found that the most significant factors in determining the success of new products were their uniqueness and superiority (Cooper, 1979). Therefore, the assessment should not focus on the technology in a vacuum; rather it should include external factors which may affect its viability.

In addition to assessing the viability of the technology, an early-stage technology assessment should also provide decision support on the design and management of the technology (Ijzerman & Steuten, 2011). Early technology assessment can be used as a tool to help guide the design of a product in order to best meet the needs of the market

In a pre-feasibility study for wind power generation in Newfoundland, Canada; Blackler and Iqbal used an eight-step philosophy to simulate and assess the proposed system. The process was as follows (Blackler & Iqbal, 2005):

1. Formulate a question
2. Build a schematic
3. Enter load details
4. Enter component details
5. Enter resource details
6. Check inputs/examine optimisation results
7. Refine the system design
8. Add sensitivity variables

The first step in the process was to formulate a question, thereby defining the purpose of the study. This was followed by developing a schematic model of the system which the rest of the simulation process continued to build upon.

Loonen et al. (2014) proposed a similar methodology for simulation-based support in product development. A schematic diagram of the process used is shown in Figure 8.

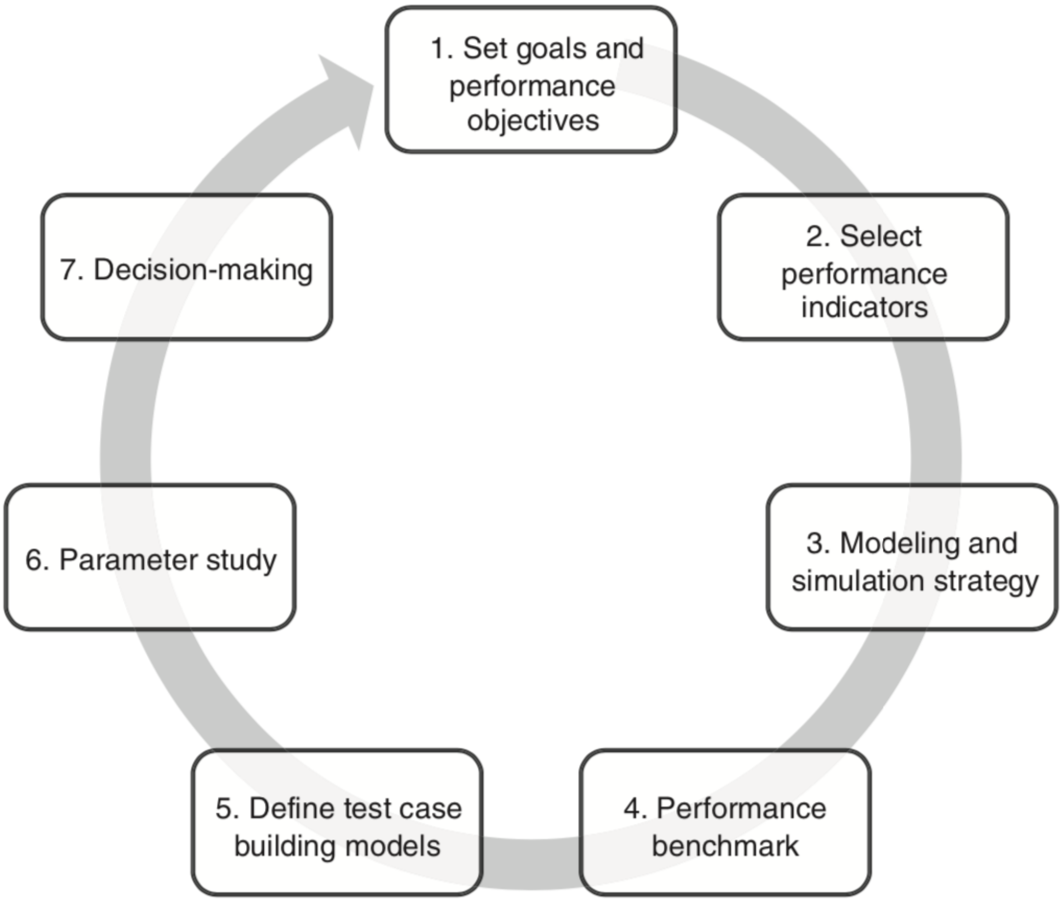

Figure 8: A schematic diagram of the process used by Loonen et al., (2014) in a simulation based technology assessment.

Although the steps of the process were described with regards to the specific field of the study, a generalised description of the steps in their framework is as follows (Loonen, et al., 2014):

1. Set goals and performance objectives: it is important to determine the purpose of the study prior to beginning. Identify and prioritise the multiple performance aspects that contribute to the success or failure of the product. This step should also specify boundary conditions.
2. Select performance indicators: The performance indicators should be identified in order to allow the sufficient evaluation of performance of the innovative technology.
3. Develop a modelling and simulation strategy: The model should reflect all relevant physical principles and address the performance indicators at an appropriate level of detail. A balance should be found between the complexity of the model and accuracy of the outputs.
4. Performance benchmark: This step provides information about the performance of the technology in its current state. The analysis can be carried out by comparing the product to direct competitors or to technologies which fulfil similar roles. This step aims to provide an understanding of the strengths and weaknesses of the product.
5. Define test case building models: A feature of product development is the inherent variability of the potential future applications of the product. Therefore, product design is essential in developing products which can accommodate a wide range of applications. Sensitivity analysis can be used as a tool to define test cases with different attributes. Sensitivity analysis is usually used to identify variables which have the greatest influence on the product performance. In this case, sensitivity analysis is used to define test case models based on ranking of design variables. The test case models represent more extreme cases than the reference model in step 4. The goals of this step are to:
    a. Accentuate differences in performance and ensuring they can be attributed to specific variations in the model's specifications
    b. Identifying the need for one family of products to be customised to different applications.
    c. Targeting niche markets with the highest potential for early implementation.
6. Parameter study: To determine the best performing model variants, or most promising directions for development, a parametric or optimisation study should be carried out. Whereas the previous step considers the variations in the overall model parameters, this

step should focus on variations in the design of components. The parameters of the components can vary beyond specifications which are currently feasible.

7. Decision-making: In this step, the results of the analysis should be compared to the goals and requirements presented in the first step. The most promising specifications and/or routes for development should then be selected.

By comparing the process presented by Blackler and Iqbal to that by Loonen et al., it can be seen that the process used by Loonen et al. included more preliminary steps before developing the model. The process by Loonen et al. formally specifies the goals and objectives of the study and identifies the key performance indicators in the initial stages of the process. This is followed by defining the modelling and analysis strategy of the study prior to developing any models. Performing these preliminary steps prior to developing the system model focuses the analysis process on factors which will determine the feasibility of the technology. This better ensures the assessment process achieves the intended purpose of the study without spending time carrying out unnecessary steps.

3. Literature Review – Energy Storage

3.1 Fundamentals of Energy and the Electricity

Energy and power are terms that are widely used, however, even in engineering circles, these terms are often used incorrectly. Moreover, with respect to energy storage, the terms are often used ambiguously. Therefore, it is essential that the concepts of energy and power are well understood.

To define energy, the concept of 'work' must first be understood. Work is done only when a force moves something (Dobson, et al., 2008). Hence, the formula for work is:

$$\begin{aligned} &Work\ done\ (joules) \\ &\qquad = Force\ (Newtons) \\ &\qquad \times Distance\ moved\ in\ the\ direction\ of\ the\ force (metres) \end{aligned}$$

Energy is defined and measured by the concept of work. Energy is defined as the ability to do work (Dobson, et al., 2008). Hence:

$$Work\ done = Energy\ transferred$$

The International System of Units (SI unit) for work done – and therefore energy – is joules (J). However, in engineering, energy is usually measured in kilowatt hours (kWh), megawatt hours (MWh), or gigawatt hours (GWh). These units are explained after the concept of power is covered; however, it is important to remember that they are units of energy, not power. 'watt hour' units are simply a multiple of joules – having the same base units.

Power is defined as the rate of work being done (Dobson, et al., 2008). Hence, it is the rate at which energy is transferred (Dobson, et al., 2008). Therefore, the basic formula for power is:

$$Power\ (watts) = \frac{Energy\ transferred\ (joules)}{time\ (seconds)}$$

The SI unit for power is watts, which is a work rate of 1 joule per second. Therefore, if work is being done at a rate of 1 watt for 60 seconds, 60 joules of energy will be transferred.

As mentioned previously, in engineering fields, 'watt hour' units are the most commonly used when discussing energy values. A watt hour (Wh) is defined as the amount of work done/energy transferred by something operating at a power of 1 watt for 1 hour. Hence, 1 Wh is equivalent to 3600 J (1 watt × 3600 seconds) and 1 kWh is equivalent to 3600 kJ.

As with energy and power, the term electricity is commonly misused. Often, the word ‘electricity’ is ambiguously used in place of ‘energy’ or ‘power’. Electricity is the term given to the set of phenomena associated with the presence and motion of electric charge. Therefore, electricity is not a quantifiable property and does not have units. The fundamental properties which make up electricity are:

- Electric charge – is the property of matter which causes it to experience a force when placed in an electromagnetic field. The electric charge of a particle or body is measured in coulombs (C) and it can be positive or negative.
- Electric current (I) – is the flow of electric charge and is measured in amperes (A).
- Electric potential (V) – the potential difference between two points is measured in volts (V)
- Resistance (R) – is the resistance to flow of electric charge measured in Ohms (Ω)

In electrical systems, 1 J of energy will be dissipated by a potential difference of 1 V across a resistance of 1 Ω for 1 second. Alternatively, 1 joule of energy will be dissipated by a current of 1 ampere passing through potential difference of 1 volt for 1 second.

The basic equations for electrical systems can be derived as follows:

$$Current = \frac{Voltage}{Resistance}$$

$$Energy = V.I.t = \frac{V^2.t}{R} = I^2.R.t$$

$$Power = \frac{Energy}{Time} = V.I = I^2R = \frac{V^2}{R}$$

3.2 The ‘Electrical Grid’

When discussing the electricity network, the term ‘electricity grid’ or more simply ‘the grid’ is commonly used. To clarify, this refers to the system which transmits and distributes electrical energy from various suppliers to end consumers (Eye & Corey, 2010). The operation of the grid can be categorised into two main sections: transmission and distribution (Eye & Corey, 2010).

Transmission involves the transfer of electrical energy from supply sources to other distribution systems. This usually involves transmission of large quantities of energy at high voltages – 400 kV or 275 kV in the UK (The Parlimentary Office of Science and Technology, 2001).

Distribution is the function which delivers electrical energy to end consumers (Eye & Corey, 2010). This takes place at voltages between 230 V and 132 kV in the UK (The Parlimentary Office of Science and Technology, 2001). The key components in electricity networks are transformers, switches and the cables. Transformers are used to step-up or step-down the voltage at which the electrical energy is being transmitted; for example, from transmission system to a distribution system.

In an alternating current (AC) power system, the supply and demand must be kept in balance. If there is a shortage or supply relative to demand, the alternating frequency of the current will drop. This can result in disconnection of some loads or a total failure of the system whereby the generating plant disconnects. On the other extreme, if the supply is greater than the demand, the frequency and the voltage of the system will rise. If the excess generation is not absorbed or supply shut off, damage may occur. (Price, 2015)

3.3 Applications for electrical energy storage on the grid

The use of energy storage devices is often discussed generally in relation to the increased level of non-dispatchable power on the grid. However, there are a number of more specific grid services which energy storage can provide. Figure 9 summarises the typical characteristics of the common grid applications for energy storage. As can be seen, the applications cover a wide range of power capacities and discharge durations. There are applications requiring less than 1 kW with discharge durations in the order of seconds, while others require a discharge duration of several hours and a rated capacity of up to 500 MW.

		Discharge Duration*		Capacity (Power: kW, MW)		Benefit ($/kW)**		Potential (MW, 10 Years)		Economy ($Million)†	
#	Benefit Type	Low	High	Low	High	Low	High	CA	U.S.	CA	U.S.
1	Electric Energy Time-shift	2	8	1 MW	500 MW	400	700	1,445	18,417	795	10,129
2	Electric Supply Capacity	4	6	1 MW	500 MW	359	710	1,445	18,417	772	9,838
3	Load Following	2	4	1 MW	500 MW	600	1,000	2,889	36,834	2,312	29,467
4	Area Regulation	15 min.	30 min.	1 MW	40 MW	785	2,010	80	1,012	112	1,415
5	Electric Supply Reserve Capacity	1	2	1 MW	500 MW	57	225	636	5,986	90	844
6	Voltage Support	15 min.	1	1 MW	10 MW	400		722	9,209	433	5,525
7	Transmission Support	2 sec.	5 sec.	10 MW	100 MW	192		1,084	13,813	208	2,646
8	Transmission Congestion Relief	3	6	1 MW	100 MW	31	141	2,889	36,834	248	3,168
9.1	T&D Upgrade Deferral 50th percentile††	3	6	250 kW	5 MW	481	687	386	4,986	226	2,912
9.2	T&D Upgrade Deferral 90th percentile††	3	6	250 kW	2 MW	759	1,079	77	997	71	916
10	Substation On-site Power	8	16	1.5 kW	5 kW	1,800	3,000	20	250	47	600
11	Time-of-use Energy Cost Management	4	6	1 kW	1 MW	1,226		5,038	64,228	6,177	78,743
12	Demand Charge Management	5	11	50 kW	10 MW	582		2,519	32,111	1,466	18,695
13	Electric Service Reliability	5 min.	1	0.2 kW	10 MW	359	978	722	9,209	483	6,154
14	Electric Service Power Quality	10 sec.	1 min.	0.2 kW	10 MW	359	978	722	9,209	483	6,154
15	Renewables Energy Time-shift	3	5	1 kW	500 MW	233	389	2,889	36,834	899	11,455
16	Renewables Capacity Firming	2	4	1 kW	500 MW	709	915	2,889	36,834	2,346	29,909
17.1	Wind Generation Grid Integration, Short Duration	10 sec.	15 min.	0.2 kW	500 MW	500	1,000	181	2,302	135	1,727
17.2	Wind Generation Grid Integration, Long Duration	1	6	0.2 kW	500 MW	100	782	1,445	18,417	637	8,122

*Hours unless indicated otherwise. min. = minutes. sec. = seconds.
**Lifecycle, 10 years, 2.5% escalation, 10.0% discount rate.
†Based on potential (MW, 10 years) times average of low and high benefit ($/kW).
†† Benefit for *one year*. However, storage could be used at more than one location at different times for similar benefits.

Figure 9: Table displaying the typical characteristics for applications of energy storage on the electrical grid (Eye & Corey, 2010).

3.3.1 Energy time-shift

This involves the storage of energy when the cost is low (when supply is plentiful, and demand is low) to be released when the cost (demand) is high. This role typically is considered to require a minimum discharge duration of 2 hours (Eye & Corey, 2010). The upper time frame of discharge required is 5 to 6 hours (Eye & Corey, 2010). For energy time shift applications, the variable operating cost and the round-trip efficiency of the storage are particularly important.

Time-shift storage devices may have synergies for other applications, namely: supply capacity, T&D upgrade referral, congestion relief, service reliability, power quality, and ancillary services (Eye & Corey, 2010).

3.3.2 Supply capacity

This is the availability of dispatchable power capacity. Reserve capacity is typically used for ‘peaking’ services (Eye & Corey, 2010). This is most commonly performed by combined cycle gas turbine plants. This supply may be priced on the wholesale price (per of energy delivered) or by capacity availability pricing, where a fixed rate is paid for a set capacity to be available over a certain time (Eye & Corey, 2010).

3.3.3 Load following

Load following is categorised as supply where the power output may vary as frequently as every minute (Eye & Corey, 2010). The output is changes in response to variations in the load and supply within an area. This is triggered by the changes in frequency and/or timeline loading (Hirst & Kirby, 1999). A schematic showing in the role of load following in balancing the grid is shown in Figure 10.

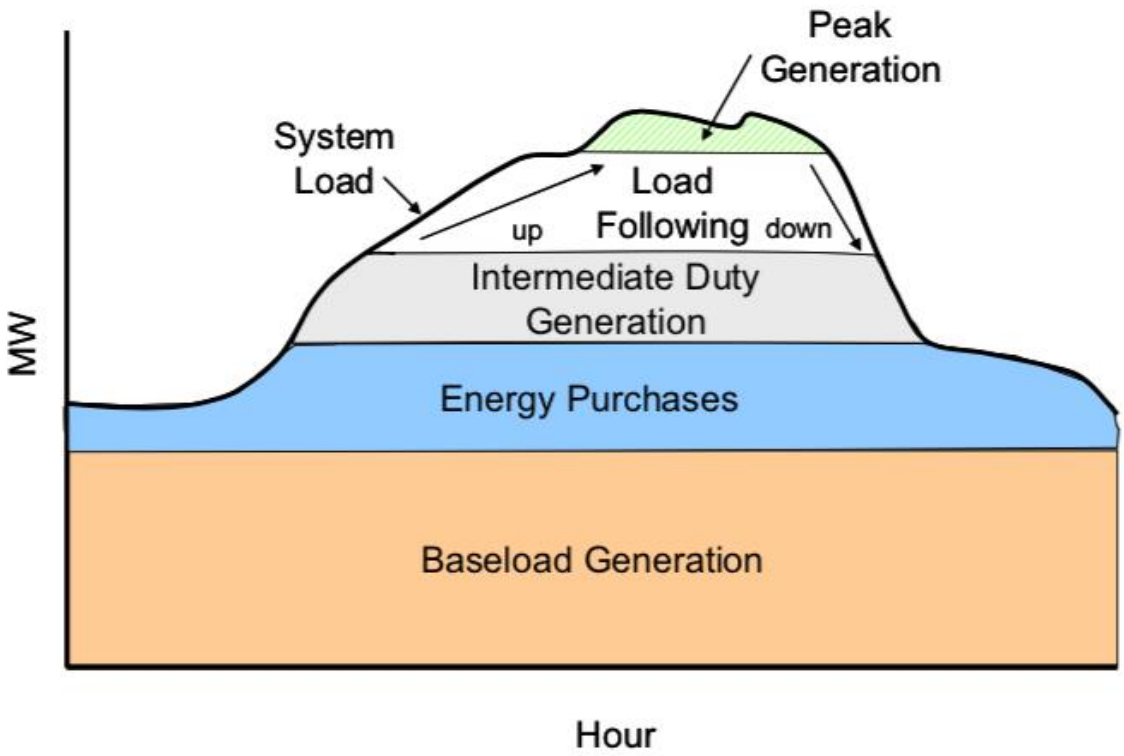

Figure 10: Diagram showing how fluctuating energy demand is typically met by supply (Eye & Corey, 2010).

Typically load following is accomplished by flexible generation plants which raise their outputs as the load increases and reduce their outputs as the load decreases. An issue with this is that the efficiency of combustion plants typically reduces when they are run below their design capacity, hence they release more emissions per unit of energy delivered. Energy storage could provide load following by discharging when the load increases and charging when the load decreases. To be suitable for load following applications, the storage must be reliable and be able to be controlled by an independent system operator (Eye & Corey, 2010). The storage would have to supply up to 2 hours of service per hour of discharge duration (Eye & Corey, 2010).

3.3.4 Area regulation

Hirst and Kirby (2000, pp. 1) describe area regulation as the 'management of actual interchange flows with other control areas to match closely to the scheduled flows'. More simply, regulation is used to reconcile the momentary differences between supply and demand (Eye & Corey, 2010). The role of area regulation is shown in Figure 11.

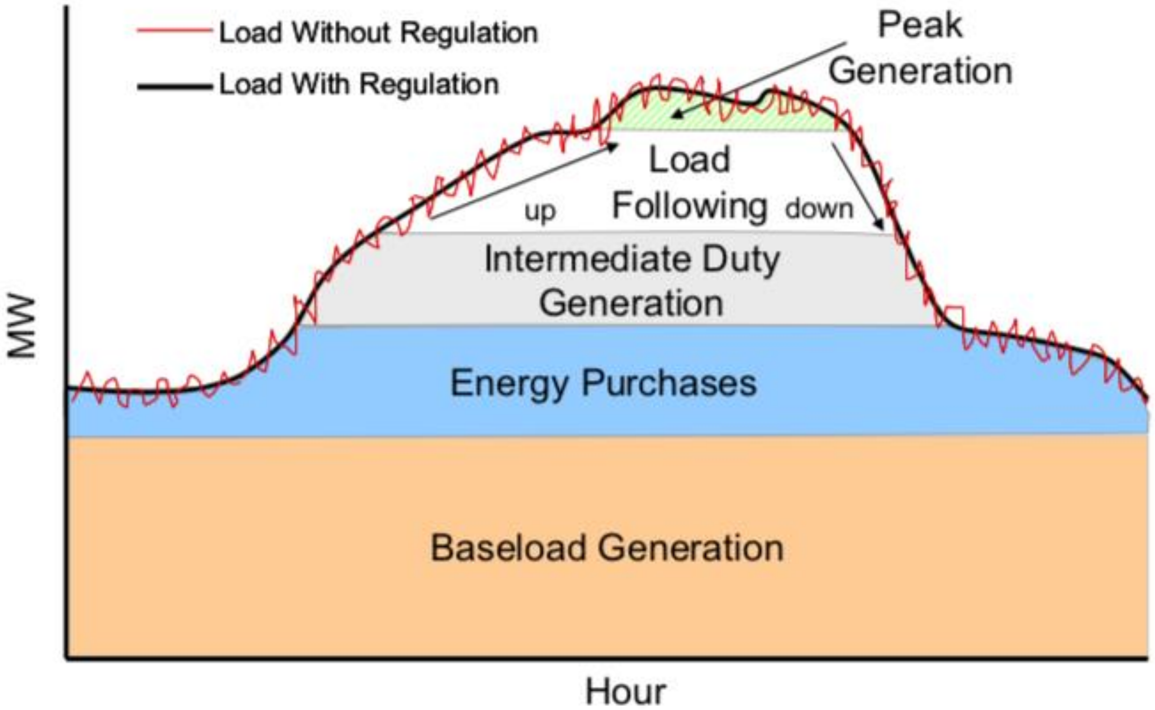

Figure 11: Profiles demonstrating the effect of area regulation on the electrical network (Eye & Corey, 2010).

As seen in Figure 11, area regulation responds to shorter fluctuations than load following. Area regulation is currently most commonly provided by flexible generation plants ramping up or down their power output. For storage technologies to provide regulation, they must have rapid response rates (less than 5 seconds) and ramp rates, they should also be reliable and have stable, high-quality power output (Eye & Corey, 2010). Devices providing regulation services cannot be used simultaneously for other services as they are required to be always available (Eye & Corey, 2010).

3.3.5 Supply reserve capacity

To ensure energy security on the grid, a supply reserve capacity should be maintained which can be called upon in the event of normal supply resources becoming unavailable unexpectedly (Eye & Corey, 2010). At a minimum, the reserve level should never be below the capacity of the largest single supply. Typically, the reserve capacity is approximately 15% - 20% of the normal supply capacity (Eye & Corey, 2010).

There are three categories of reserve capacity (Eye & Corey, 2010):

1. Spinning reserve – is capacity which is online but unloaded. Spinning reserve should be able to respond within 10 minutes in the event of generation or transmission outages. For frequency responsive spinning reserves, the response time is within 10 seconds.
2. Supplemental reserve – is generation capacity which may be offline, or that contains a block of variable or interruptible loads, that can be available within 10 minutes. Supplemental reserves are not synchronised with the grid and are used after all spinning reserves are loaded.
3. Backup supply – is generation that has a response time of less than an hour and acts as a backup for spinning and supplemental reserves.

Whilst supply reserve capacity provides a means to maintain the power supply, storage may be particularly effective for this application. Storage could possibly provide twice its capacity for reserves as it could simultaneously stop charging and begin discharging.

3.3.6 Voltage support

This involves providing power to the grid in order to keep the grid voltage within an acceptable range (Mohd, et al., 2008). To do this, the reactance of the grid must be managed (Eye & Corey, 2010). Therefore, the role of voltage support is to offset reactive effects to maintain the grid voltage (Eye & Corey, 2010).

Voltage support is usually provided by flexible generation sources capable of generating reactive power. Conventional power factor correction is achieved using capacitors; however, this is not suitable for voltage support, as capacitors draw increasing current when voltage drops (Eye & Corey, 2010).

Storage for voltage support must be able to supply reactive power and must be able to respond quickly (within seconds). However, the discharge duration for voltage support ranges from a few minutes up to an hour (Eye & Corey, 2010).

3.3.7 Transmission support

Transmission support applications are those which compensate for anomalies on the electrical system, including voltage sag, unstable voltage, and sub-synchronous resonance (Eye & Corey, 2010). The types of transmission support are (Eye & Corey, 2010):

1. Transmission stability damping – this is improving the dynamic stability which increase load carrying capacity
2. Sub-synchronous resonance damping – involves providing real and reactive power at sub-synchronous frequencies to increase the line capacity.
3. Voltage control and stability – increasing the load carrying capacity by improving the dynamic voltage stability and reducing transient voltage dips
4. Reduction of under-frequency load shedding – manages frequency drops due to large system disturbances

For transmission support, energy storage devices must be capable of extremely rapid response times (below one second), operating at a partial state of charge, extremely reliable, and be capable of withstanding many charge and discharge cycles. Transmission support is typically required for between 1 and 20 seconds. (Eye & Corey, 2010) For transmission support, storage devices should also be capable of delivering both real and reactive power (IEEE Standards Coordinating Committee 21, 2008).

3.3.8 Transmission congestion relief

In many distributed areas, peak power demand is increasing faster than transmission capacity, causing congestion during times of peak demand. For this application, energy storage could be distributed on the load side of congestion points to supply energy during peak times, thereby reducing the demand on the transmission lines (Eye & Corey, 2010). Storage for transmission congestion relief would require the same properties as those required for time-shift and supply capacity applications (Eye & Corey, 2010).

3.3.9 T&D Upgrade deferral

T&D upgrade deferral involves delaying or avoiding upgrading a transmission/distribution system to delay or avoid the upgrade costs. This can be achieved by implementing relatively little energy storage when the peak demand on the system is close to its maximum capacity (Eye & Corey, 2010). Storage can be installed to deliver the excess power demand downstream of the overloaded transmission or distribution node, thereby preventing the need to completely upgrade the T&D section (Eye & Corey, 2010). In a similar role, energy storage can be used to reduce the load on T&D systems to extend their lifespan. The typical discharge duration required for T&D upgrade deferral is between 3 and 6 hours, however, this varies significantly from case to case (Eye & Corey, 2010).

3.3.10 Substation on-site power

Battery storage systems are already widely implemented to power switching, communication and control equipment at substations when the grid is not energised. Storage devices must be reliable and require low maintenance (Eye & Corey, 2010).

3.4 Key parameters for energy storage systems

3.4.1 Power capacity

This is the rated power of the device, listed in Watts, Kilowatts or Megawatts. Hence, it is the rate at which the device can deliver energy under normal operating conditions. This is the nominal maximum discharge rate under normal conditions (Eye & Corey, 2010). Some types of energy storage are capable of delivering energy at above their rated power for short durations; this is known as the emergency power capacity (Eye & Corey, 2010).

3.4.2 Energy storage capacity and density

This is the quantity of energy which the device is able to store (Castillo & Gayme, 2014). Hence, it is measure in kilowatt-hours, megawatt-hours or gigawatt-hours. Typically, the quoted energy storage capacity of a device is the total quantity of energy stored in the device and not the total retrievable quantity of energy (Ibrahim, et al., 2008). Therefore, this value may be somewhat misleading, particularly if the output efficiency of the device is low. Along with the power capacity, the energy storage capacity is a fundamental property that determines which applications a device can be used for.

A common term used when discussing energy storage is the energy density of a device. This is the energy storage capacity per unit volume of the device (Castillo & Gayme, 2014). The energy storage density of a technology has a significant influence on the practicality of the technology. Technologies which take up a large volume may be difficult to implement in locations where space is limited.

3.4.3 Discharge duration

This is the time over which the storage device can deliver the power. Hence, the discharge time may be presented as:

$$Discharge\ duration = \frac{Usable\ energy\ stored \times discharge\ efficiency}{Operating\ power}$$

As shown by the formula, the discharge duration of a device is a function of the energy storage capacity and the power output. However, it is a useful term by which to evaluate the suitable applications for a technology. This is because applications for energy storage are often described by the required power capacity and the typical duration of power supply required.

3.4.4 Round trip efficiency

This is the ratio of the energy discharged by the device to the energy required to charge the device, per cycle (Castillo & Gayme, 2014). Although a single characteristic value is usually given for energy storage devices, the efficiency is not necessarily constant. It may depend of the power output or the level of charge of the system (Ibrahim, et al., 2008). Hence, the true efficiency of an operational device can be complex to determine.

A factor which affects the round-trip efficiency of a device is the self-discharge rate. This is the rate at which a storage device may lose charge while not in use (Eye & Corey, 2010). A device which is susceptible to self-discharge will lose stored energy while it is dormant. This means, the energy it is capable of outputting will reduce over time. Hence, the round-trip efficiency of such a device is dependent on the cycle time. As a result, devices with high self-discharge rates are typically not well suited to applications with long periods between charging and discharging.

The round-trip efficiency of a device plays a significant role in determining its likely economic viability. For the operational model whereby energy is bought and stored when the cost is low, and released when the price is high, poor energy efficiency effectively increases the operating cost of the device relative to the income (Díaz-González, et al., 2012).

3.4.5 Lifetime/lifecycles

This is the time in years or the number of cycles for which the device will operate to a sufficient standard. Whether the life is measured in years or cycles depends on the type of technology, and can be affected by the operating mode (Castillo & Gayme, 2014). For example, the lifespan of lithium ion batteries is reduced as the depth to which they are discharged in each cycle is increased (Hesse, et al., 2017).

3.4.6 Response time and ramp rate

Response time is the time required for the storage device to go from no power output to maximum power output (Eye & Corey, 2010). This is an important factor in determining which applications an energy storage technology can be used for. In applications where the demand time and power cannot be predetermined, energy storage may need to be deployed rapidly. Therefore, energy storage devices with slow response times are unsuitable for these applications.

3.4.7 Charge time

This is the time required for the storage device to charge completely from a state of no charge (Castillo & Gayme, 2014). It is advantageous for an energy storage device to be able to charge rapidly, as this means it can be available to be deployed more often.

3.4.8 Scalability/modularity

The scalability or modularity of a storage type refers to the flexibility of sizing a system (Eye & Corey, 2010). Scalability is a factor which influences the range of applications for which a technology can be deployed. The capacity of some technologies can easily be increased, such as aqueous flow batteries by simply increasing the size of the storage tanks. Other storage types, such as pumped hydro, are constrained by design aspects, making them difficult to increase the capacity of the system.

3.4.9 Power quality

Power quality from a storage device is determined by a number of factors, such as power factor, voltage stability, waveform, and harmonics (Eye & Corey, 2010). Depending on the application of the energy storage device, the relative importance of power quality factors varies.

3.5 Background of SMGES

The proposed suspended mass gravitational energy storage (SMGES) device consists of a large weight that is suspended by cables wound onto electric winches. The weight is then to be raised to store energy in the form of gravitational potential energy and lowered to release energy. The company which proposed the technology have envisaged the weight being suspended in an underground shaft; either a disused mineshaft or a purpose bored shaft. A schematic diagram of the system is shown in Figure 12.

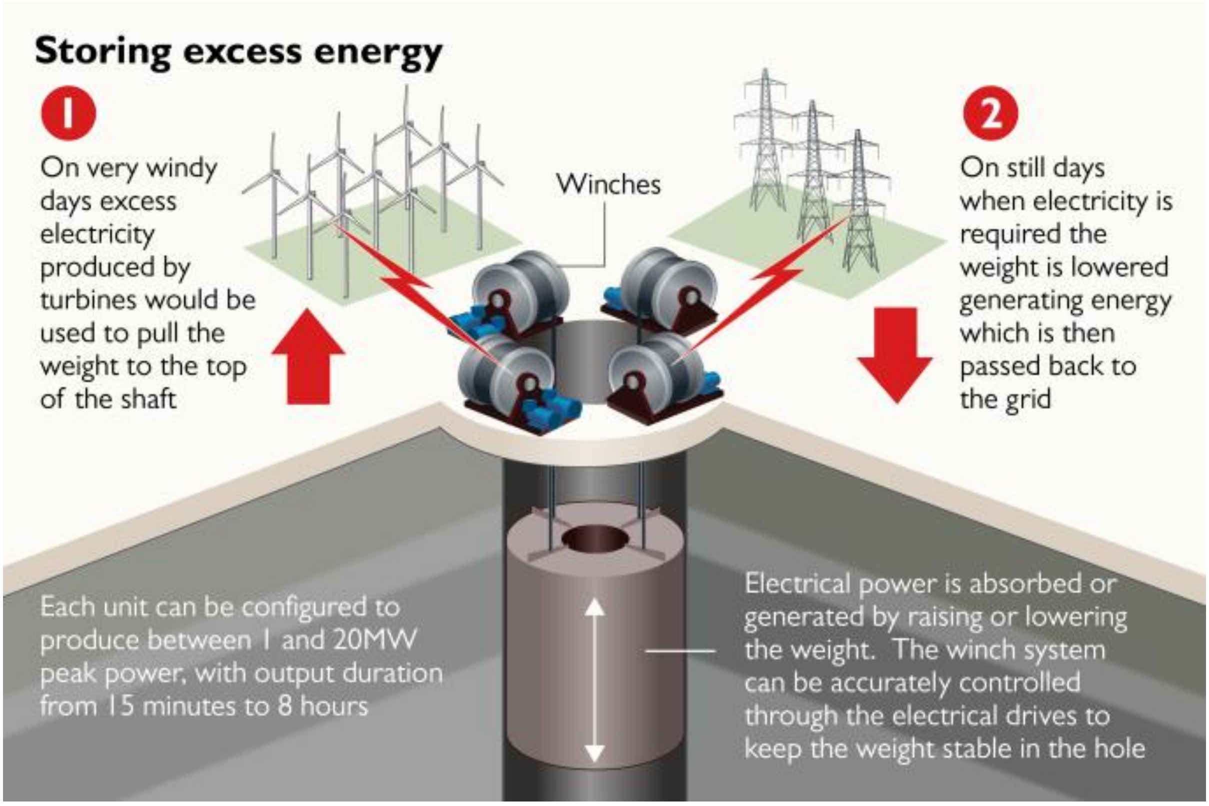

Figure 12: Schematic diagram of a SMGES device from The Sunday Times (Cameron, 2018).

Figure 12 shows that the system is envisaged to consist of electric drum winches and a cylindrical mass. It is also noted that the systems could produce a peak power of between 1 MW and 20 MW, with discharge durations of 15 minutes to 8 hours.

3.6 Suspended Mass Gravitational Energy Storage Design

3.6.1 Pulleys

Pulleys allow the force required to hold or raise a mass to be reduced. In an ideal system, the tension on either side of a cable wrapped around a pulley is equal. Therefore, a force twice the magnitude of the tension acts on the body which the pulley is attached to. Hence, a single pully, with one cable (hence, two strands), attached to a mass halves the force to be applied to one end of the cable in order to raise the mass. As a result, to raise the mass by a certain height, twice the length of cable must be pulled through. For an arrangement of more pulleys, the mechanical advantage is equal to the number of strands attached to the mass (Slocum, 2008). As a rule of thumb, a pulley should have a diameter approximately twenty times that of the cable (Slocum, 2008).

$$F_{weight} = n_{strands}T_{cable}$$

3.6.2 Winches and cables

A winch is a device used to pull or let out a cable by winding it onto and off of a drum, respectively. For a given cable tension, the torque on a winch depends on the diameter of the drum and the thickness of the layers of cable already wound onto it. Hence, as more layers of cable are laid onto the drum, the torque on the drum increases as the effective diameter increases (Slocum, 2008). A larger diameter drum reduces the stress on the cable and increases the length of cable which can be spooled per layer. Conversely, it increases the torque on the drum and hence motor (Markey, 2001).In the process of designing a winch system, the first step is to determine the cable thickness and length required (Markey, 2001). From this, the dimensions of the drum can be determined.

Cables – also known as wire ropes – typically come with various ratings which describe their performance characteristics. For design purposes, the most important value is the minimum breaking force of the rope (MBF). This is the maximum design force which the rope should be used, after the safety factor is applied to the expected load. According to European Standards BS EN 13001-3-2:2014, the formula to calculate the design force for lifting ropes is (Technical Committee CEN/TC 147, 2014):

$$F_{\mathrm{Sd,s}} = \frac{m_{\mathrm{Hr}} \cdot g}{n_{\mathrm{m}}} \cdot \phi \times f_{\mathrm{S1}} \times f_{\mathrm{S2}} \times f_{\mathrm{S3}} \times \gamma_{\mathrm{p}} \times \gamma_{\mathrm{n}}$$

Where:

- m_{Hr} is the mass of the hoist load
- g is the acceleration due to gravity
- n_{m} is the mechanical advantage of the cable(s) supporting m_{Hr}
- f_{s1}, f_{s2} and f_{s3} are rope force increasing factors
- γ_p is the partial safety factor ($\gamma_p = 1.34$ for regular loads)
- γ_n is the risk coefficient
- ϕ is the dynamic factor for inertial and gravity effects. $\emptyset = 1 + \emptyset_5 \frac{a}{g}$ for accelerating or decelerating suspended loads, where a is the acceleration and ϕ_5 is the dynamic load factor caused by acceleration ($1 \leq \phi_5 \leq 1.5$ is typical for gearboxes with smooth change of forces) (Technical Committee CEN/TC 147, 2014).

The safety factor used to determine a suitable rope MBF varies depending on the situation. BS ISO 16625:2013 standards suggest that a factor of 3.55-5.6 for hoists with multiple layers of spooling (Technical Committee MHE/3/1, 2013). Typically, a value of 5 is used in lifting applications.

Cables typically come with a minimum diameter ratio between the drum and the cable, specified by the manufacturer. However, it is suggested that a drum diameter larger than the minimum is utilised to improve spooling and extend the wire's lifespan (Markey, 2001). The European Standards EN14492-2 recommend a diameter ratio of at least 15:1 for hoists (British Standards Institute, 2019). Whereas, the hoisting equipment manufacturer, Lebus, recommends that the drum-to-cable diameter ratio should be greater than 25:1 (Seidenather, 2007). A table of the recommended ratios for various wire rope constructions is shown in Figure 13 (Cookes, 2013). The width of the drum is typically determined by what appears to be correct to the designer (Markey, 2001).

Construction	Suggested D/d* ratio	Minimum D/d* ratio
6x7	72	42
19x7 or 18x7 Rotation resistant	51	34
6x19 Seale	51	34
6x27 H Flattened strand	45	30
6x31V Flattened strand	45	30
6x21 Filler wire	45	30
6x25 Filler wire	39	26
6x31 Warrington Seale	39	26
6x36 Warrington Seale	35	23
8x19 Seale	41	27
8x25 Filler wire	32	21
6x41 Warrington Seale	32	21
6x42 Filler	21	14

Figure 13: Suggested drum-to-cable diameter ratios for various wire rope strand constructions (Cookes, 2013).

As can be seen in Figure 13, the suggested drum-to-cable diameter ratio for a given cable is highly dependent on the number of strands. Typically, more strands make the wire rope more flexible (Cookes, 2013). As a result, a lower drum-to-cable diameter ratio is required for ropes with more strands. Conversely, ropes with fewer strands are less flexible and require a larger drum-to-cable diameter ratio (Cookes, 2013).

Once the drum dimensions have been determined, the requirements of the gearbox and motor can be calculated. Although the efficiency of heavy-duty winches is difficult find in literature, according to Markey (2001), spur-geared and planetary-geared winches typically have efficiencies between 80 – 85%. The Canadian Coast Guard quotes the efficiency of electric drive winches on their vessels to range between 70 – 85% (De Angelis, 2009). These efficiencies represent the entire winch efficiency, including the motor, gearbox and drum winding efficiencies.

3.6.3 Shaft considerations

For the proposed SMGES system, the mass would likely be suspended in a vertical shaft in the ground. This would present two options; to use an existing shaft or to sink a new shaft. Suitable existing shafts may be disused mine shafts. In the United Kingdom, vertical mine shafts are typically between 2.7 m and 9.6 m in diameter, with depths between 600 m and 1200 m for coal mines (Jones, et al., 2004). The deepest mineshaft currently operational in the United Kingdom is between 1100 m and 1400 m (Israeli Chemicals Ltd, 2019). It is estimated that there are approximately 250,000 disused mineshafts in the United Kingdom (Chambers, et al., 2007). However, most of the abandoned mines in the United Kingdom have likely flooded or be partially collapsed (Batchelor, et al., 2005). Most modern mine shafts are lined with a circular concrete lining. The other common types of shaft lining are steel or timber for older shafts (de la Vergne, 2008).

Sinking a new shaft for the storage device would represent a large capital expenditure. Figure 14 shows the estimated costs of sinking new mine shafts using different techniques.

Method	Size	Fixed costs $'000	Depth variable costs $/m
Conventional sinking	4.0m dia	1,558	12,322
Conventional sinking	6.0m dia	3,624	15,980
Conventional sinking	8.0m dia	3,663	17,979
Raise boring*	1.8m dia	120	1,600
Raise boring*	2.4m dia	120	3,100
Raise boring*	3.0m dia	188	4,061
Raise boring*	4.0m dia	262	6,083
Blind shaft drilling	4.0m dia	1,797	13,448
Shaft strip and line	8.0m dia	2,212	17,681
V-Mole	6.0m dia	5,071	12,613
Longhole raising*	3.0 x 3.0m	0	500
Longhole raising*	1.5 x 1.5m	0	300

Figure 14: The estimated costs, in Australian Dollars, of sinking new mine shafts using different techniques (McCarthy & Livingstone, 1993).
**Does not include shaft lining or equipment.*

Based on the cost models in Figure 14, the estimated cost of sinking a 1000 m deep shaft using the conventional sinking method in 1993, would have been 19.6 million Australian Dollars (McCarthy & Livingstone, 1993). According to the Reserve Bank of Australia's Inflation Calculator tool, this is equivalent to approximately 36.5 million Australian Dollars, today (Reserve Bank of Australia, 2019). This value should only be used to give the order of magnitude of shaft sinking costs as it does not take into account the changes in technology or sinking methods. In a more recent example, Caledonia Mining Corporation spent 44 million US Dollars sinking a 1200 m deep shaft in Zimbabwe, which was completed in 2019 (The Telegraph, 2019). Based on these figures, sinking a new shaft in the UK would most likely cost tens of millions of Pounds.

4. Methods

4.1 Explanation of the technology assessment procedure

For the purpose of analysing energy storage systems, a procedure was developed. The procedure was influenced by those suggested by Loonen et al., (2014), and Blackler and Iqbal (2005). These were adapted to be more practical for the assessment of energy storage systems. The process was designed to ensure the assessment was performed in a focused manner and avoid redundant analysis. To achieve this, formal preliminary steps were included before the model should be developed. These preliminary steps were intended to ensure the model was created to meet the purpose of the study without unnecessary complexity, which would add cost to the study. A schematic of the process developed is shown in Figure 15, followed by a summary of each of the steps.

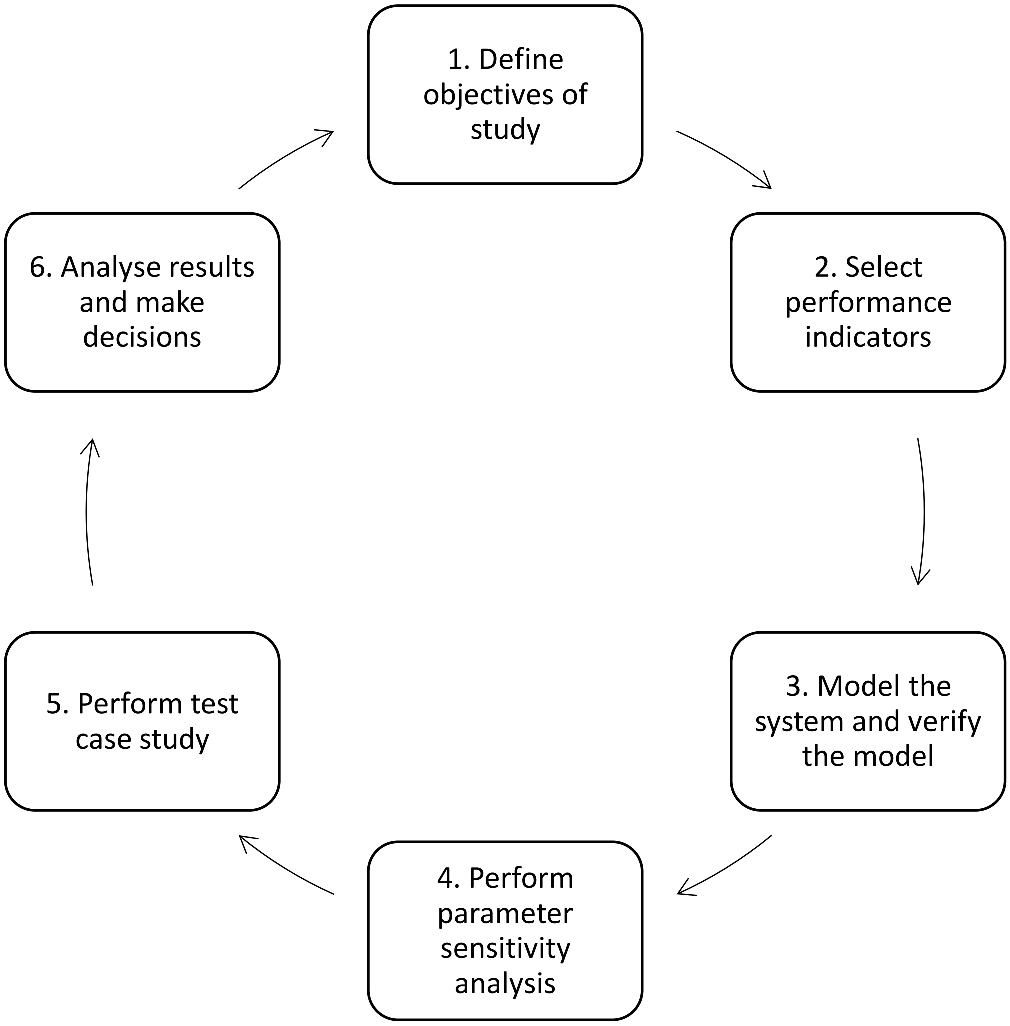

Figure 15: Schematic of the early stage energy storage technology assessment process.

1. Define objectives of study: This step should be used to determine the purpose of the study and explicitly describe what it aims to achieve. Carrying out this step should focus the study as a whole.
2. Identify performance indicators: The key performance aspects of the technology should be recognised. Hence, the metrics which are to be used to judge the performance should be identified. The key performance indicators should be chosen to best meet the objectives set out in Step 1.
3. Model the system: A model of the system should be developed which sufficiently captures the features and physics of the product. Sufficient accuracy should be achieved without unnecessary complexity. Once the model has been completed, a series of checks should be carried out to ensure the physical system has been correctly modelled to the level required for the analysis.
4. Perform parameter sensitivity analysis: A sensitivity analysis of the various parameters should be performed. The purpose of the sensitivity analysis is to determine how the performance of the technology is affected by individual aspects of the design. The sensitivity analysis should consider aspect levels which could be currently expected as well as levels which could be achieved in the future. The sensitivity analysis should show which design factors are key to the performance of the system. It should also highlight the areas in which technology advancement would be most beneficial to the system. This can be used as a tool to focus research where it will provide the greatest benefit.
5. Perform test case study: The model should then be configured to meet a number of test case application scenarios. The test case scenarios should cover a wide range of possible applications of the system. The different scenarios should evaluate the system in various configurations, thereby testing different characteristics of the system. The relevant values of the key performance indicators should be stored and used to compare the performance of the model with competitors and alternative technologies within the field.
6. Analyse results and make decisions: The results obtained in the test case scenarios and the sensitivity analysis should be thoroughly analysed. The analysis should review the key performance indicators of the system to meet the specified objectives of the study. Decisions should be made on whether the system is likely to be viable. If further analysis is required, additional tests should be added, and the evaluation process should be carried out again.

4.2 Application of procedure to the SMGES

4.2.1 Objectives of the study

The aim of this study is to determine the potential performance of the proposed SMGES technology. This should include the realistic performance expected with current technology levels as well as show how the performance may improve if technology was advanced. The study should highlight the relative strengths and weaknesses of SMGES technology. By doing this, the most suitable applications for SMGES should be identified. For the identified applications, the performance and characteristics of the SMGES technology should be objectively compared with established technologies which provide the same or similar services.

4.2.2 Selection of performance indicators

To effectively evaluate the characteristics of the SMGES technology, the key parameters which will determine whether the technology is viable or not, should be identified. Typically, the most important characteristics of energy storage devices are the energy storage capacity, energy storage density, power capacity, round trip efficiency, response time, charge time, and lifespan. However, the applications and therefore performance requirements for energy storage vary considerably. Therefore, developing one system model and reviewing the performance characteristics would not give a wholistic view of the performance potential for the technology in different applications.

To get a more relevant understanding of the performance potential of the technology, the model should be configured to meet realistic outputs, and the required system parameters should then be reviewed. In this sense, some of the typical performance characteristics of energy storage devices shall be used as inputs to the model, while the system configuration will be used as performance indicators.

The performance criteria which the system model shall be configured to meet are the following:

1. Energy storage capacity
2. Power output capacity
3. Response time

These characteristics were chosen to define the system as these are typically the most important specifications for energy storage devices.

The key system design parameters to meet these specifications, which will indicate the potential viability of the technology are:

1. Mass of weight
2. Shaft height
3. Drop speed
4. Acceleration of weight
5. Number of winches and strands
6. Cable diameter
7. Winch drum diameter
8. Peak winch torque

The mass of the suspended weight, and the shaft height required to meet the energy storage capacity are two highly important metrics. For the SMGES technology, the idea of energy storage density is hard to quantify. However, the required mass of the weight and the height of the shaft will give an indication of the scale of the device required to meet the energy storage capacity. Additionally, the size of the mass will indicate the manufacturing requirements and challenges. The required shaft depth will also help to determine the viability by comparing it to the depth of mine shafts which could be utilised.

The drop speed and acceleration of the weight required to meet the response time are important characteristics in determining the feasibility of the system. To fast drop speed may result in excessive let out speeds for the winches. The acceleration of the weight fundamentally cannot be greater than the acceleration due to gravity. However, the maximum acceleration may be further limited by the winches, as slack in the cables must be avoided, as it can lead to wear and breakages.

The number of winches and strands, cable diameter, and winch drum diameter all indicate the scale and mechanical complexity required for the system. Although determining a cost model of the system would be complex and is out of the scope of this project, the system requirements can be compared with alternate systems. The cable diameter and number of strands are important as the cost for these may be high. Additionally, all of these components will be subjected to wear, and therefore will need to be replaced periodically.

Finally, the peak winch torque is a key parameter as it dictates the requirements of the gearbox and electric motor/generator to be connected to the system. The higher the torque on the winch, the greater the reduction ratio of the gearbox which will be required.

5. Modelling the System

The mathematical models of the system were created in MATLAB. Other high-level programming languages or software packages, such as Python or Microsoft Excel, could have been used. MATLAB was chosen as it is user friendly and allows the easy repetition of the model in different configurations. It has further advantages over Excel in that the equations are visible to the user.

An initial mathematical model of the SMGES system was developed. This model was used as a platform to check the modelling was performed correctly, before carrying out tests. Through developing and checking the basic model, a better understanding of the characteristics of SMGES systems was attained. This aided in the process of selecting test case applications, as well as analysing the system.

5.1 Basic SMGES model

The basic system model requires the user to specify the energy storage capacity, output power capacity, shaft height, response time, number of winches and number of cable strands. The model then calculates the required mass and volume of the weight, drop speed of the weight, discharge duration, cable specifications and winch specifications.

To develop the model, a number of assumptions were made. The assumptions were made in line with the overall aim of the case study; to effectively determine the feasibility of SMGES systems. Therefore, factors which would have added additional complexity to the model without providing improved accuracy to the results were neglected.

List of assumptions:

- Efficiency of power conditioning equipment was not taken into consideration.
- The let-out efficiency and take-up efficiency of the winches are equal.
- The shaft height represents the height through which the mass can move.
- The modelled system could be manufactured and installed.
- A suitable control system would be developed to manage the winch and mass positioning.
- The shaft could withstand the forces around the opening.
- The weight would be effectively stabilised without adding further drag.
- The air gap around the mass would be sufficient to avoid any significant air pressure effects.

- The acceleration of the weight from stationary to peak velocity would be perfectly constant, as would the deceleration phase.
- The mass is equally supported by all of the cables.
- The pulley friction is negligible in relation to the tension caused on the cables.
- The winding of the cables onto the winch drum would be perfect, with no spaces between adjacent loops.

5.1.1 Inputs and parameters

The first stage of the model defines the various inputs and fixed parameters of the system. The list of parameters is shown in Table 2.

Table 2: Descriptions of the design terms used in the SMGES model.

Parameter	**Description**
Energy	This is energy storage capacity of the system in kilowatt-hours. This represents the quantity of energy which can be output by the system, after losses in the system. It does not consider the losses or inefficiencies of power conditioning equipment.
Power	This is the rated power output required of the system. As with the energy storage, it represents the power output from the SMGES system prior to power conditioning.
Shaft height	This is the height through which the weight can travel. It does not take into account the height of the weight or space which may have to be left at the bottom of the shaft.
Response time	This is the time taken for the system to begin producing the rated power output from a state of no power output.
Number of winches	This is the number of individual winches connected to the mass.

Number of strands	The number of strands represents the number of vertical cables one would see if they looked at a cross-section of the shaft. Therefore, a cable fixed at the top of the shaft, passing through one pulley connected to the mass and then up to the winch, is said to be two strands.
Winch efficiency	This is the total energy efficiency of the winch systems. This includes losses associated with winding cables on the drum, gearbox and transmission losses, and conversion losses in the electric motor/generator.
Density	This is the average density of the material which the weight is manufactured from.
Safety factor	This is how many times greater the minimum braking strength of a cable should be than the peak load expected to act on the cable.
Drum-to-cable diameter ratio	This is the ratio of the drum's diameter to the cable's diameter.
Winch ratio	This is the nominal ratio of the width of the drum to the diameter of the drum.
Weight aspect ratio	This is the ratio of the height of the cylindrical mass to its diameter.

5.1.2 Calculations

The first calculation in the script is to determine the suspended mass required to meet the specified energy storage capacity. In a constant gravitational field, the gravitational potential energy of a raised mass is:

$$E = mgh_s$$

Where:

- m is the mass.
- h_s is the height through which the mass is raised.

Hence, the mass required for the desired energy output capacity is:

$$m = \frac{E}{\eta_w g h_s}$$

η_w is the overall winch efficiency.

The volume (*V*) of the weight was then calculated for the specified weight density.

$$V = \frac{m}{\rho}$$

Where, ρ is the material density of which the weight is comprised.

The diameter (*d*) and height (*h*) of the weight are then calculated using the predefined ratio of height to diameter (r_{dh}). The equation to calculate the diameter was derived as follows:

$$V = \frac{\pi}{4} d^2 h$$

$$V = \frac{\pi}{4} d^2 r_{dh} d$$

$$V = \frac{\pi}{4} d^3 r_{dh}$$

$$d = \sqrt[3]{\frac{4V}{\pi r_{dh}}}$$

$$h = r_{dh} d$$

Following this, the required drop speed of the mass is calculated using the equation:

$$v_{drop} = \frac{P}{\eta_w m g}$$

Where, P is the rated power of the system.

The acceleration (*a*) of the weight is then calculated from the response time of the system as follows:

$$a = \frac{v_{drop}}{t_{resp}}$$

The discharge duration of the system at the rated power is then calculated as follows:

$$T_{discharge} = \frac{h_{shaft}}{v_{drop}}$$

The next set of calculations determine the configuration of the cables and winches, respectively. The first step is to calculate the required cable diameter based on the peak cable tension. To calculate the peak tension using the equation shown in section 3.6.2, the dynamic factor ($\emptyset$) is first calculated by the formula:

$$\emptyset = 1 + \emptyset_5 \frac{a}{g}$$

Where, $\emptyset_5$ is the dynamic load factor. For the model, a dynamic load factor of 1.5 is used. This is the boundary value of the dynamic factor between gearboxes with smoothly changing forces and gearboxes with suddenly changing forces (Technical Committee CEN/TC 147, 2014). This value is used as it represents the best case for the given system.

After the dynamic factor is calculated, the peak cable tension (F_{cab}) is calculated by the formula:

$$F_{cab} = \frac{mg\emptyset\gamma_p\gamma_n}{N_{strands}}$$

Where:

- γ_p is the partial safety factor (γ_p = 1.34 is used as this is the value for regular loads (Technical Committee CEN/TC 147, 2014)).
- $N_{strands}$ is the number of strands as explained in Table 2.

This equation was derived from equation describe in section 3.6.2. The difference is that the rope force increasing factors are omitted. These factors can be omitted as they only apply to hoisting of loads with non-vertical strands.

The minimum tension which the cables should be able to withstand – the design tension – is then calculated by multiplying the peak cable tension by the defined safety factor (n_s) as follows:

$$F_{design} = n_s F_{cab}$$

Using the design tension, an appropriate cable diameter is selected. Selecting an appropriate wire rope for a task is not a process which can easily be automated, as there is a wide array of strand winding configurations which have unique performance characteristics. To simplify the cable selection, a cable range was selected from a manufacturer's catalogue as an example.

The chosen cable was called QS816V(G) and manufactured by Teufelberger. This was a filled and compacted rope recommended for hoisting. The rope was suggested for applications where high minimum breaking force (MBF) and extreme resistance to crushing were required. It was suitable for multiple layer spooling on a winch drums and had a high resistance to internal corrosion (Teufelberger, 2019). Therefore, this rope is likely to be suitable for the SMGES application. The grade of cable selected was 1960 MPa with an 8×26 strand construction. The MBF of this rope was among the best of the ropes researched, for a given diameter. This particular rope was used as the rated performance characteristics were available for a wide range of diameters; from 10 mm to 70 mm.

The data sheet for the cable was copied into Microsoft Excel. A graph was then plotted of the MBFs for the corresponding diameters and a trendline was plotted. Hence, the equation of the trendline describes the minimum breaking force of the cable as a function of the cable diameter. The plot is shown in Figure 16.

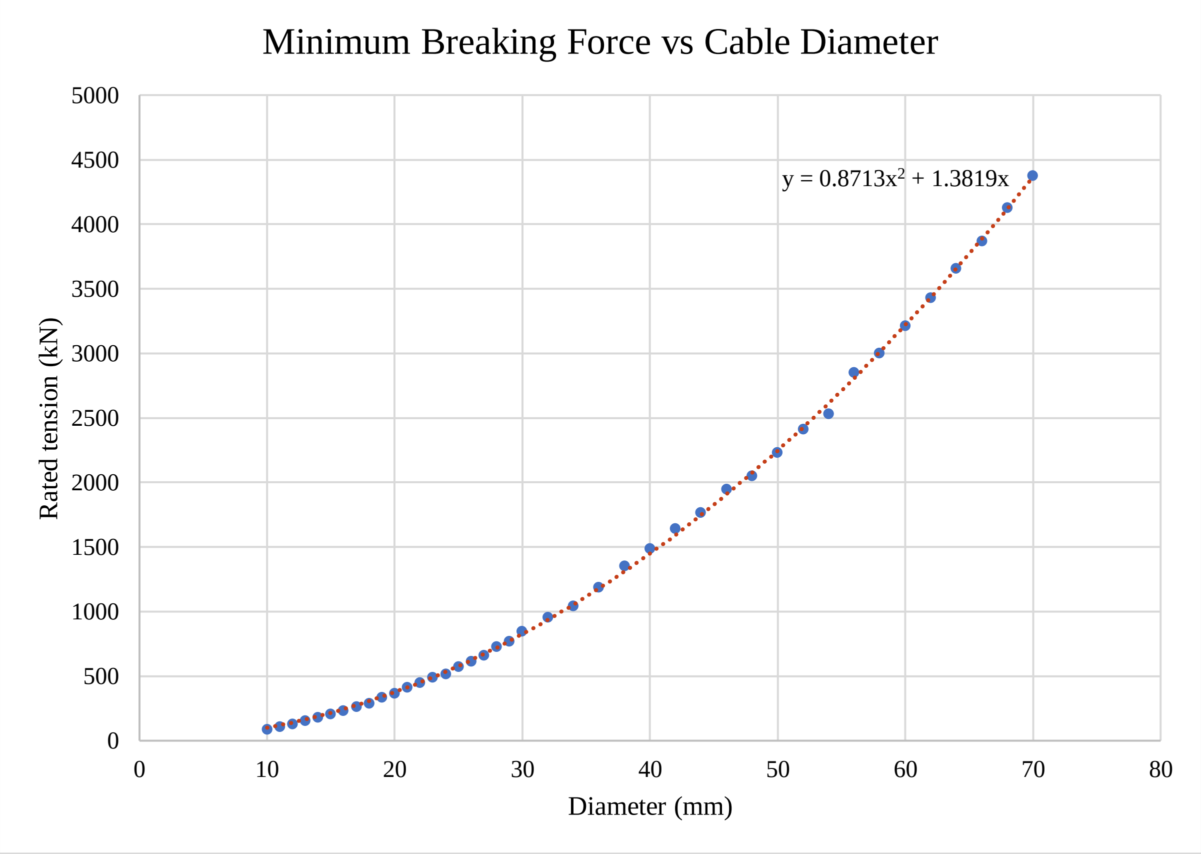

Figure 16: A graph showing the relationship between the diameter of the cable and the minimum breaking force.

The equation for the MBF in kilonewtons as a function of cable diameter is:

$$MBF = 0.871{d_{cable}}^2 + 1.382d_{cable}$$

The MBF is a second-degree polynomial of the cable diameter. This was expected as, under ideal conditions, the tensile strength of a wire is directly proportional to the cross-sectional area. For a circular cross-section, the area is proportional to the diameter squared.

A similar graph was plotted for the mass of the cable per unit length against the corresponding diameter. The trendline was plotted and the equation describing the mass per unit length of cable as a function of the diameter was obtained. The graph is shown in Figure 17.

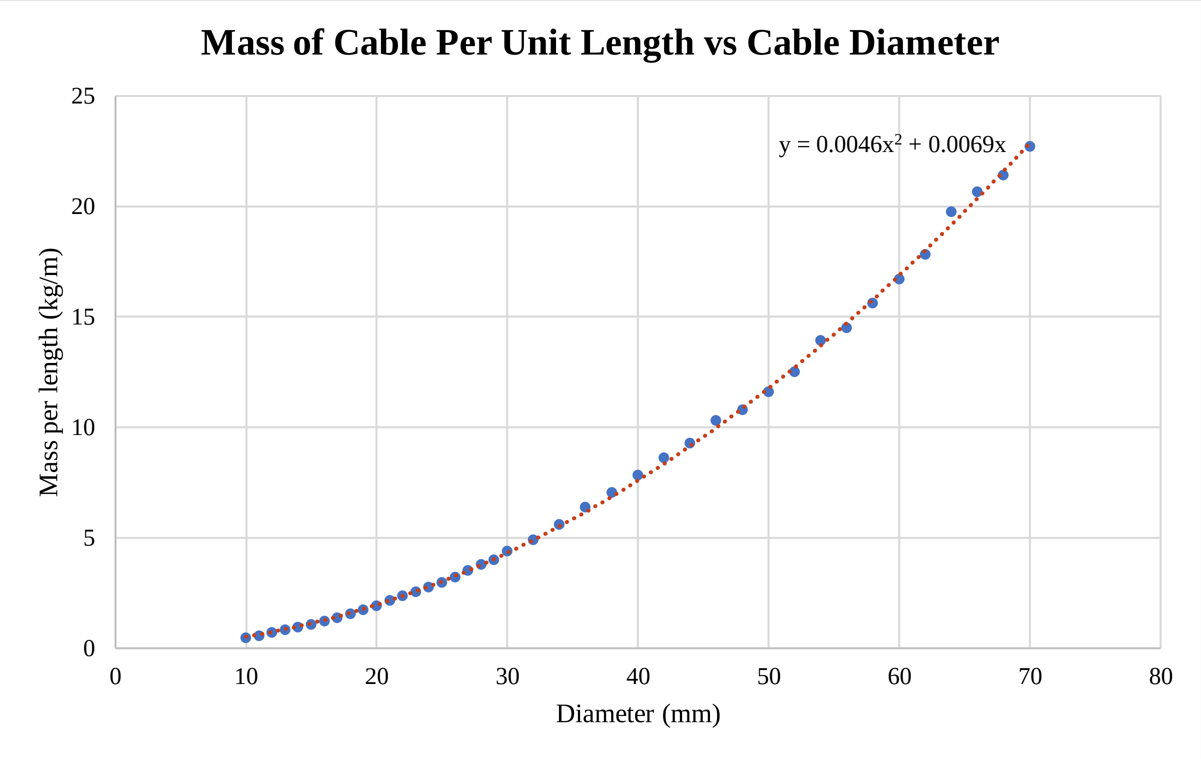

Figure 17: A graph showing the relationship between the diameter of the cable and its mass per unit length.

The equation of the trendline of the graph gives that:

$$\delta_{rope} = 0.0046{d_{cable}}^2 + 0.0069d_{cable}$$

As with the MBF of the rope, the specific mass is a second-degree polynomial function of the diameter.

To determine a suitable cable diameter for the given design tension, a 'while' loop was implemented in the model. The process of the loop is as follows:

While: $MBF < F_{design}$

$d_{cable} = d_{cable} + 1 \text{ mm}$

$MBF = 0.8713{d_{cable}}^2 + 0.0069d_{cable}$

End

In this loop, the MBF and the design force are first compared. If the MBF is less that the design tension, the cable diameter is increased by 1 mm. The MBF is then recalculated using the new diameter and the loop begins again. Once the MBF is greater than the required design tension, the loop terminates. This process ensures that the cable diameter is always an integer of millimetres; which is typically how cables are sold. An alternative process which could have been used would be to rearrange the quadratic equation to obtain the diameter as a function of the required MBF. However, as the rearranged equation would have two solutions, this method would require a mathematical proof or other testing means to ensure the correct solution was used.

Once the cable diameter is selected, the weight of the cable per unit length is calculated using the trendline equation from Figure 17.

The next stage of calculations determines the winch drums' dimensions. The diameter of the winch drums is calculated using the drum-to-cable diameter ratio (r_{dc}), as shown:

$$d_{drum} = r_{dc} d_{cable}$$

For the base case model, a drum-to-cable diameter ratio of 32 was used. This value was based on the recommended drum-to-cable diameter ratio for wire ropes given by Cookes (2013), shown in Figure 13. The table recommended a ratio of 32 for wire ropes with an 8×25 filled strand construction, which is very similar to the 8×26 filled strand construction of the example rope. Therefore, this ratio was deemed suitable to give a realistic drum diameter for the basic system model.

Next, the length of the cable to be wound onto each winch drum is calculated as follows:

$$l_{per\_drum} = \frac{n_{strands} h_{shaft}}{n_{winches}}$$

Once the diameter of the drum is calculated, the width of the drum can be determined. As the width of a winch drum is typically chosen by what looks right to the engineer, to determine the drum width, a series of steps are taken in the model. The process followed in shown in Figure 18.

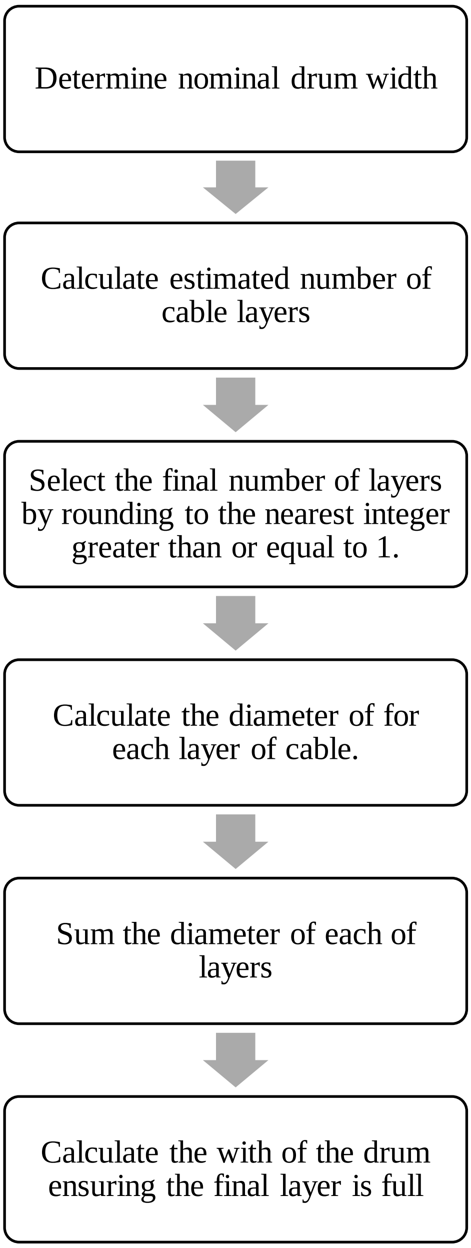

Figure 18: Schematic of the process by which the drum sizing calculations are performed in the mathematical model.

To determine the nominal drum width, a width-diameter ratio is chosen. The nominal width is not the final width which the drum is designed to. The final width of the drum is calculated so that when the weight is fully raised, the outermost layer of cable on the drum would be full.

The nominal ratio was deemed reasonable by reviewing winches used in hoisting with large diameter wire ropes. The fact that a number of winches would have to be arranged around a relatively narrow shaft was also taken into consideration. The wider the winch drums, the further away from the shaft opening the winches would need to be located in order to fit.

The nominal drum width is calculated by the formula:

$$b_{drum\_nom} = r_{dw} d_{drum}$$

From the nominal drum width, the estimated number of layers is calculated. The equation is as follows:

$$n_{layer\_est} = \frac{Total\ centroidal\ area\ of\ rope}{Circumferential\ area\ of\ drum}$$

$$n_{layer\_est} = \frac{Cable\ width \times cable\ length}{drum\ circumference \times estimated\ width}$$

$$n_{layr\_est} = \frac{l_{pe\_drum} d_{cable}}{\pi d_{drum} b_{drum\_nom}}$$

The next step determines the number of layers by rounding the estimated number of layers to the nearest integer. To ensure the number of layers is not rounded down to 0, an 'if' function is implemented as follows:

If: $n_{layer\_est} < 1$

$n_{layer} = 1$

Else:

$n_{layer} = round(n_{layer\_est})$

Once the number of layers of cable is determined, the width of the drum can be calculated. To simplify the calculation, it was broken into a number of steps. First, the diameter of each of the layers is calculated using the following 'for' loop:

For: $i = 1: n_{layer}$

$d_{layer}[i] = d_{drum} + d_{cable} + 2(i-1)d_{cable}$

End

The diameter calculated in the loop represents the diameter of the centroid of the outermost layer of cable. A representation of this is shown in Figure 19. The equation accounts for the outermost layer and the inner layers of cable. For the outermost layer, the distance to be added to the drum diameter is one diameter of the cable, as the layer diameter is measured from the centroid of the cable on either side of the drum as shown in Figure 19. For the inner layers on the drum, twice the diameter of the cable should be added, as there is a cross-section of cable on both sides of the drum.

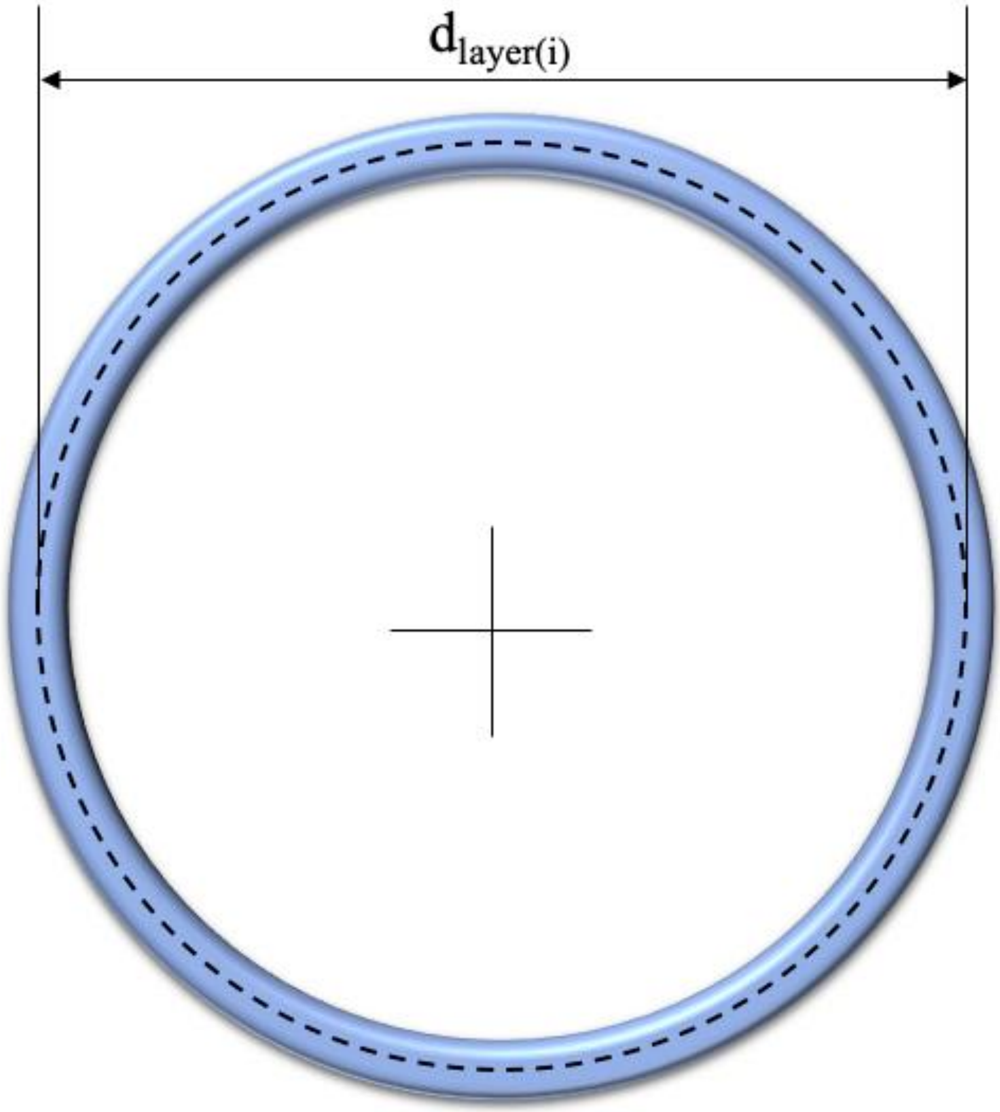

Figure 19: Diagram showing the measurement described as the diameter of each layer in the model.

Next, the sum of the layers' diameters was calculated using the following 'for' loop:

For: $i = 1: n_{layer}$

$$Sum_{d\_layers} = Sum_{d\_layers} + d_{layer}[i]$$

End

The sum of the layers' diameters is then used to determine the design width of the drum. The equation for the width was derived as follows:

$$l_{per\_drum} = \pi Sum_{d\_layers} n_{loops\_per\_layer}$$

$$l_{per\_drum} = \pi Sum_{d\_layers} \frac{b_{drum}}{d_{cable}}$$

Hence, the width is calculated by:

$$b_{drum} = \frac{l_{per\_drum} d_{cable}}{\pi Sum_{d\_layers}}$$

The final calculation in the model is to determine the peak torque on the drum. The maximum torque would occur on the drum when the drum is wound to the final layer of cable, but the final layer is still on the first loop. This is because the maximum torque occurs when the diameter is greatest while carrying the highest load, including the weight of the cable. Hence, the length of cable on the outermost layer is calculated by:

$$l_{outer\_layer} = \frac{\pi d_{max} b_{drum}}{d_{cable}}$$

Finally, the peak drum torque is calculated as follows:

$$T_{drum} = \frac{d_{layer}[n_{layer}]}{2} \left(F_{cab} + m_{cab} g l_{outer\_layer}\right)$$

5.1 Verification of the model calculations

It is highly important when modelling a system to check the model is correct. Simple errors in the code can cause incorrect results which may be within the expected range; and therefore, not be noticed. This is particularly relevant when using a programming software such as MATLAB, as the equations in the script are typed out in a line using standard keyboard symbols. Therefore, the equations do not visually resemble typical mathematical equations. This makes it more difficult to see differences between the equation in MATLAB and the reference mathematical equation.

To ensure the correctness of the SMGES system model, a number of checks were carried out. Firstly, simple hand calculations were performed where possible to check the correctness of the model. The first series of check calculations were performed for the mobile phone battery application configuration, which was used in the test case analysis. This was chosen for the first model check as the smaller energy and power rating result in smaller numbers throughout the model; which are easier to work with. Therefore, apparent outlier values can be more easily noticed. The manual test calculations are described below.

Firstly, the height, mass, and winch efficiency in the model were used to check the energy storage capacity calculation was correct using the equation:

$$E = \eta_{winch} m g h_{shaft}$$

The model specified a mass of 173 kg was required for a shaft of 25 m and a winch efficiency of 85%. Multiplying these values and the acceleration due to gravity gives an energy storage value of 36000 Joules. A Watt-hour is equivalent to 3600 Joules; therefore, 36000 Joules represents 10 Wh, which is correct.

The rated power was then checked using the equation:

$$P = \eta_{winch} m g v$$

For the drop speed of 0.0035 mm/s with a 173 kg mass, the power output was calculated to be 5.0 W, which is correct.

The peak cable tension was checked by performing a calculation to determine the expected cable tension based on the weight of the mass and the acceleration rate. The formula used was:

$$F_{cab} = \frac{m(g + a\emptyset_5)\gamma_p}{N_{strands}} = \frac{173(9.81 + 0.0347 \times 1.5)1.34}{2} = 1140\ N$$

This is the expected result, and it shows that the cable tension is greater than the force required to slow the dropping mass at the given acceleration.

The cable design tension was then to be manually checked against the wire rope datasheet used to create the cable sizing equation, to confirm that the cable diameter specified by the model was correct. This could not be performed for the mobile phone battery example as the cable diameter specified by the model was below the smallest cable diameter in the datasheet. Therefore, the football stadium scenario was used to check the rope diameter. The peak cable tension for this scenario was 595 kN, therefore, the design tension was 2975 kN. In the datasheet, this fell between the MBF for cables with diameters of 56 mm and 58 mm, which have MBFs of 2800 kN and 3000 kN, respectively. Therefore, a cable diameter of 58 mm would be used. This is the same as the cable diameter specified in the model. The calculation to determine the cable weight was also checked using the football stadium example, by the same method.

Checking the drum diameter was done for the mobile phone battery example. To check this, the cable diameter was multiplied by 32 and divided by 1000 to convert the units to metres.

The drum width calculation was checked by performing a different method to that implemented in the model. This was done to prevent any errors in the model from being repeated during the check.

First, the length of rope per winch drum was calculated as follows:

$$l_{per\_drum} = \frac{h_{shaft} N_{strands}}{N_{winches}} = \frac{25 \times 2}{1} = 50\ m$$

Next, the drum width calculation was checked. Although there are no significant characteristics dependent on the drum width, the calculation involves a number of parameters which are calculated previously. Therefore, checking the width of the drum is calculated correctly, implicitly checks that the other parameters were also calculated correctly. The first step in checking the drum width calculation is to determine the length of cable which would be wound in one annulus of rope on the drum. To do this, firstly, the diameter of each layer of cable was calculated as follows:

$$d_1 = d_{drum} + d_{cable} = 0.064 + 0.002 = 0.066\ m$$

$$d_2 = d_1 + 2d_{cable} = 0.066 + 2(0.002) = 0.070\ m$$

$$d_3 = d_2 + 2d_{cable} = 0.070 + 2(0.002) = 0.074\ m$$

$$d_4 = d_3 + 2d_{cable} = 0.074 + 2(0.002) = 0.078\ m$$

$$d_5 = d_4 + 2d_{cable} = 0.078 + 2(0.002) = 0.082\ m$$

$$d_6 = d_5 + 2d_{cable} = 0.082 + 2(0.002) = 0.086\ m$$

$$d_7 = d_6 + 2d_{cable} = 0.086 + 2(0.002) = 0.090\ m$$

$$d_8 = d_7 + 2d_{cable} = 0.090 + 2(0.002) = 0.094\ m$$

As a preliminary check, 0.094 m was the same as the outer layer diameter calculated in the model. Next, the length per annulus was calculated by:

$$\begin{aligned} l_{annulus} &= \pi \left(d_1 + d_2 + \cdots + d_{n_{layer}} \right) \\ &= \pi(0.066 + 0.070 + 0.074 + 0.078 + 0.082 + 0.086 + 0.090 + 0.094) \\ &= 2.0\ m \end{aligned}$$

Next, the number of annuli of rope required for the length of rope per drum was calculated as follows:

$$N_{annuli} = \frac{l_{per\_drum}}{l_{annulus}} = \frac{50}{2.0} = 25$$

Finally, the required drum width was calculated by multiplying the number of annuli of cable required by the diameter of the cable, as follows:

$$b_{drum} = N_{annuli} d_{cable} = 25 \times 0.0020 = 0.050\ m$$

This drum width was equal to that calculated in the model. This process checked that the calculations for the layer diameter, the sum of diameters calculation, and the drum width are correct.

Finally, the peak winch torque calculation was checked as follows:

$$T_{drum} = \frac{d_{max}}{2}\left(F_{cab} + m_{cab\_per\_m} g l_{outer\_layer}\right)$$

$$= \frac{d_{max}}{2}\left(F_{cab} + m_{cab_{per_m}} g(\pi d_{max} N_{annuli})\right)$$

$$= \frac{0.094}{2}(1140 + 0.0322(9.81)(\pi 0.094 \times 25)) = 53.7\ Nm$$

This was equal to the value calculated by the model. In addition to showing that the torque was calculated correctly, this check shows that the length of the outer layer was also computed correctly.

An additional check carried out on the model, was to verify the power using values of torque and the rotational speed of the winches.

Firstly, the cable tension when the weight is descending steadily was calculated as follows:

$$F_{cab\_drop} = \frac{mg}{N_{strands}} = \frac{173 \times 9.81}{2} = 849\ N$$

The torque on the winches when the cable is at the outer layer and the weight is dropping at a steady rate was then calculated as follows:

$$T_{steady} = F_{cab}\frac{d_{max}}{2} = 849\frac{0.094}{2} = 39.9\ Nm$$

The rotational speed of the winches to achieve the rated power output of the system in this situation was then calculated as follows:

$$\omega_{winch} = \frac{P}{\eta_{winch} T_{steady}} = \frac{5}{0.85 \times 39.9} = 0.148\ rad/s$$

This rotational speed was then checked by calculating the rotational speed from the drop speed of the mass as follows:

$$v_{let-out} = v_{drop} \frac{N_{strands}}{N_{winches}} = 0.0035 \frac{2}{1} = 0.0070\ m/s$$

$$\omega_{winch} = \frac{v_{let-out}}{r_{max}} = \frac{2v_{let-out}}{d_{max}} = \frac{2 \times 0.0070}{0.094} = 0.149 \frac{rad}{s}$$

The rotational speeds calculated by the two different methods were within the expected tolerance range accounting for rounding errors. This series of calculations checks that the mass of the weight, outer cable layer diameter, and drop speed were computed correctly in the model.

6. Sensitivity analysis

A sensitivity analysis of the system as a function of design parameters was carried out. The purpose of the sensitivity analysis was to give further insight into how the performance of the SMGES system is dependent on individual design parameters. Knowledge of these characteristics will help to envisage the performance potential of the technology. The sensitivity analysis should highlight which are the key aspects to make the technology viable.

Ideally, the sensitivity analysis should identify the levels which design parameters would need to meet in order for the system to be viable. This is challenging however, as there are not necessarily clear distinctions which determine at which point the system becomes viable. Furthermore, the sensitivity analysis cannot be performed for all possible configurations of the system, therefore, parameters which make one configuration viable may not be applicable all configurations. Conversely, if the achievable design parameters make the example case not viable, this does not mean all configurations of the system will not be viable for achievable parameters.

To give the SMGES system the best chance of being proved to be potentially viable, the sensitivity analysis should be performed on a base case scenario suited to the strengths of the SMGES system. This is because if it can be clearly shown that the system is not viable for even the most favourable scenario, then it is unlikely to be viable in less suited scenarios. A base case model with performance characteristics aligned to the applications which the SMGES is most well suited, was created.

6.1 Model description

A script was developed to perform sensitivity analysis on the SMGES model for the key parameters. To achieve this, the basic system model was converted to a function script in MATLAB. This was done by implementing the inputs and parameters for the basic model as inputs to the function. The function runs the mathematical model of the SMGES system and returns key system specifications. The MATLAB script of the function can be seen in Appendix B: MATLAB Scrips Used to Perform the Sensitivity Analysis. A schematic diagram showing the inputs and outputs of the function, is shown in Figure 20.

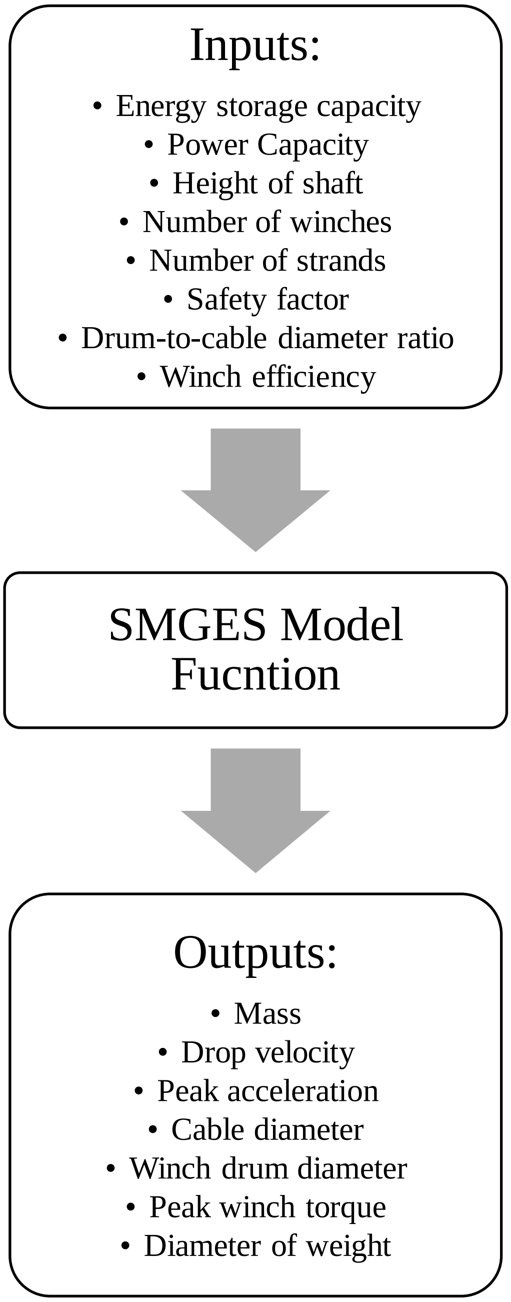

Figure 20: Schematic showing the inputs and outputs of the SMGES function.

To perform the sensitivity analysis, a script was written to evaluate the SMGES function a specified number of times, varying the input being tested for each evaluation. Figure 21 shows the process which the sensitivity analysis script follows.

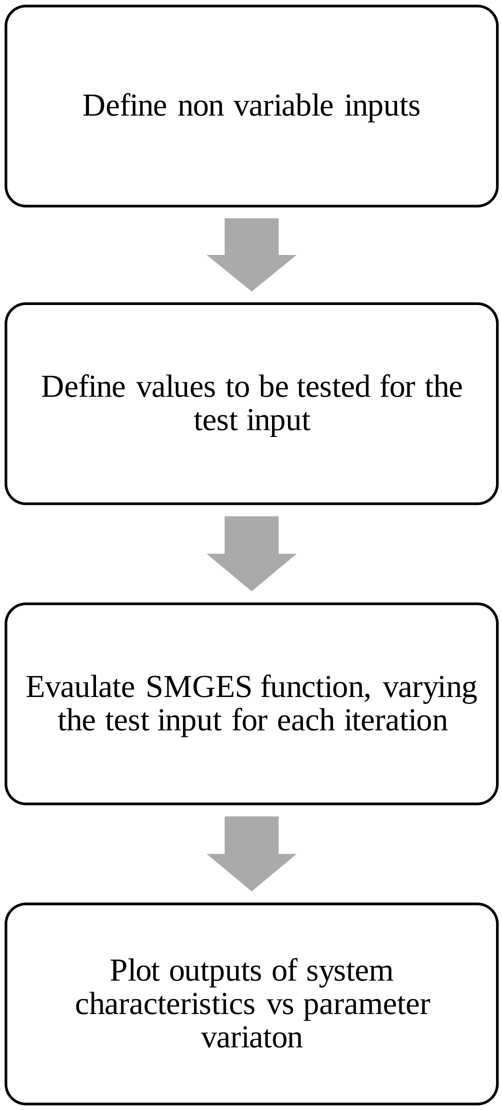

Figure 21: Schematic diagram of the sensitivity analysis process.

To define the values of the variable parameter, an array of values is created. To evaluate the SMGES function for the different configurations, a 'for' loop is performed, storing the outputs for each variation of the variable in the array.

6.1.1 Base case model used in sensitivity analysis

The model was selected based on the understanding of the system characteristics discovered when developing and checking the model. The characteristics were chosen to suit the strengths of the SMGES technology, within the bounds of a suitable application. The characteristics were chosen to fall within the range suitable for grid power area-regulation, as this was identified as an application with requirements in line with the strengths of SMGES. The characteristics of the chosen system are shown in Table 3.

Table 3: The system requirements of the base case model used in the sensitivity analysis.

Parameter	**Value**
Energy storage capacity	3 MWh
Power capacity	20 MW
Response time	5 s
Drum-to-cable diameter ratio	32
Cable safety factor	5.0
Winch efficiency	85%
Winch drum width-diameter ratio	2

As shown in Table 3, the base case model was chosen to have a high rated power in comparison to the energy storage capacity. This was selected based on knowledge gained about the nature of the modelled system; which appeared to be suited to high power applications with relatively low energy storage capacity.

6.2 Sensitivity analysis results

The characteristics of the base case model used in the analysis are shown in Table 4.

Table 4: The characteristics of the base case model of the sensitivity analysis.

Parameter	**Value**
Mass	1295 tonnes
Shaft height	1000 m
Number of winches	16
Number of strands	64
Drop speed	1.85 m/s
Acceleration	0.370 m/s^2
Cable diameter	40 mm
Drum diameter	1.28 m
Peak winch torque	385 kNm
Round trip efficiency	72%

The base model system used in the sensitivity analysis was chosen to have a shaft height of 1000 m. To meet the energy storage capacity required, this would require a suspended mass of 1295 tonnes. This mass could be suspended from 16 winches with 64 cable strands, each with a diameter of 40 mm. Hence, pulleys providing a mechanical advantage factor of 4. The winches would require a drum diameter of 1.28 m. Therefore, the peak torque on each winch would be 385 kNm. To meet the power output of the system, a drop speed of 1.85 m/s would be required. To reach this drop speed in a response time of 5 s, the acceleration of the mass would be 0.37 m/s^2. For a winch efficiency of 85%, the system would have a round trip efficiency of 72%.

6.2.1 Varying shaft height

The first design factor which was varied in the sensitivity analysis was the shaft height. Figure 22 shows how the suspended mass required and the drop speed vary with the shaft height.

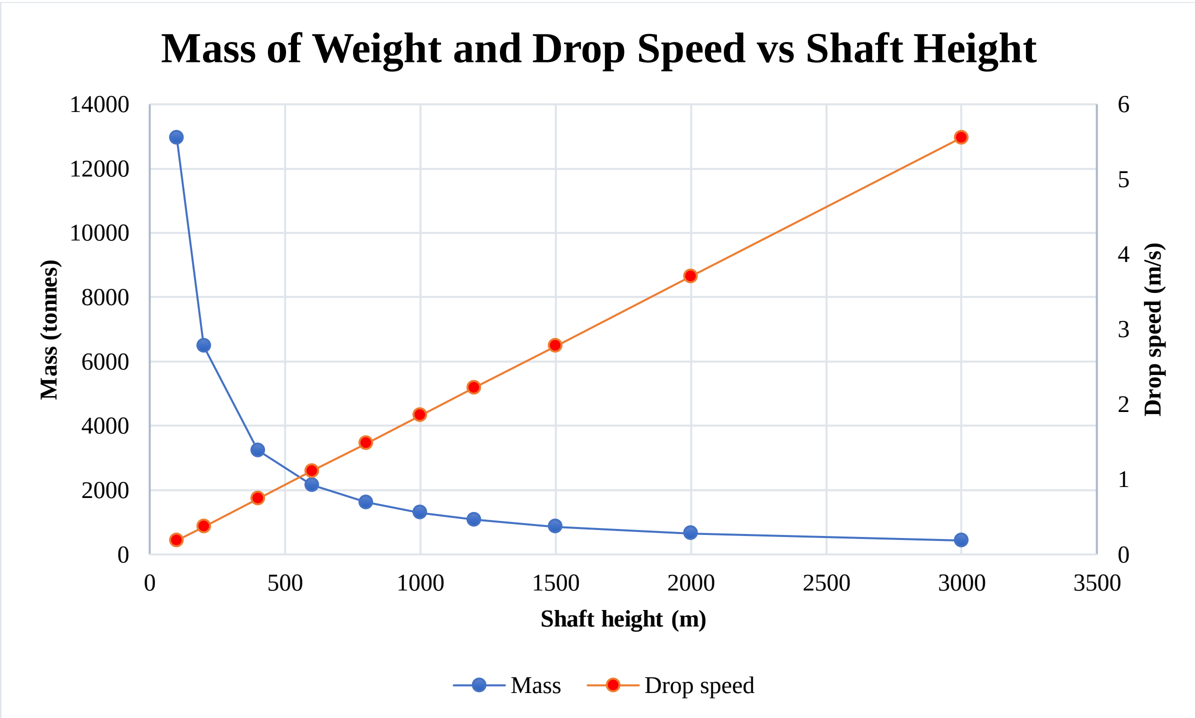

Figure 22: Plot showing how the required mass and the drop speed vary with the shaft height.

As can be seen in Figure 22, the mass required to store a given quantity of energy varies as a hyperbola with shaft height. This is because energy is a function of the product of height and mass. Therefore, mass is a function of energy divided by height. Where the energy stored is fixed, mass is a function of shaft height to the power of negative 1. Therefore, the rate at which the required mass decreases as a function of shaft height, decreases with increasing shaft height.

The drop speed required to meet the specified power output of the system increases linearly with the shaft height of the system. This result can be understood by algebraically manipulating the equation used to calculate the drop speed in the system model. The drop speed in the model was calculated by:

$$v_{drop} = \frac{P}{\eta_w m g}$$

By substituting in the equation used to calculate the mass, the formula can be rearranged as follows:

$$v_{drop} = \frac{P}{\eta_w \frac{E}{\eta_w g h_s} g} = \frac{P h_s}{E}$$

As the required power and energy of the system do not vary with the height of the shaft, the drop speed of the mass is directly proportional to the height of the shaft. As a result, the acceleration of the mass is also directly proportional to the shaft height. This can be seen in Figure 23.

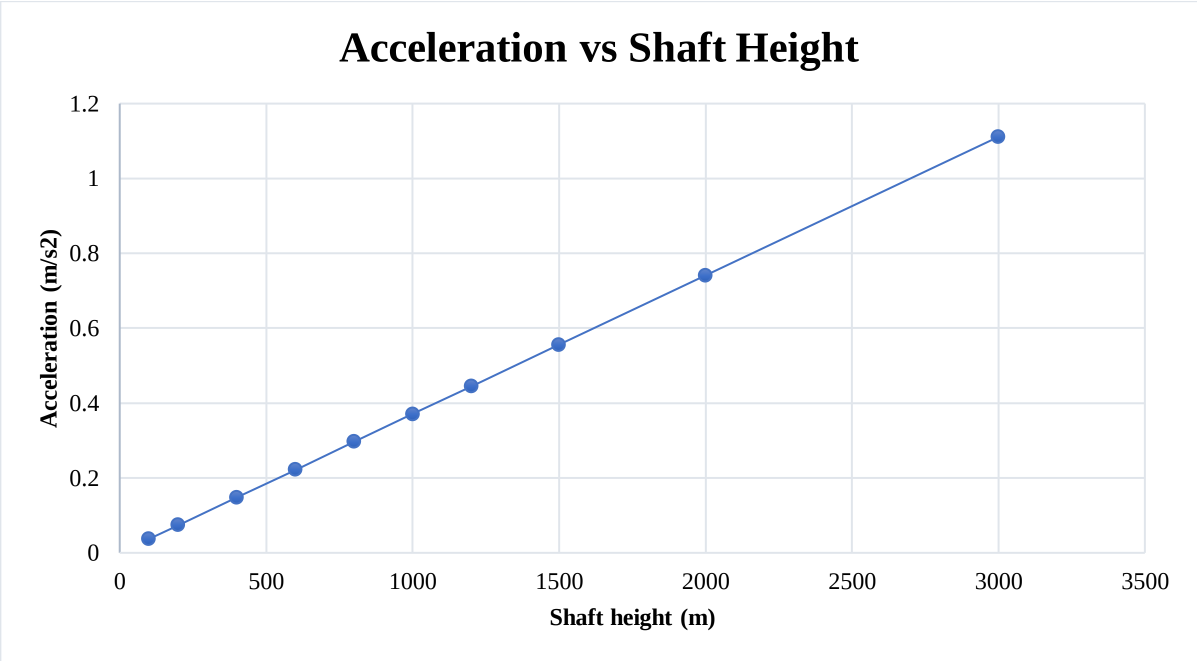

Figure 23: Plot showing how the acceleration of the mass changes with shaft height.

The acceleration of the weight is calculated by dividing the drop speed of the weight by the response time of the system. Hence, if the response time of the system does not vary with the height of the shaft, the acceleration is also directly proportional to the shaft height.

Figure 24 shows that the cable diameter and drum diameter vary close to a hyperbola with respect to the shaft height. This shows that the dominant parameter in determining the cable diameter is the mass. The points do not strictly lie on a hyperbola as the cable diameter is rounded up to the nearest integer.

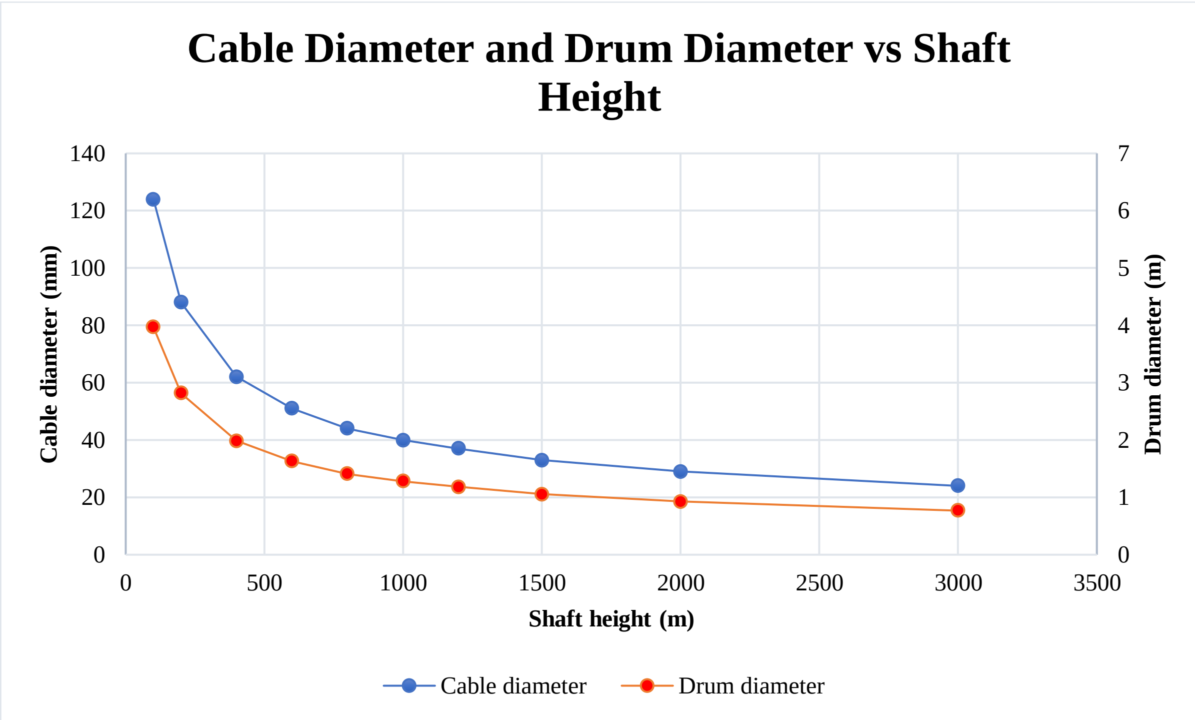

Figure 24: Plot showing the variation of the required cable diameter and drum diameter with shaft height.

It can be seen in Figure 24 that the traces of each series follow the same form. This was expected, as the drum diameter is directly proportional to the cable diameter in the model. In this example, the drum diameter is 32 times that of the cable.

It can also be seen in Figure 24 that for a shaft height of 200 m, a cable diameter of 88 mm is required. This is greater than the largest cable diameter of 70 mm supplied by the manufacturer for this grade of wire rope. However, for a shaft height of 400 m, the required wire rope diameter is 62 mm. This is within the range of cable diameter's manufactured for this type of rope.

The variation of the peak winch torque as a function of the shaft height is shown in Figure 25.

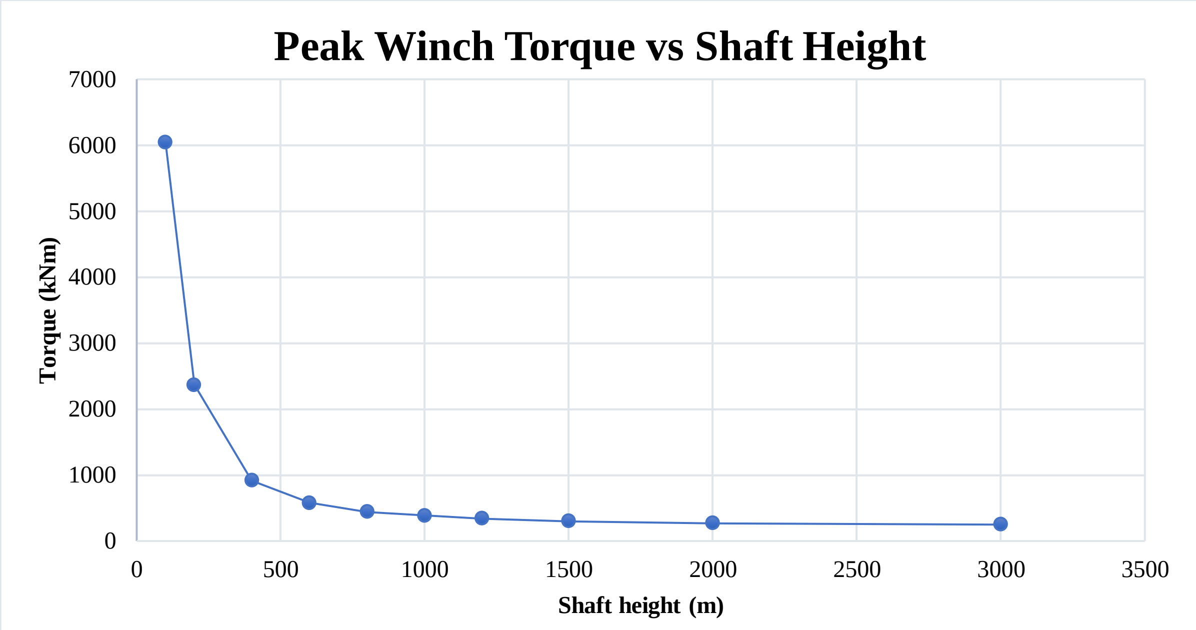

Figure 25: Plot displaying the change in peak winch torque with shaft height.

As with the cable diameter, the peak torque on the drum follows a somewhat hyperbolic shape with respect to the shaft height. For small shaft heights, the torque is extremely high. This is caused by the heavy mass, which requires cables with a large diameter, this in turn requires a large drum diameter. Torque is the product of a force and the perpendicular distance between its line of action and the pivot. Hence, the cable tension is high, which compounds with the large radius at which it acts, resulting in a high torque on the drum.

The trace which the points follow is not strictly a hyperbola as there are additional factors which determine the maximum torque on the winch. For example, as the height of the shaft increases, so too does the drop velocity, as shown in Figure 22. Consequently, the acceleration required to meet the response time of the system also increases. This increases the force required to accelerate the mass relative to the weight. This combined with a longer cable length, which causes the outer diameter of the fully wound winch to be large as there are more layers, this can cause the peak torque on the drum to reach a minimum and begin to increase as the shaft height increases further.

6.2.1 Varying cable safety factor

For the sensitivity analysis to the wire rope safety factor, the mass, drop speed, and acceleration were unaffected. This is because these values are calculated prior to the cable sizing and are not dependent on it. In the system model, the first aspect which the cable safety factor affects is the diameter of the cable, followed by the drum diameter, as shown in Figure 26.

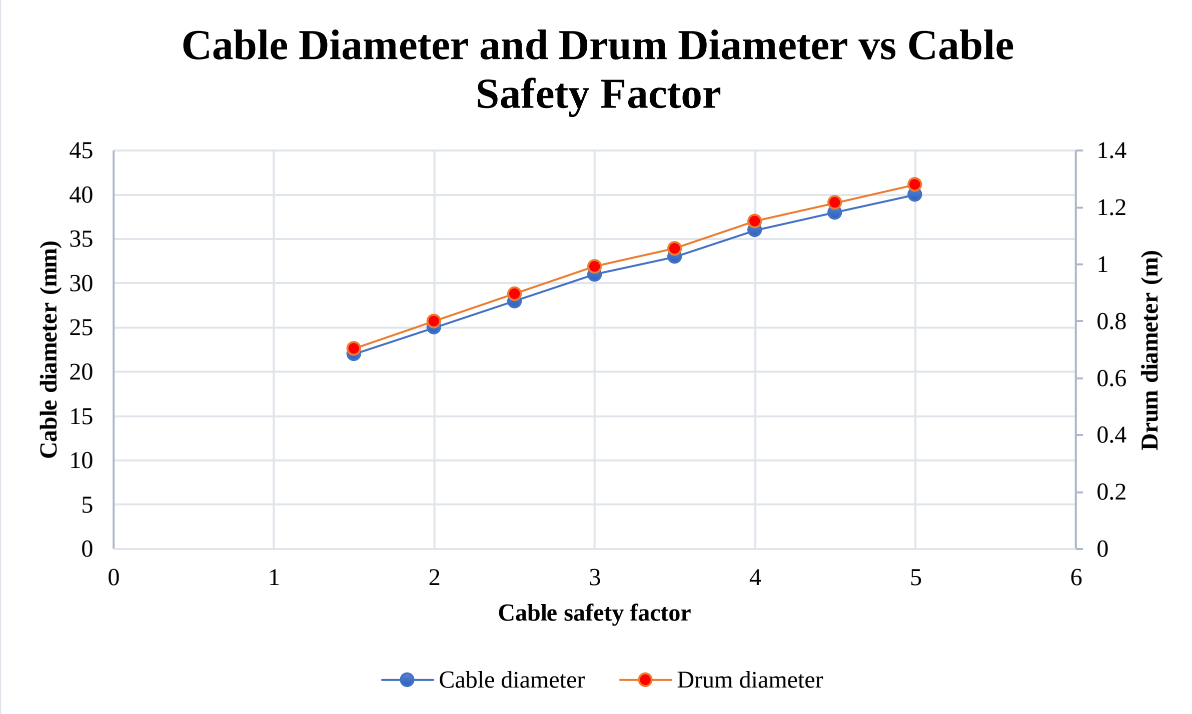

Figure 26: Plot showing how varying the cable safety factor affects the cable diameter and drum diameter.

Figure 26 shows that both the cable diameter and drum diameter increase as the safety factor increases. At the base case safety factor of 5, the required cable diameter is 40 mm, whereas, for half that safety factor, or 2.5, the required cable diameter is 28 mm. At the lowest safety factor tested, 1.5, the required cable diameter is 22 mm. The drum diameter exactly follows the trend of the cable diameter, as they are directly proportional.

The curvature of the cable diameter line in Figure 26 is not obvious, partly due to the rounding up of the required diameter to the nearest integer. The tensile strength of wire rope is broadly proportional to the cross-sectional area of the rope – with the exception of variance due to strand construction. The cross-sectional area of the wire rope is approximately proportional to the diameter of the rope squared. Conversely, the diameter of the rope is roughly proportional to the square of the cross-sectional area. Increasing the safety factor increases the required tensile strength of the rope proportionately. Hence, the cable diameter required is proportional to the square of the cable safety factor.

Increasing the cable safety factor also increases the torque placed on the winch, as shown in Figure 27. At a safety factor of 2.5, the peak torque on the drum is 385 kNm, whereas for a safety factor of 2.5 the peak torque is 305 kNm. The most significant cause of this increase is the increase in drum diameter. As the drum diameter increases, so does the distance at which the tension acts from the drum pivot, thereby increasing the torque.

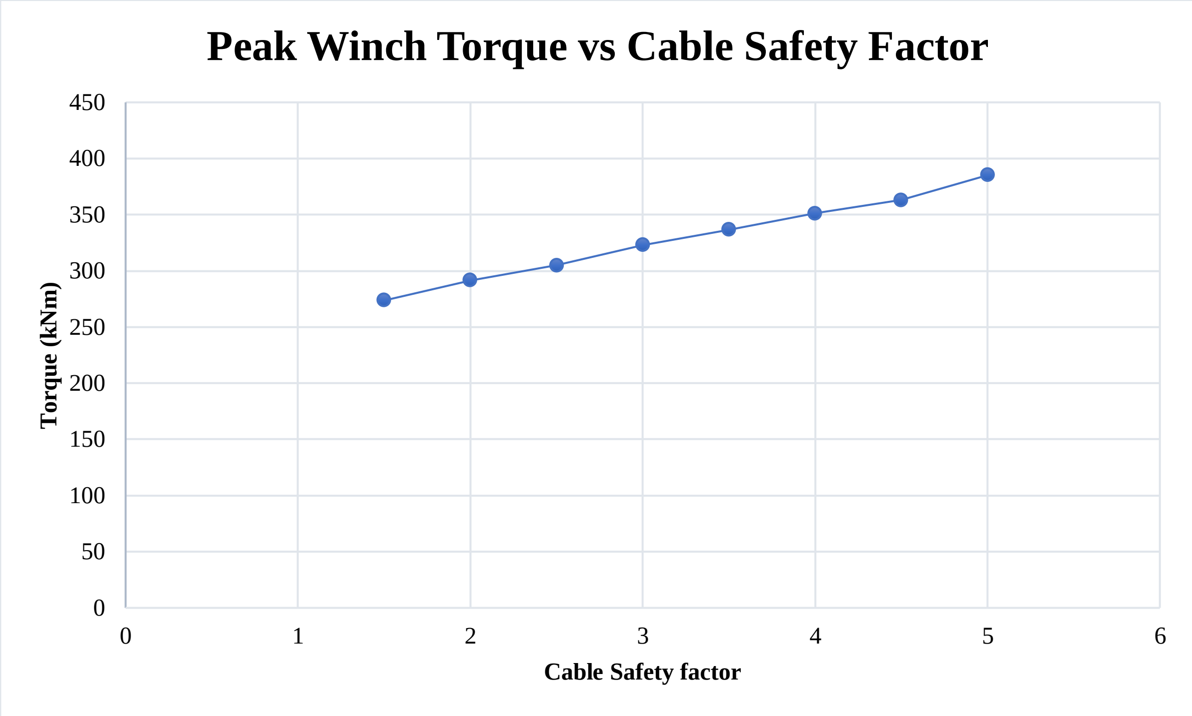

Figure 27: Plot showing how varying the cable safety factor changes the peak winch torque.

As can be seen in Figure 27, the line through the points does not follow an obvious trend. This is because there are a number of factors which influence the torque on the winch. As the safety factor increases, so too does the cross-sectional area of the cable, hence, the weight of the cable increases proportionally. Therefore, the tension in the cable increases slightly due to its own weight. Another aspect which affects the trend is the number of layers of cable on the drum when fully wound. As the drum diameter increases with the cable safety factor, so too does the circumference of the drum. Therefore, the number of layers required to completely raise the mass is less. If all other parameters were equal, fewer layers would reduce the torque on the drum. However, due to the increased cable diameter, the thickness of each layer of cable on the drum is greater, somewhat counteracting the effect of fewer layers.

6.2.2 Varying winch efficiency

Figure 28 shows the effects which increasing the efficiency of the winch would have on the mass required and the drop speed of the weight.

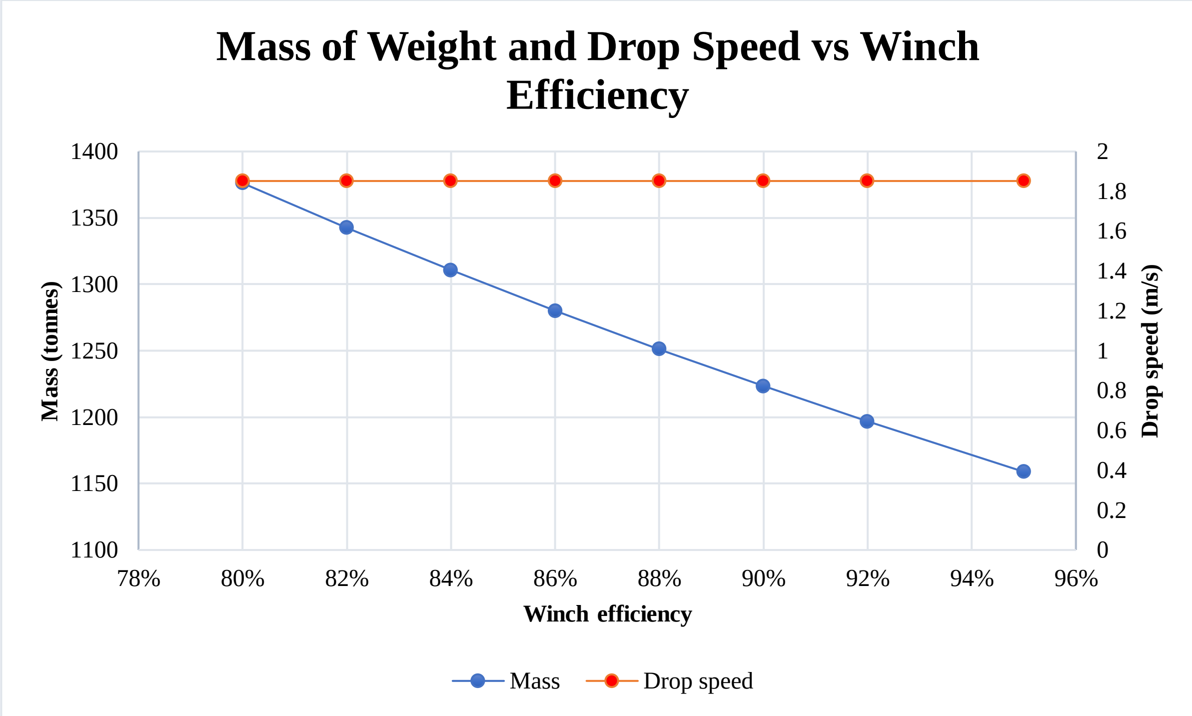

Figure 28: Plot showing how the winch efficiency affects the mass and drop speed required of the system.

As can be seen in Figure 28, as the winch efficiency improves, the mass required to meet the specified energy storage capacity decreases. For an efficiency of 80%, a mass of 1380 tonnes is required. For an efficiency value of 95%, the required mass is 1160 tonnes. Although the curvature in the line is not obvious, the mass does not vary linearly with the winch efficiency. Rather, the mass varies as a hyperbola with the winch efficiency. This is shown by the equation used to calculate the mass in the model:

$$m = \frac{E}{\eta_w g h_s}$$

If the achievable efficiency was less than those values tested, the mass required would increase at a greater rate as the efficiency is reduced. It should be noted that only the output, or generating, efficiency affects the required mass to provide a specified output quantity of energy. If the take-up and let-out efficiencies of the winches were different, the take-up efficiency would affect the amount of energy required to raise the mass, but not the energy which could be discharged once the mass is raised.

Figure 28 also shows that the required drop velocity does not vary with a change in winch efficiency, even though a winch efficiency term is present in the equation used to calculate the drop speed. This can be explained by manipulating the equation used to calculate the drop speed in the model.

$$v_{drop} = \frac{P}{\eta_w mg} = \frac{P}{\eta_w \frac{E}{\eta_w g h_s} g} = \frac{P h_s}{E}$$

The manipulation shows that by substituting in the equation used to calculate the mass, the winch efficiency term is cancelled out. Therefore, the drop speed is independent of the winch efficiency. The drop speed does not vary, as when the winch efficiency increases – which would result in the velocity decreasing proportionally, if all other parameters were kept constant – the mass decreases proportionally. If the mass were to decrease without a change in efficiency, the drop speed would have to increase to produce the same power. Hence, these two effects balance exactly, and the drop speed is constant with respect to winch efficiency. As a result, the required acceleration of the mass is also constant.

Since the mass required reduces as the efficiency of the winches increases, the required cable diameter decreases, as shown in Figure 29.

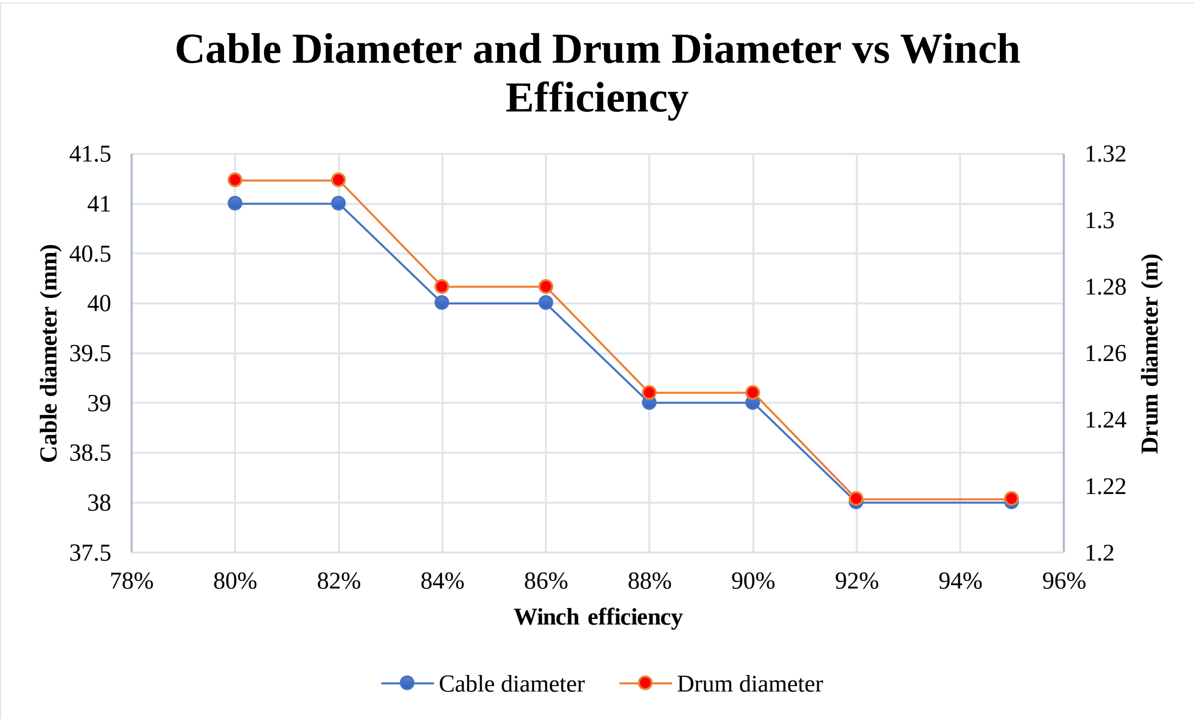

Figure 29: Plot showing how the cable diameter and drum diameter vary with the winch efficiency.

Figure 29 shows how the cable diameter and drum diameter reduce in a discontinuous fashion with respect to winch efficiency. This is a result of the rounding up of the cable diameter to the nearest millimetre integer. The stepped nature of the plots is more apparent in Figure 29, than other plots of the cable and drum diameters due to the relatively small variation in the cable diameter over the range of efficiencies tested. For a winch efficiency of 80%, the required cable diameter is 41 mm. At a winch efficiency of 95%, the cable diameter is 3 mm less, at 38 mm. Were the cable diameter not rounded up, the trend would follow the shape of the mass as a function of winch efficiency.

The effect of increasing the efficiency of the winch on its peak torque, is shown in Figure 30.

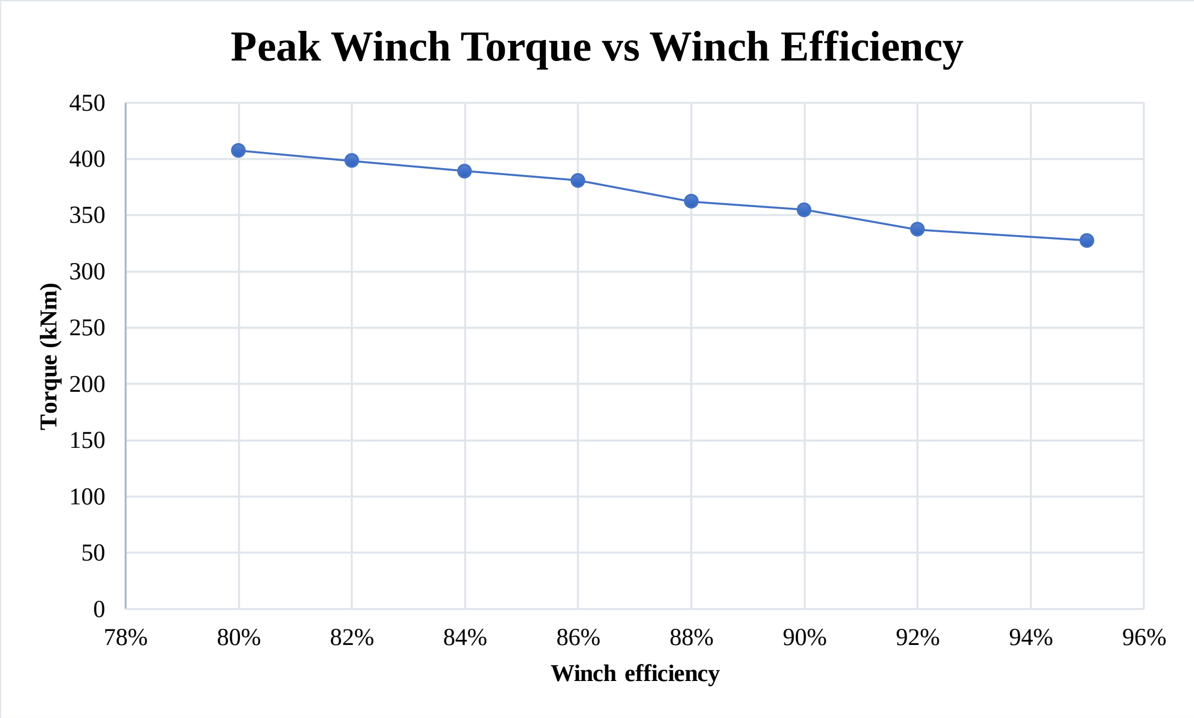

Figure 30: Plot showing the affect which the winch efficiency has on the peak winch torque.

As can be seen, the winch torque decreases as the winch efficiency increases. The torque is reduced from 408 kNm at an efficiency of 80%, to 328 kNm at an efficiency of 95%. The main factor in the trend of the winch torque is the mass of the weight. However, the trend is also affected by the variance of the winch drum diameter as a function of cable thickness. This in turn, and in conjunction with cable thickness, affects the winding of the drum.

6.2.3 Varying drum-to-cable diameter ratio

Of the key performance indicators considered, varying the drum-to-cable diameter ratio only affects the winch drum diameter and the peak winch torque. This is because the other characteristics are calculated prior to the drum diameter, and therefore are unaffected by it. The effects of varying the drum-to-cable diameter ratio on the drum diameter and the peak winch torque are shown in Figure 31.

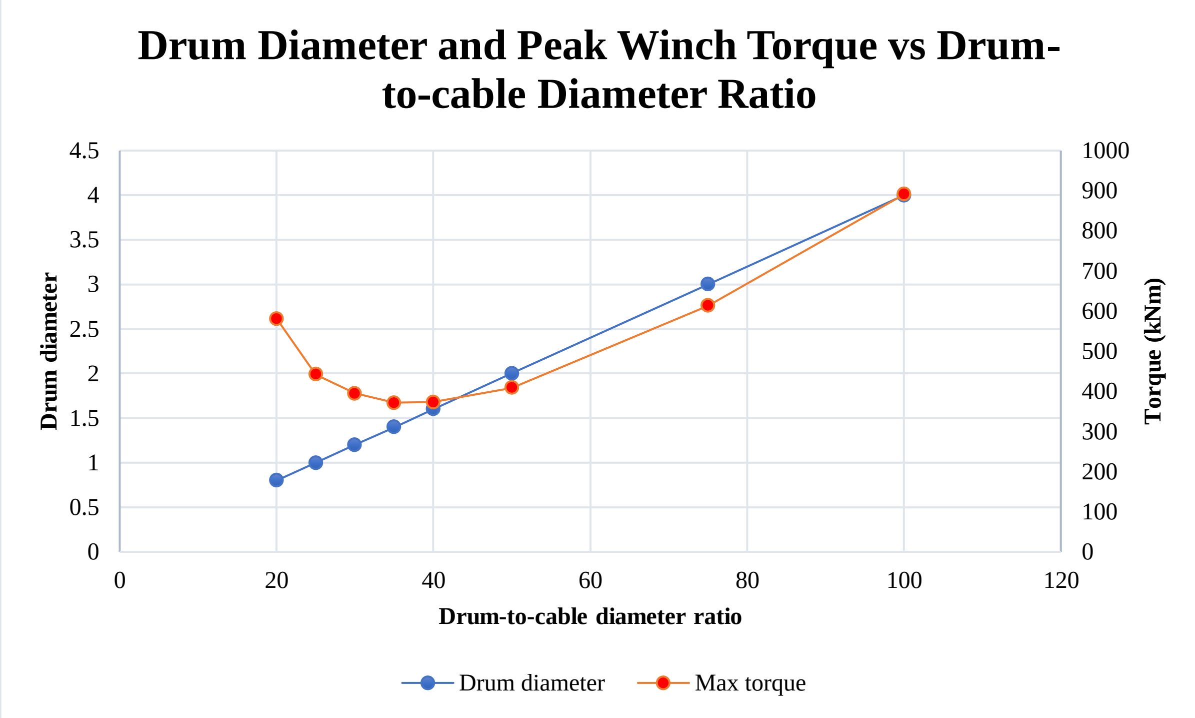

Figure 31: graph displaying how the drum-to-cable diameter ratio affects the diameter of the drum and the peak torque on the winches.

As can be seen in Figure 31, the drum diameter increases linearly as the drum-to-cable ratio is increased. At a drum-to-cable diameter ratio of 20, the drum diameter is 0.8 m, while at a ratio of 50, the drum diameter would be 2 m. Hence, if a drum-to-cable ratio of 100 was required, the drum diameter would be 4 m. This result expected as the drum diameter is simply calculated by multiplying the cable diameter by the drum-to-cable diameter ratio. Therefore, for a fixed cable diameter, as the drum-to-cable diameter ratio is varied, the drum diameter varies proportionally.

The peak winch torque does not follow the same linear trend as the drum diameter when the drum-to-cable diameter ratio is varied. At low drum-to-cable diameter ratios, the peak winch torque decreases as the drum-to-cable diameter ratio increases. However, at high drum-to-cable diameter ratios, the peak winch torque increases with the ratio. At a drum-to-cable diameter ratio of 20, the peak winch torque is 581 kNm, while for a ratio of 100, the torque is 891 kNm. Of the drum-to-cable diameter ratios tested, the minimum peak winch torque occurs at a ratio of 35. The torque at this ratio was 371 kNm, while the second lowest torque value occurs at a ratio of 40. These results show that a drum-to-cable diameter ratio could be determined to minimise the winch torque.

The cause of this trend is the effect which the increasing drum diameter has on the winding, and therefore radius at which the tension acts on the drum. When the drum-to-cable diameter ratio is low, the circumference is relatively small, and therefore more layers of cable are required to raise the mass. For drum-to-cable ratios below approximately 35, the greater number of layers causes the outer layer diameter to be larger than for cases where the drum is slightly larger but has fewer layers wound on to it. However, above a drum-to-cable diameter ratio of approximately 40, the increase in the diameter of the drum is more significant than the decreased diameter as a result of fewer layers, and the torque increases with an increasing drum-to-cable diameter ratio. This result is not immediately obvious when thinking of the system, however, it shows that a smaller drum diameter is not always desirable when designing for minimum winch torque.

6.2.4 Varying number of winches and strands

Changing the number of winches, and proportionally the number of strands, does not affect the mass, drop speed, or acceleration required. The effects of varying the number of winches and strands on the cable diameter and drum diameter are shown in Figure 32.

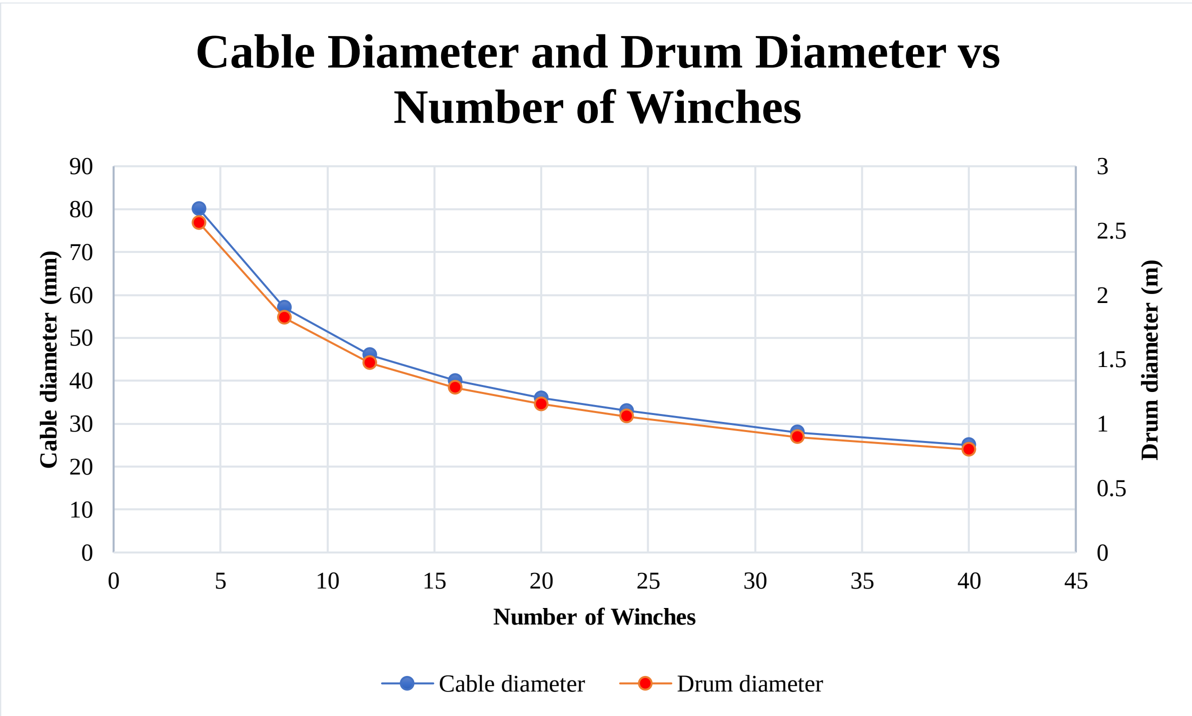

Figure 32: Plot showing how the number of winches and strands affects the required cable diameter and drum diameter.

Figure 32 shows that both the cable diameter and winch drum diameter decrease as the number of winches and cables increase. For 4 winches, a cable diameter of 80 mm is required with a winch diameter of 2.56 m. These are twice the cable and drum diameters required compared to the base case scenario with 16 winches. For 40 winches, which results in 160 cable strands, the required cable diameter is 25 mm, and the winch drum diameter is 0.8 m. The cable and drum diameters follow a hyperbolic trend with respect to the number of winches and strands.

The effect which varying the number of winches has on the peak winch torque is illustrated in Figure 33.

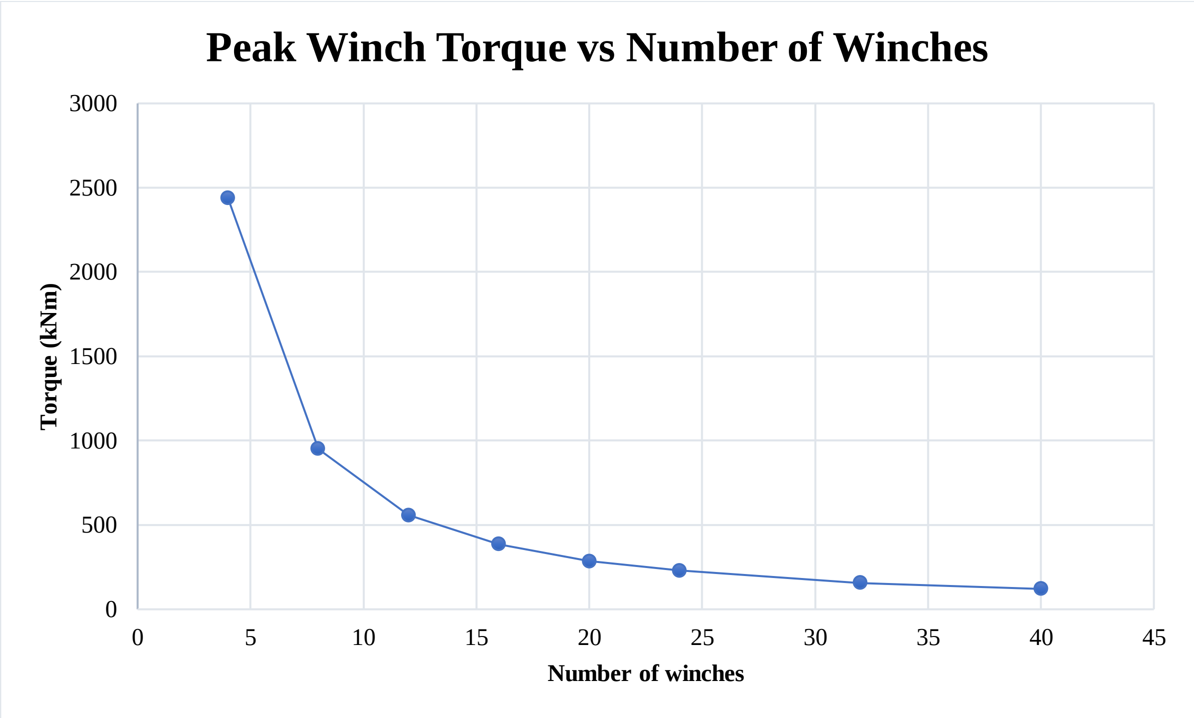

Figure 33: Plot showing how varying the number of winches impacts the torque on each winch.

As shown in Figure 33, when the number of winches is low, the peak winch torque reduces significantly as the number of winches increases. For 4 winches and 16 cable strands, the peak winch torque is 2440 kNm. For 8 winches and 32 strands, the peak winch torque is reduced to 950 kNm. As the number of winches increases, the incremental decrease in torque reduces. For 16 winches, the peak torque is 385 kNm while for 40 winches, the torque is 121 kNm.

The shape of the trend is caused by the torque being a function of the product of cable tension and the radius of its line of action. As the number of winches is increased, the cable tension and the drum diameter both reduce. Hence, the product of these compounds decreases, meaning the peak winch torque is sensitive to the number of winches and strands.

6.2.5 Varying response time

Reducing the response time of the system requires the weight to be brought to the peak drop speed, and stopped, faster. Therefore, the required acceleration of the weight is greater. The trend of the acceleration as a function of response time is shown in Figure 34, along with the required cable diameter. It should be noted that Figure 34 uses a logarithmic scale on the x-axis to better illustrate the trend over a wide range of response times.

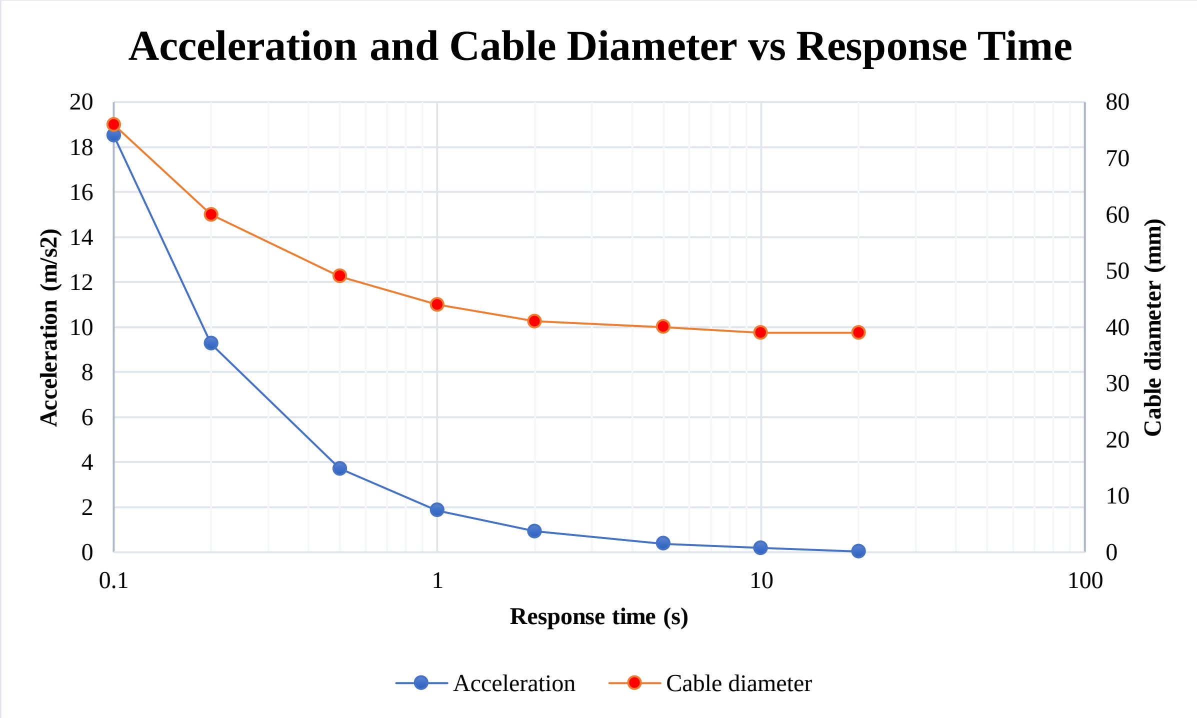

Figure 34: Graph showing how the acceleration of the mass and the cable diameter are affected by the response time.

Figure 34 shows that the required acceleration of the weight reduces as the response time increases. For a response time of 0.1 s, the required acceleration is 18.5 m/s^2; this is nearly twice the acceleration due to gravity. Therefore, this acceleration could not be achieved by gravity alone. For a response time of 0.2 s, the required acceleration is 9.3 m/s^2, which is slightly below the acceleration due to gravity. This acceleration rate may be physically achievable for the weight; however, other system factors would need to be considered, such as slack in the cables. For a response time of 0.5 s, the acceleration required is 3.7 m/s^2. The acceleration of the mass is a hyperbola with respect to response time, as acceleration is calculated by:

$$a = \frac{v_{drop}}{t_{response}}$$

The required cable diameter also reduces as the response time increases. This is because in the model, the stopping response time is considered to be equal to the start-up response time. Therefore, to stop the weight faster, a greater resultant force must act on the weight. Figure 34 shows that below a response time of approximately 2 s, the response time plays a significant role in determining the rope diameter. For a response time of 0.1 seconds, the required cable diameter is 76 mm. At a response time of 1 s, the required cable diameter is 44 mm. The cable diameter is required cable diameter is 41 mm for a response time of 2 s. After this point, the response time has a small effect on the cable diameter. For a response time of 20 s, the cable diameter is 39 mm, only 2 mm less that for 2 s.

The reason that the response time has a significant impact on the cable diameter for fast response times, but a small impact as the response time increases, is due to the significance of the force required to accelerate/decelerate the mass, compared to the weight of the mass itself. For a response time of 0.1 s, the acceleration of the mass is 18.5 m/s^2; close to double the acceleration due to gravity. The resultant force required to cause an acceleration twice that of gravity, is twice the weight. Hence, for the cables to slow the mass travelling down the shaft at the peak velocity, the sum of the cables' tensions must be close to triple the weight of the mass. This is because the force required to stop the falling mass, is equal to the resultant force required for the acceleration, added to the weight of the mass. From this it can be seen that when the response time is 10 s, the acceleration is 0.185 m/s^2, which is less than 2% of the acceleration due to gravity. Hence, adding this to the weight in order to slow the falling mass requires a cable tension of approximately 2% greater than when the mass is stationary.

The required drum diameter and peak winch torque follow similar trends to the required cable diameter as a function of response time. These can be seen in Figure 35.

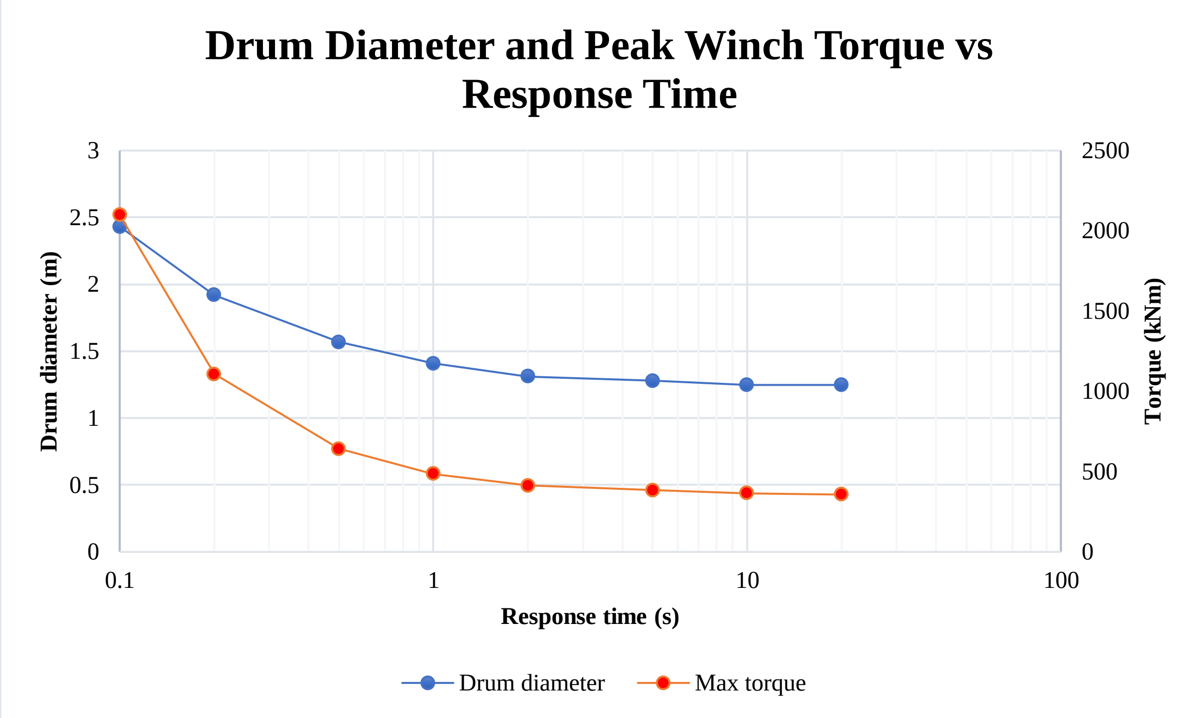

Figure 35: Plot displaying how the required response time affects the drum diameter and peak winch torque.

The drum diameter follows the exact same trend as the cable diameter, since it is directly proportional to it in the model. Hence, below a response time of approximately 2 s, the response time affects the drum diameter significantly.

The peak winch torque is also highly dependent on the response time of the system, below response times of 2 s. For a response time of 0.1 s, the peak winch torque is 2100 kNm. This reduces to 1110 kNm for a response time of 0.2 s, and 640 kNm for a response time of 0.5 kNm. For a response time of 1 s, the peak winch torque is 490 kNm. The effect which varying the response time has on the peak winch torque is even more significant than for other parameters, as the peak winch torque is a function of the product between the diameter and the cable tension. Increasing the cable tension increases the torque, but it also results in a larger drum diameter, which further causes the winch torque to increase.

7. Test Case Scenarios

7.1 Test case scenarios assessment procedure

In order to gauge the characteristics of SMGES technology if it was to be used in real world applications, a number of realistic test cases were considered. The chosen test cases were defined by the energy storage capacity, required power, and response time. The test cases to be examined are shown in Table 5.

Table 5: Description of the required specifications of the test case scenarios used.

Test case scenario	Energy capacity (MWh)	Rated power (MW)	Response time (s)
Mobile-phone battery	10 Wh	5 W	0.1
Stadium supply	20	10 (Manni, et al., 2018)	5
Grid energy time shift	200	50	60
Voltage support	2.5	5	5
Area regulation	10	20	1
T&D upgrade deferral	2	0.5	60
Supply reserve capacity	100	100	10

The cases were chosen by reviewing the required power and duration for various applications found in the literature. Applications with a range of power to energy storage ratios and response times were then selected. Some of the test cases selected – such as the mobile phone battery – may not be feasible for alternative reasons, however, the purpose of various test cases is to determine the relative strengths and weaknesses of the technology. Hence, a variety of applications were chosen.

To select the specifications of each scenario, the number of strands and number of winches were first selected. The MATLAB script used in the sensitivity analysis was then run for a series of different heights. If the specifications of the system were not suitable, the number of winches and strands were adjusted, and the script rerun. A suitable configuration was chosen based on engineering judgement and the following general guidelines:

1. Feasible shaft height – the deepest disused mine shafts in the United Kingdom are likely to be around 1500 m. Therefore, where reasonable, the height of the shaft was chosen to be at or below this depth.
2. Choose the number of winches and strands such that the cable diameter was reasonable – the maximum diameter of the sample cable was 70 mm. Therefore, the configuration was chosen to keep the specified diameter below this.
3. Minimise peak winch torque where possible – a higher winch torque would require a greater torque reduction ratio, or an electric motor rated to a higher torque. This would increase the costs of the winches and may be less efficient.

As shown in the sensitivity analysis section, the design parameters of SMGES tend to conflict. Therefore, no single configuration is objectively the best. If the system were to be developed in practice, the configuration which has the lowest cost would likely be chosen. However, without an accurate cost model, this could not be determined.

7.2 Results of test case scenarios

A summary of the system specifications for the test cases examined, is shown in Table 6. From the specifications shown, it is noticeable how physically large the systems would be.

Table 6: Description of the modelled system configurations for the test case scenarios.

	Mobile phone battery	**Football stadium**	**Voltage support**	**Area regulation**	**T&D upgrade deferral**	**Supply reserve capacity**
Energy capacity (MWh)	10 Wh	20	2.5	10	2	100
Power capacity (MW)	5 W	10	5	20	0.5	100
Response time (s)	0.1	5	5	1	60	60

Shaft height (m)	25	1500	1500	1200	1200	3000
Suspended mass (tonnes)	0.173	5750	720	3600	720	14,400
Number of winches	1	32	16	20	20	60
Number of strands	2	128	32	80	40	240
Cable diameter (mm)	2	58	41	61	37	67
Drum diameter (m)	0.064	1.86	1.31	1.95	1.18	2.14
Drop speed (m/s)	0.0035	0.21	0.83	0.67	0.083	0.83
Winch torque (kNm)	0.054	1760	500	1690	320	4130

As can be seen in Table 6, SMGES would require significant infrastructure per unit of energy stored. The mobile phone battery example effectively highlights this concern. Although considering SMGES for such an application is impractical for other reasons, the comparison gives a tangible sense of the space and convenience difference between lithium-ion batteries and SMGES systems.

The mobile phone battery considered weighs 41 grams and has a volume of approximately 17,000 mm^3 (1.7×10^{-5} m^3) (Apple Inc., 2019). In comparison, the modelled SMGES system required a mass of 173 kg, with a vertical drop range of 25 m. For a steel weight, this is a volume of 0.022 m^3 which represents a cylinder with a diameter of 0.24 m and a height of 0.48 m. Therefore, the volume of the shaft for such a system would be at least 1.2 m^3; this is more than 70,000 times the volume of the lithium ion battery.

A positive characteristic of the SMGES system is highlighted by the mobile phone battery scenario; this is the power capacity of the system. To meet the peak power rating of the mobile phone battery, the weight of the SMGES would have to drop at a rate of 3.5 mm/s. To reach this speed within the nominal response time of 0.1 s, an acceleration rate of 0.035 m/s^2 is required. In an ideal system, the mass could be accelerated by gravity at 9.8 m/s^2. In a real system there would be additional constraints, however, a response time two orders of magnitude shorter, should be achievable for the power output. This suggests that the SMGES system would be better suited to applications with a high power to energy capacity ratio.

For the grid scale applications, Figure 36 puts the height and mass of the weight of the required systems in perspective. Figure 36 compares the height of the shafts to the height of the Burj Khalifa, the tallest building in the world, and the masses to that of an Airbus A380, the largest commercial aeroplane. The Burj Khalifa is 831 m tall, while the maximum take-off mass of an Airbus A380 is 560 tonnes.

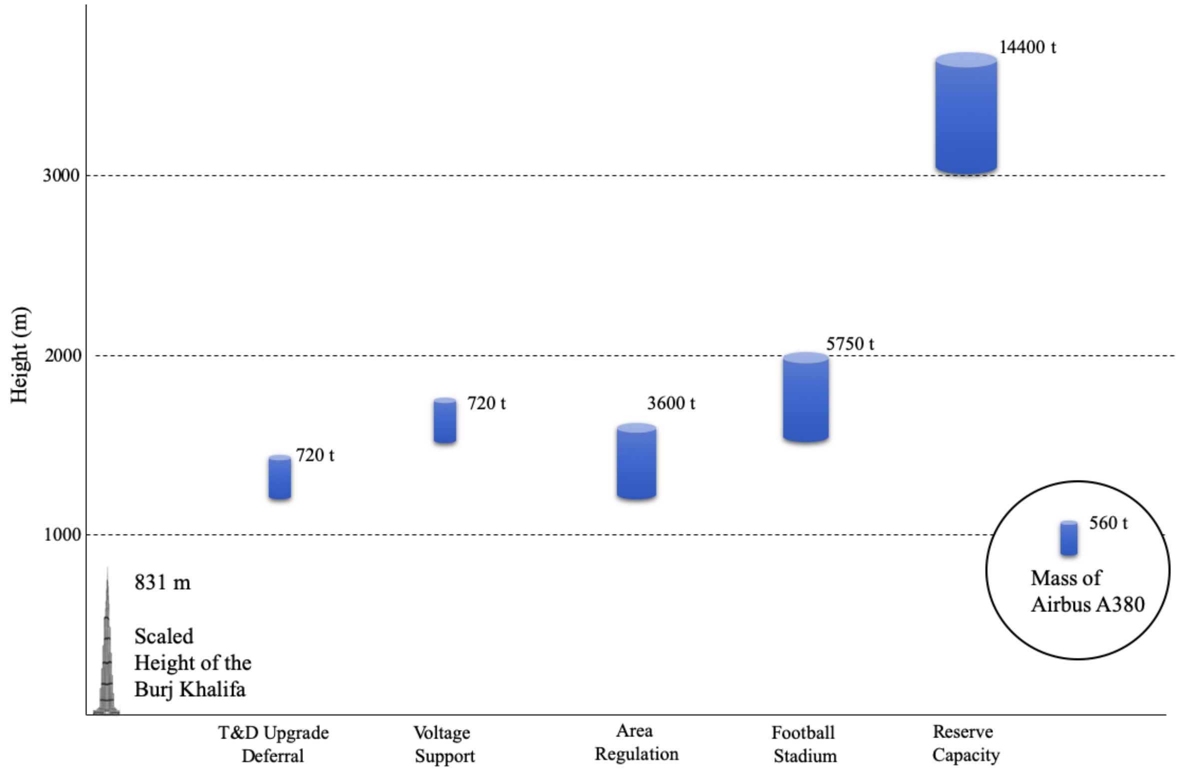

Figure 36: Diagram displaying the mass and the shaft height in comparison to the mass of a fully loaded Airbus A380 and the Burj Khalifa[1].

[1] The size of the cylinders in the diagram are proportional by mass, to the reference cylinder of the Airbus A380. However, the height of each cylinder is not proportional to the height scale shown. The position of the bottom of each cylinder represents the shaft height, relative to the vertical axis scale. This is proportional to the scaled image of the Burj Khalifa.

The second situation in Table 6 shows the requirements for a SMGES system capable of powering a large football stadium for the duration of a match. For a shaft height of 1500 m, a depth which disused mineshafts may be available, the system would require a mass of 5750 tonnes. As shown in Figure 36, this shaft would be 1.8 times the height of the Burj Khalifa, while the suspended mass would be more than 10 times the mass of a fully loaded Airbus A380.

If the weight for the football stadium example was a solid steel cylinder, it could have a diameter of 7.8 m and a height of 15.5 m. However, a weight this large may rather be made of a cheaper material which can be transported to the site more easily. For the weight to be manufactured from a concrete cylinder, it would have a diameter of 9.1 m and a height of 36.6 m. To support this mass while keeping the diameter of the cables feasible, would require 32 winches with pulleys reducing the cable tension by a factor of 4.

The requirements of the football stadium example could be achieved by using four 40 ft shipping containers of lithium-ion battery banks, such as those sold by LG Chem (LG Chem, 2018). These come ready to operate, with the cooling and power control systems integrated in the container. This bank would have a volume of approximately 270 m^3. Assuming the concrete cylinder could be suspended in a shaft with a diameter of 9.5 m, the shaft would have a volume of 106,000 m^3. This is more than 390 times the volume of the battery system.

The T&D upgrade deferral application using SMGES, would require a shaft 1200 m deep, for a mass weighing 720 tonnes. This is nearly 1.5 times the height of the Burj Khalifa with the mass approximately 1.3 times that of a fully loaded Airbus A380 aeroplane. If this weight was a concrete cylinder, it could have a diameter of 5.8 metres and a height of 11.5 m. For a solid steel cylinder, the diameter would be 3.9 m with a height of 7.8 m. This could be suspended from 20 winches, with pulleys giving a mechanical advantage factor of 2; hence, 40 strands of 40 mm in diameter. Assuming the mass was suspended in a shaft of 6.2 m in diameter, the volume of the shaft would be 36,000 m^3. Once again, a lithium-ion battery bank could be used for this application. A single 20 ft container battery bank could meet the requirements of this application. This would have a volume of 34 m^3; less than one thousandth of the volume of the SMGES system.

The area regulation and voltage support examples present somewhat more well-suited applications for SMGES. Both of these cases require relatively high power outputs, for less than an hour in duration. For a 1500 m deep shaft, the voltage support example would require a mass of 720 tonnes. For a mass of the same dimensions as the transmission and distribution example, the shaft would have a volume of 45,000 m^3. The mass could be suspended by 32 strands of 41 mm, connected to 16 winches. Each winch would require a diameter of 1.3 m. This configuration required the fastest drop speed of the examples tested, however, the speed is still below 1 m/s. Although the characteristics of this example are not ideally suited to lithium ion batteries, a single 40 ft container battery bank could likely fulfil this application. This would have a volume of 68 m^3. Therefore, the SMGES system would have a volume approximately 660 times greater than the lithium ion system.

For a shaft 1200 m deep, the area regulation example would require a mass of 3600 tonnes. This mass would have a diameter of 6.6 m and a height of 13.2 m if manufactured from steel. It would have a diameter and height of 7.8 m and 31.2 m respectively, if it was concrete with a diameter to height ratio of 1:4. This mass is roughly equivalent to the mass of 6.5 fully loaded Airbus A380 aeroplanes. For 20 winches with 80 strands, a cable diameter of 61 mm would likely be required. As a result, the winch drum would require a diameter of approximately 2 m. A noticeable result of this example is that even for a response time of 1 s, the required acceleration of the mass would be less than 1 m/s^2. This function could likely be achieved using four 40 ft containers of lithium ion batteries. For this case, the volume of the shaft for the SMGES system would be roughly 240 times that of the battery bank.

To provide supply reserve capacity to the scale modelled in the example, a SMGES would require a 14400-tonne mass in a shaft 3000 metres deep. There are no mine shafts this deep in the United Kingdom, although there are some to this depth in South Africa. This is more than 3.5 times the height of the Burj Khalifa, or equivalent to 30 football pitches laid end to end. The mass of this size would require a diameter of 12.4 m with a height of 49.6 m, if it was to be manufactured from concrete. To suspend this mass by cable with a diameter less than 70 mm would require 240 cable strands, and 60 winches. To implement this system in a shaft of depth available in the United Kingdom would require a mass of around 30000 tonnes, and thus was deemed unreasonable.

A notable result from the modelled scenarios was the low drop speed and acceleration for the systems to meet the peak power output specified. All of the modelled scenarios required drop speeds below 1 m/s. Therefore, for response times of 1 s, the maximum acceleration rate required is less than 1 m/s^2. As 1 m/s^2 is roughly one-tenth the acceleration due to gravity, this is well within what is theoretically possible. Therefore, for the given energy storage capacities and response times, the power output of the systems could likely be increased.

These results highlight the relative strengths and weaknesses of potential SMGES systems. The technology seems capable of achieving high power output and fast response rates. Conversely, the energy storage capacity of SMGES is a relative weakness. The results highlighted the physical scale of the SMGES systems required to meet the specifications. The volume and mass of the system are orders of magnitude greater than those of other storage technologies. This would significantly increase the logistical, engineering, and construction challenges of implementing a SMGES system.

7.3 Comparison between SMGES and lithium ion battery storage

7.3.1 Comparison of physical characteristics

A comparison of the SMGES technology was made compared to lithium ion battery storage. For the comparison, the base case model used for the sensitivity analysis was used. Hence, the system required an energy storage capacity of 3 MWh, a rated power of 20 MW, and a response time of 5 s. A summary of the specifications of the SMGES system is shown in Table 7.

Table 7: A summary of the SMGES system specifications for the direct comparison analysis with lithium ion batteries.

Parameter	**Value**
Energy	3 MWh
Power	20 MW
Response time	5 s
Shaft height	1000 m
Mass	1295 tonnes
Number of winches	16
Number of strands	64
Drop speed	1.85 m/s
Acceleration	0.370 m/s
Cable diameter	40 mm
Drum diameter	1.28 m
Peak winch torque	385 kNm
Round trip efficiency	72%

The energy and power of the system were chosen specifically to suit the characteristics of SMGES. From the test case scenarios and the sensitivity analysis, it was shown that SMGES is better suited to high power applications, with a discharge duration below 1 hour. These specifications fall within the suitable range for area regulation, and possibly for voltage support and short-term wind power integration.

A simplified schematic diagram of the cross section of the SMGES system used in the comparison, is shown in Figure 37.

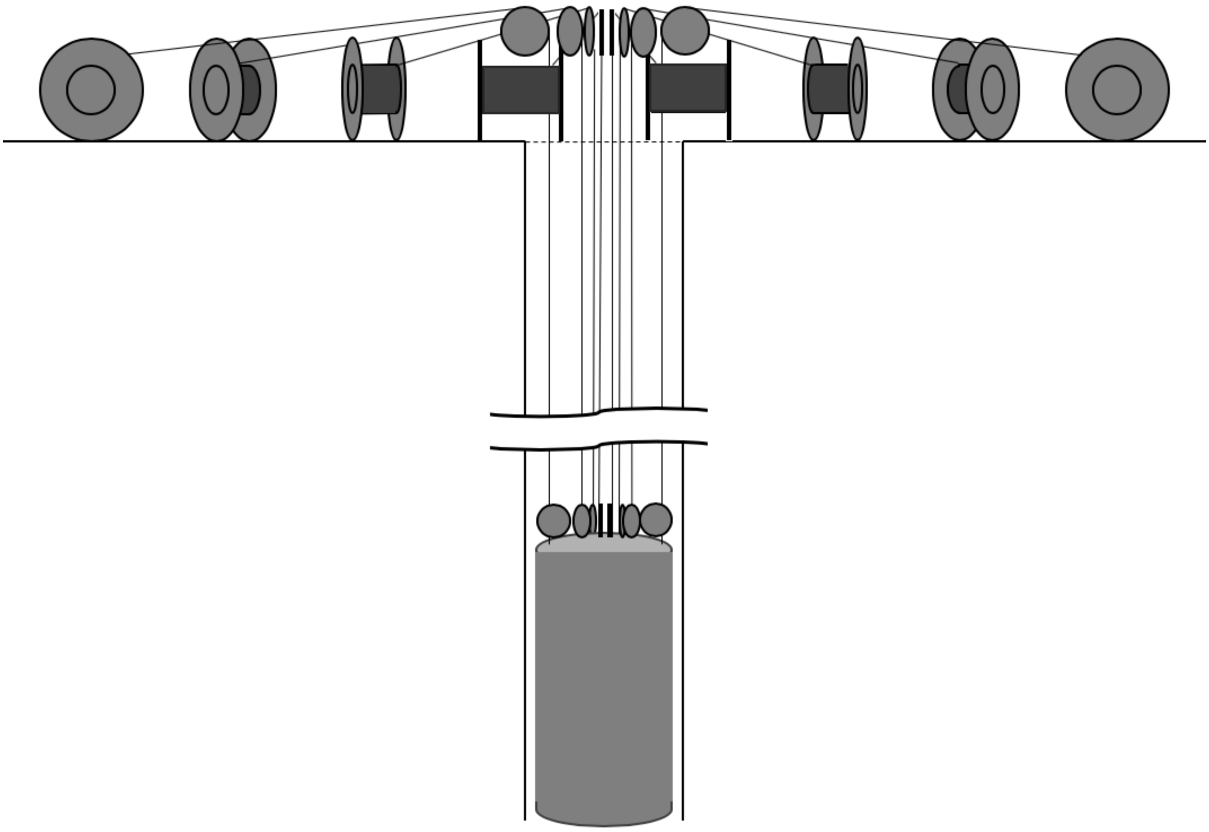

Figure 37: Simplified schematic of the SMGES system modelled in for the comparison between SMGES and lithium ion battery storage.

The diagram is not to scale, does not show any head gear or electrical equipment, and as it is a cross section it only shows 8 of the 16 winches in the system. The diagram also only displays 8 wire rope strands, in order to aid the clarity of the schematic. However, it can be seen that even a simplified schematic of the system, appears far more complex than the rendered images used in press release publications.

To compare the system to a suitable lithium ion battery system, the LG Chem 40ft HC ISO Container M48128P6B was considered. This is the 'High power' system, specifically designed for short duration applications of less than 1 hr (LG Chem, 2018). The rated usable energy storage capacity is 4.0 MWh. Therefore, rated power is greater than 4 MW. Hesse et al., note that for grid battery energy storage projects, power to energy capacity ratios are typically between 4:1 and 1:4 (Hesse, et al., 2017). Taking the largest typical power to energy ratio would suggest that the high-power LG Chem device could produce a peak power of 16 MW. However, for the purpose of this study, a more conservative power to energy capacity ratio of 2:1 was used. This indicates a peak power capacity for the system of 8 MW. This suggests that at full power output, the system would have a discharge duration of 30 minutes.

To meet the power capacity requirements of the example, 2.5 of the LG Chem battery systems would be required. For the purpose of this study, it was assumed that the characteristics of the device could be linearly scaled, hence, a container of half the length could provide 2 MWh of energy at 4 MW power output. The overall system would therefore be rated to store 10 MWh, with a peak power output of 20 MW. This is more than triple the required energy storage capacity. However, the lifespan of lithium ion batteries is improved for shallower depths of discharge (Hesse, et al., 2017). Therefore, excessively high energy storage capacity would only be an issue if it caused the cost of the system to be too high.

7.3.2 Cost comparison of the systems

It is difficult to accurately estimate the cost of the lithium ion battery system. The cost of lithium ion technology varies considerably from case to case. Furthermore, due to the significant recent investment in the development of lithium ion battery technology, the cost of batteries is reducing rapidly. According to a model developed by DNV GL, the average cost per kilowatt hour of lithium ion batteries was estimated to reduce from 500 US$/kWh in 2015 to 225 US$/kW in 2018 (DNV GL, 2016). According to IRENA (2017), the cost of installed lithium ion battery storage ranges between 200-840 US$/kWh. Based on a cost estimated by IRENA, the expected cost of the installed battery system would be between 2-8 million US Dollars.

Based on the cost of 40 mm cables being 15.00 euro/m, and the SMGES system designed requiring 64,000 m of cable, the cost of the cables required for the SMGES system would be approximately 960,000 Euros. At the time of writing, one Euro was equivalent to US$1.10. Therefore, the cables would cost approximately US$1,050,000.

Based on a 20-tonne winch from a supplier in China, a winch of the size required would cost approximately US$10,000 per winch (Alibaba, 2019). This equates to the winch systems costing approximately US$160,000. It should be noted that the winch used for a guide price was not capable of varying its speed, and the drum capacity could not hold 4000 m of 40 mm cable. Additionally, the winch motor was not designed to operate as a generator. However, no winches which met the specific requirements could be found. It is likely that the winches would have to be custom made with variable drives. Therefore, in reality the winches would likely cost significantly more than this guide price.

Determining the additional costs to develop a SMGES system are difficult to estimate, as there are no similar systems. The other major equipment costs are likely to be the cost of power conditioning equipment and the control equipment. Estimating the cost of both of these is challenging, as the requirements of the system are dissimilar to most other energy generation technologies. The power conditioning equipment required would be unique as the power output of 16 winches would have to be synchronised. Additionally, a control system would have to be developed to regulate the raising and lowering of the mass.

For conventional energy generation and storage technologies, the balance of plant (BOP) costs range from approximately 260 US$/kW for wind power and 280 US$/kW for combustion plants, to approximately 1500 US$/kW for geothermal (NREL and Black & Veatch, 2012). The construction and installation costs of generation and storage plants range from 20 US$/kW and 70 US$/kW for combustion turbines and combine-cycle gas turbines, to nearly 2900 US$/kW for nuclear plants. The construction and installation of biomass plants is typically around 575 US$/kW, while for geothermal it is between 500-700 US$/kW, depending on the technology used. Compressed air energy storage (CAES) has construction and engineering costs of approximately 30 US$/kW, however, this value does not include the cost of preparing the cavern, which represents a cost of 360 US$/kW. (NREL and Black & Veatch, 2012)

The costs for engineering and construction and the BOP costs for other energy generation and storage technologies ranged from between 240 US$/kW to 2220 US$/kW (NREL and Black & Veatch, 2012). CAES has the lowest BOP, engineering, and construction costs per kilowatt, of large-scale storage types, with an estimated cost of approximately 440 US$/kW (NREL and Black & Veatch, 2012). It should be noted that these figures are from 2012; since then lithium ion battery technology has significantly reduced in cost.

If it is assumed that the SMGES technology would have similar BOP, engineering, and construction costs as CAES, for a 20 MW system, these costs would be US$8,800,000. These costs alone, are higher than the expected upper limit of a lithium ion battery system with the same power output. If the winch and cable costs are added to this, the cost of the system would be roughly 10 million US Dollars. This still does not include the land costs, or the planning and legislative costs.

If the BOP and engineering and construction costs were to be similar to those of a gas turbine plant per kilowatt of rated power, the costs would be around US$5,700,000. If the equipment costs are added, the system cost would be roughly US$6,900,000 before land, planning, and legislative costs are added.

Although SMGES would likely have a high power to energy storage capacity ratio, it is not necessarily safe to assume that the engineering and construction costs of the system per kilowatt would be low compared with other technologies. Due to the physical scale of the SMGES system, tasks such as preparing the shaft, manufacturing the weight, and transporting and installing the equipment would be expensive. Lifting and moving the equipment into place would require specialist equipment, which would have to be transported to the location of the shaft. The condition of the shaft would also need to be examined prior to committing to the construction of the system, this would require specialised equipment.

Overall, although the estimated cost ranges for the SMGES system and the lithium ion battery system overlap, it is highly unlikely that the SMGES system would be cheaper. Furthermore, the cost of lithium ion batteries is reducing rapidly. Conversely, the aspects which contribute significantly to the costs of SMGES are relatively mature technologies. Therefore, their costs are unlikely to reduce considerably relative to new technologies.

8. Discussion

8.1 SMGES technology

The results of the analysis in this project highlighted the relative strengths and weaknesses of SMGES technology. From the analysis performed, the strength of the technology would be the power capacity and response time for a given energy storage capacity. Even for the highest power applications tested, a SMGES system could theoretically respond from producing no power to producing the rated power in a matter of seconds. This would make SMGES systems most suited to high power, fast response applications such as area regulation or voltage support.

The analysis showed that SMGES would have an extremely poor energy storage capacity for the physical size of the device. To store significant quantities of energy, the mass and shaft height required are exceptionally large. This is a fundamental flaw in this method of storing energy as it relates to the basic principles of physics which the system is defined by. Therefore, no technological advancement can change this property of the technology. The sensitivity analysis performed for shaft height vs mass showed that to store megawatt hours worth of energy, the shaft would need to be well over 500 m in depth with a mass in the order of thousands of tonnes.

As a result of the size of these systems, the implementation of SMGES devices is constrained to locations where deep vertical shafts already exist – such as deep mine shafts. This would limit the possible implementation of SMGES systems significantly as few mineshafts in the United Kingdom would be deep enough and wide enough to be useful. Disused mineshafts may also be in poor condition, making them unsuitable for use. It would be technically achievable to bore new shafts specifically for the implementation of a SMGES, however, the costs of sinking shafts to the depths required for these systems make this unrealistic. As a result, the possible implementation of SMGES is significantly limited.

The characteristics of SMGES place the technology in competition with battery energy storage among other less mature technologies such as flow batteries. In comparison to batteries, SMGES technology may have some advantages such as a higher power output capacity compared for a given energy storage capacity. Moreover, SMGES systems would not suffer from self-discharge. However, most characteristics of battery storage are far superior to those of the SMGES technology. Lithium ion battery storage has a round trip efficiency of roughly 20% more than what could be expected of SMGES. The energy storage density of batteries is orders of magnitude greater than that of SMGES.

Although the power capacity of SMGES systems could be higher than battery storage devices, currently there are no wide spread applications requiring such high power and short discharge duration. Therefore, the high power capacity of SMGES is somewhat redundant in the UK grid composition. Unless new applications arise whereby extremely high power output is required for periods in the order of minutes, it does not seem likely that SMGES will be utilised for grid or off-grid energy storage services.

The development potential of SMGES is also limited. The components which SMGES technology relies upon, notably, winches, cables, and electric motors, are all technologies which have been used commercially for many years. Therefore, they are mature technologies which are unlikely to undergo drastic improvements. It is possible that the efficiency and function of winches for energy generation could be improved as they have not traditionally been used with efficiency as the primary focus. However, no developments will improve the fundamental issue with SMGES, which is the energy storage capacity, by orders of magnitude.

The rough cost comparison between a lithium ion battery system and the SMGES system shows that for a 20 MW, 3 MWh system, the SMGES system would almost certainly be more expensive. It is plausible that the SMGES system could be less costly, but this would require the lithium ion battery system to be at the very upper end of the cost estimate range and the SMGES system to be well below the lower estimated of the cost range.

8.2 Energy storage early-stage assessment process discussion

The energy storage technology assessment process enabled an effective review of the SMGES technology to be carried out. Although the preliminary steps of the process were relatively simple to complete compared with the technical analysis of the system, they were useful in achieving the goals of the project. By setting out the objectives of the study prior to starting, a general direction was gained from the start. Following this, explicitly identifying the key performance indicators which would determine whether the storage device is viable or not, focused the technical analysis to determine these characteristics.

Developing the modelling and analysis strategy also helped with performing the technical analysis of the system. Writing out the process by which the model was to be developed and analysed in advance required careful thought to be put into the strategy. This reduced the amount of redundant work which can occur when one begins modelling or analysing a system without a set plan. However, the initial modelling and analysis strategy was changed during the process. Due to unknown characteristics of the SMGES, after carrying out the test case scenarios, some changes were made to the modelling assessment strategy. Notably, because of the clear strengths and weaknesses of the system which placed the system in competition with battery energy storage, the direct comparison between the two technologies was added. Iterating some steps of the process should be encouraged where necessary. As the purpose of the process was specifically to assess energy storage technologies in the earliest stages of invention, there are likely to be unknown characteristics which may only be noticed during the technical analysis. Adjustments should be made to the modelling and analysis strategy to explore these characteristics.

9. Conclusion

Through the completion of this project, a framework by which to assess new energy storage technology was successfully developed. The framework provided a structured method by which to evaluate the viability of suspended mass gravitational energy storage. Carrying out the preliminary steps of the framework focused the assessment on the key aspects which would determine the viability of the technology. This prevented significant time being spent on inconsequential analysis of the system. The process also ensured that the assessment considered a wide array of uses and applications of the technology. This prevented neglecting possible applications whereby the technology would be ideally suited.

From the assessment carried out in this project it was concluded that SMGES would likely have some advantageous properties; notably, it would be capable of very high power output with a short response time. However, practical systems would be limited to very few locations in the United Kingdom due to the scarcity of deep shaft mines which would be in suitable condition for use. The engineering challenge of manufacturing the systems would be immense relative to the benefits gained from the system. The SMGES technology is fundamentally limited by the physical size of the system required per unit of energy stored. Research and development may be able to improve the round-trip efficiency of the systems. However, this would not reduce the size of the systems enough to make them widely deployable. Therefore, research and development costs would be shared by a relatively small number of systems.

Currently there are no widescale applications for energy storage devices with the characteristics that would make SMGES technology commercially viable. The analysis showed that even applications with the specifications tailored to SMGES systems characteristics could likely be met by a lithium ion battery system. The equivalent lithium ion battery system would be physically smaller by orders of magnitude, have far greater location flexibility, could be installed faster, and would likely cost significantly less.

Overall, from the assessment carried out in this project, significant investment in research and development of SMGES cannot be recommended. The application of such systems would be extremely niche. Therefore, it is recommended that research and development funding should be spent of technologies which would have a greater impact.

10. Recommendations and Future Work

From the research and analysis carried out, it was concluded that SMGES is unlikely to have a significant role in the energy storage market Therefore, it was recommended that significant funding should not be spent on developing the technology.

To improve the confidence level in the conclusions of this project, it would be useful to develop a cost model for the system. Developing a cost model of the SMGES technology would be challenging but may be possible using expert knowledge of the mining sector. The costs of preparing the shaft is likely to be a major system cost. Therefore, accurate functions of the costs of overhauling disused mineshafts would be required. The winch and headgear equipment and installation costs would also need to be relatively accurately modelled. To do this, it is likely that significant data on the costs of mining would be required, thus, information and support from a mining company would be needed. As the winches required for the system would probably need to be custom made, quotations from winch manufacturers for different configurations would also be needed. Finally, cost models of the power conditioning equipment required would need to be determined.

Developing a dynamic cost model of the SMGES technology which is suitably accurate for the purpose would be challenging. However, it would be useful if further analysis of the system was desired. A dynamic cost model would allow an optimisation of the system to be performed. By optimising the cost of the system, a more precise analysis of the economic viability of the technology could be performed. This would more definitively support the conclusions of the study.

Overall, the early-stage technology assessment procedure carried out in this project was effective. It is therefore recommended that a similar procedure be applied to other new energy storage technologies which are vying for public funding. This would increase the development of viable energy storage technologies by preventing funding being spent on technologies which are fundamentally flawed. Hence, it is recommended that the government funding institutions implement similar systems in order to make more cost-effective decisions.

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Appendix A: MATHCAD Model of SMGES System

```
% SWMGES_model.mat
% This script models the performance characteristics of a
% suspended weight gravitational storage device
clear all
clc

% Fixed values
g = 9.81; % m.s-2

% System inputs
Energy = 3000; %kWh
Power = 20000; %kW
h_shaft = 1000; % m
t_start = 5; %s

%% System parameters
% Basic configuration
NumStrands = 64;
NumWinches = 16;

% rho_weight = 2400; % kg.m-3
rho_weight = 7850;
eff_winch = 0.85;

% Cable sizing factors
safety_factor = 5.0;
phi_5 = 1.5;
gamma_p = 1.34;
gamma_n = 1;
winch_ratio = 2;
Drum_cab_rat = 32;
weight_wd_ratio = 4;

%% Calculations
```

```
% Calculate the mass and volume to meet the energy storage requirement
m_weight = Energy*3600000/(eff_winch*g*h_shaft)%kg
vol_weight = m_weight/rho_weight %m^3
d_weight = (4/weight_wd_ratio*vol_weight/pi)^(1/3) %m for h=4d

% Calculate drop rate and acceleration to meet power and start-up specs
v_drop = 1000*Power/(eff_winch*m_weight*g)
peak_accel = v_drop/t_start

%Calculate the discharge time of the system at rated power
T_discharge = h_shaft/v_drop; %s

% Calculating cable forces and sizing
phi = 1+(peak_accel*phi_5)/g
peak_tens_cab = m_weight*g*phi*gamma_p*gamma_n/(NumStrands*1000) %kN
design_tens = peak_tens_cab*safety_factor %kN

d=0;
tens_x = 0;

while tens_x < design_tens
    d = d + 1;%mm
    tens_x = 0.8713*d^2+1.3819*d; %kN
end

d_cable = d
cab_weight = 0.0046*d_cable^2+0.0069*d_cable

%% Calculate drum dimensions
d_drum = d_cable*Drum_cab_rat/1000 %m
length_per_drum = NumStrands*h_shaft/NumWinches; %m
w_drum_est = winch_ratio*d_drum; %m
n_layer_est = length_per_drum*d_cable/1000/(pi()*d_drum*w_drum_est);

if n_layer_est < 1.0
```

```
    n_layer = 1.0;
else
    n_layer = round(n_layer_est)
end

for i = 1:n_layer
    d_layers(i)=d_drum+d_cable/1000+(i-1)*2*d_cable/1000; %m
end

sum_diams = 0; %m

for l = 1:n_layer
    sum_diams = sum_diams+d_layers(l); %m
end

w_drum = length_per_drum*d_cable/(pi()*sum_diams)/1000 %m
length_outer_layer=pi*d_layers(n_layer)*w_drum/(d_cable/1000)
d_max=d_layers(n_layer)
torque_drum =
(d_max/2)*(peak_tens_cab+cab_weight*g*length_outer_layer/1000)%kNm
```

Appendix B: MATLAB Scrips Used to Perform the Sensitivity Analysis

MATLAB script used to evaluate the function of the SMGES model

```
% SMGES_tester.m
% This script tests configurations of the SMGES_func function
clc
clear all

%% Define inputs
Energy = 3000; %kWh
Power = 20000; %kW
% Depth = 1000; %m
Response_time = 5; %s
NumStrands = 64;
NumWinches = 16;
Safety_factor = 2;
Drum_cable_ratio = 20;
Winch_efficiency = 0.92;

%% Variable parameter options
Num_tests = 10;

% Energy = [100,200,500,1000,1500,2000]; %kWh
% Power = [100,200,500,1000,1500,2000]; %kW
Depth = [100,200,400,600,800,1000,1200,1500,2000,3000]'; %m
% Response_time = [0.1,0.2,0.5,1,2,5,10,60]; %s
% Num_strands = [16,32,48,64,80,96,128,160];
% Num_winches = [4,8,12,16,20,24,32,40];
% Safety_factor = [1.5,2,2.5,3,3.5,4,4.5,5]';
% Winch_efficiency = [0.80,0.82,0.84,0.86,0.88,0.90,0.92,0.95];
% Drum_cable_ratio = [20,25,30,35,40,50,75,100];

%% Run SMGES function
X = zeros(Num_tests,7);
```

```
for i = 1:Num_tests
    X(i,:) =
SMGES_func(Energy,Power,Depth(i),Response_time,NumStrands,NumWinches,Safety
_factor,Drum_cable_ratio,Winch_efficiency);
end


Mass = X(:,1); % tonnes
Velocity = X(:,2); %m/s
Accel = X(:,3); %m/s^2
Cable_diameter = X(:,4); %mm
Drum_diameter = X(:,5); %m
Drum_torque = X(:,6); %kNm
Weight_diameter = X(:,7);
```

MATLAB function of SMGES mathematical model

```
% SMGES_func.mat
% This script models the performance characteristics of a
% suspended weight gravitational storage device
function FF =
SMGES_func(Energy,Power,h_shaft,t_start_stop,NumStrands,NumWinches,safety_f
actor,Drum_cab_ratio,eff_winch)
% Fixed values
g = 9.81; % m.s-2
rho_weight = 2400; % kg.m-3

% Cable sizing factors
% safety_factor = 5.0;
phi_5 = 1.5;
gamma_p = 1.34;
gamma_n = 1;
winch_ratio = 2;

%% Calculations
% Calculate the mass and volume to meet the energy storage requirement
m_weight = Energy*3600000/(eff_winch*g*h_shaft);%kg
vol_weight = m_weight/rho_weight; %m^3
d_weight = (vol_weight/pi)^(1/3); %m for h=4d

% Calculate drop rate and acceleration to meet power and start-up specs
v_drop = 1000*Power/(eff_winch*m_weight*g);
peak_accel = v_drop/t_start_stop;

% Calculating cable forces and sizing
phi = 1+(peak_accel*phi_5)/g;
peak_tens_cab = m_weight*g*phi*gamma_p*gamma_n/(NumStrands*1000);%kN
design_tens = peak_tens_cab*safety_factor;%kN

d=0;
tens_x = 0;
while tens_x < design_tens
```

```
    d = d + 1;%mm
    tens_x = 0.8713*d^2+1.3819*d; %kN
end

d_cable = d;
cab_weight = 0.0046*d_cable^2+0.0069*d_cable;

%% Calculate drum dimensions
length_per_drum = NumStrands*h_shaft/NumWinches; %m
d_drum = d_cable*Drum_cab_ratio/1000;%m
w_drum_est = winch_ratio*d_drum; %m
n_layer_est = length_per_drum*d_cable/1000/(pi()*d_drum*w_drum_est);

if n_layer_est < 1.0
    n_layer = 1.0;
else
    n_layer = round(n_layer_est);
end

for i = 1:n_layer
    d_layers(i)=d_drum+d_cable/1000+(i-1)*2*d_cable/1000; %m
end

sum_diams = 0; %m
for l = 1:n_layer
    sum_diams = sum_diams+d_layers(l); %m
end

w_drum = length_per_drum*d_cable/(pi()*sum_diams)/1000; %m
d_max = d_layers(n_layer);
length_outer_layer=pi*d_max*w_drum/(d_cable/1000);
torque_drum =
(d_max/2)*(peak_tens_cab+cab_weight*g*length_outer_layer/1000); %kNm

FF = [m_weight/1000,v_drop,peak_accel,d_cable,d_drum,torque_drum,d_weight];
end
```

Appendix C: Tables of Results for Test Case Scenarios

The results obtained for each of the test case applications is shown below. The results shown are for the configurations described in section 7.2. The row highlighted in yellow in each table represents the configuration used in the analysis in section 7.2.

Table 8: SMGES configuration results for the mobile phone battery application example.

Shaft height (m)	Mass (tonnes)	Drop speed (m/s)	Acceleration (m/s^2)	Cable diameter (mm)	Winch drum diameter (m)	Peak winch torque (kNm)
1	4.317	0.00014	0.0014	12	0.384	5.623
2	2.159	0.00028	0.0028	9	0.288	2.110
4	1.079	0.00056	0.0056	6	0.192	0.705
8	0.540	0.00111	0.0111	4	0.128	0.236
10	0.432	0.00139	0.0139	4	0.128	0.200
15	0.288	0.00208	0.0208	3	0.096	0.106
20	0.216	0.00278	0.0278	3	0.096	0.084
25	0.173	0.00347	0.0347	2	0.064	0.054
30	0.144	0.00417	0.0417	2	0.064	0.047
40	0.108	0.00556	0.0556	2	0.064	0.039

Table 9: SMGES configuration results for the football stadium application example.

Shaft height (m)	Mass (tonnes)	Cable diameter (mm)	Drop speed (m/s)	Acceleration (m/s^2)	Winch drum diameter (m)	Peak winch torque (kNm)
100	86346	225	0.014	0.0028	7.20	36350
200	43173	159	0.028	0.0056	5.09	13667
400	21587	113	0.056	0.0111	3.62	5451
600	14391	92	0.083	0.0167	2.94	3499
800	10793	80	0.111	0.0222	2.56	2663
1000	8635	71	0.139	0.0278	2.27	2283
1200	7196	65	0.167	0.0333	2.08	2001
1500	5756	58	0.208	0.0417	1.86	1758
2000	4317	50	0.278	0.0556	1.60	1562
3000	2878	41	0.417	0.0833	1.31	1386

Table 10: SMGES configuration results for the voltage support application example.

Shaft height (m)	Mass (tonnes)	Drop speed (m/s)	Acceleration (m/s^2)	Cable diameter (mm)	Winch drum diameter (m)	Peak winch torque (kNm)
100	10793	0.06	0.011	159	5.09	12256
200	5397	0.11	0.022	113	3.62	4583
400	2698	0.22	0.044	80	2.56	1774
600	1799	0.33	0.067	65	2.08	1105
800	1349	0.44	0.089	56	1.79	813
1000	1079	0.56	0.111	51	1.63	668
1200	899	0.67	0.133	46	1.47	574
1500	720	0.83	0.167	41	1.31	501
2000	540	1.11	0.222	36	1.15	436
3000	360	1.67	0.333	30	0.96	377

Table 11: SMGES configuration results for the area regulation application example.

Shaft height (m)	Mass (tonnes)	Drop speed (m/s)	Acceleration (m/s^2)	Cable diameter (mm)	Winch drum diameter (m)	Peak winch torque (kNm)
100	43173	0.06	0.06	202	6.46	26319
200	21587	0.11	0.11	144	4.61	10072
400	10793	0.22	0.22	102	3.26	4188
600	7196	0.33	0.33	84	2.69	2770
800	5397	0.44	0.44	73	2.34	2194
1000	4317	0.56	0.56	66	2.11	1883
1200	3598	0.67	0.67	61	1.95	1687
1500	2878	0.83	0.83	55	1.76	1553
2000	2159	1.11	1.11	49	1.57	1444
3000	1439	1.67	1.67	41	1.31	1374

Table 12: SMGES configuration results for the T&D upgrade deferral example.

Shaft height (m)	Mass (tonnes)	Drop speed (m/s)	Acceleration (m/s^2)	Cable diameter (mm)	Winch drum diameter (m)	Peak winch torque (kNm)
100	8635	0.007	0.00012	127	4.06	6255
200	4317	0.014	0.00023	90	2.88	2328
400	2159	0.028	0.00046	64	2.05	937
600	1439	0.042	0.00069	52	1.66	582
800	1079	0.056	0.00093	45	1.44	443
1000	863	0.069	0.00116	40	1.28	373
1200	720	0.083	0.00139	37	1.18	325
1500	576	0.104	0.00174	33	1.06	283
2000	432	0.139	0.00231	28	0.90	245
3000	288	0.208	0.00347	23	0.74	217

Table 13: SMGES configuration results for the supply reserve capacity application example.

Shaft height (m)	Mass (tonnes)	Drop speed (m/s)	Acceleration (m/s^2)	Cable diameter (mm)	Winch drum (m)	Peak winch torque (kNm)
100	431732	0.028	0.0005	368	11.78	158498
200	215866	0.056	0.0009	260	8.32	61260
400	107933	0.111	0.0019	184	5.89	23085
600	71955	0.167	0.0028	150	4.80	13802
800	53967	0.222	0.0037	130	4.16	10143
1000	43173	0.278	0.0046	116	3.71	8122
1200	35978	0.333	0.0056	106	3.39	6874
1500	28782	0.417	0.0069	95	3.04	5894
2000	21587	0.556	0.0093	82	2.62	4869
3000	14391	0.833	0.0139	67	2.14	4130

Appendix D: Data Used in the Comparative Cost Estimation

Table 14: Cost data of various energy storage and generation technologies from the report by NREL and Black & Veatch (2012).

Type	BOP	Engineering and construction	Total
Nuclear	–	970	970
Gas turbine	263	20	283
CCGT	719	68	787
Pulverised coal	1770	215	1985
Biomass	995	575	1570
Hydrothermal geothermal	1520	505	2025
Enhanced geothermal	1520	700	2220
Hydroelectric	– [2]	238	238
Ocean wave	–	925	925
Tidal	–	1060	1060
Photovoltaic	185	55	240
Concentrating solar trough	– [3]	544	544
Concentrating solar tower	– [4]	540	540
Onshore wind	257	79	336
Offshore wind	894	165	1059
Offshore floating	1260	252	1512
CAES	50	390	440
Pumped-storage	– [5]	390	390
Battery	1330	140	1470
Average	897	412	979

[2] Hydroelectric power had costs 556 $/kW for pumphouse equipment.

[3] Trough type concentrating solar had a cost of 1300 $/kW for the power block equipment.

[4] Tower type concentrating solar had a cost of 950 $/kW for the power block equipment.

[5] Pumped-storage had powerhouse costs of 835 $/kW.

Appendix E: Datasheet for Teufelberger QS816V(G) Wire Rope

Table 15: Data for the wire rope used to develop the SMGES mathematical models (Teufelberger, 2019).

Diameter (mm)	MBF (kN)	Mass (kg/m)
10	89	0.46
11	107	0.55
12	129	0.69
13	156	0.81
14	179	0.93
15	205	1.06
16	232	1.2
17	261	1.35
18	291	1.55
19	335	1.71
20	365	1.89
21	414	2.15
22	451	2.34
23	492	2.54
24	517	2.75
25	574	2.97
26	615	3.19
27	659	3.51
28	726	3.76
29	768	3.98
30	846	4.37

Diameter (mm)	MBF (kN)	Mass (kg/m)
32	957	4.9
34	1,046	5.59
36	1,186	6.36
38	1,354	7.03
40	1,486	7.81
42	1,641	8.6
44	1,768	9.27
46	1,949	10.3
48	2,050	10.78
50	2,232	11.6
52	2,414	12.5
54	2,532	13.91
56	2,850	14.5
58	3,004	15.6
60	3,214	16.7
62	3,432	17.8
64	3,657	19.74
66	3,870	20.63
68	4,128	21.4
70	4,375	22.7