**Supporting information for: An Economic Analysis of Energy Storage Systems Participating in Resilient Power Markets**

## 1.1 Life-cycle cost model

Total life-cycle cost (LCC) is a widely accepted metric that assesses the economic implications of a project (Díaz-González, Sumper, & Gomis-Bellmunt, 2016). An ESS's life-cycle cost represents the cost per given power output in an annualized form over the project's lifespan. This can be seen in Eq. 1. A second metric that is widely used in economic analysis is the levelized cost of storage (LCOS), shown in Eq. 2. This is calculated by diving the LCC by the number of yearly operating hours. The LCOS quantifies the financial requirements that utility companies or storage operators need to charge the overall storage system per unit of dispatched energy in order to cover the associated costs.

Life-cycle cost models for ESSs typically consider the capital, operating, replacement and disposal-related costs as main components. This type of costing approach is well discussed in several reports and has been adopted to assess the ESSs considered. Karellas and Touganatos explain this calculation method (Moseley & Garche, 2014).

$$C_{LCC} = C_I + C_{O\&M} + C_R + C_{EOL} \qquad \text{Eq (1)}$$

Where $C_{LCC}$ is the annualized life-cycle cost, $C_I$ is the investment costs, $C_{O\&M}$ are the operating and maintenance costs, $C_R$ is the replacement cost and $C_{EOL}$ accounts for the cost of disposal. All terms are expressed in an annualized form $\left(\frac{£}{\text{kW·yr}}\right)$.

$$LCOS = \frac{C_{LCC}}{n \cdot h} \qquad \text{Eq (2)}$$

$LCOS$ is the levelized cost of storage $\left(\frac{£}{\text{kWh}}\right)$, and $n$ is the annual cycles and $h$ is the cycle duration (h).

All costs in Eq. 1 are expressed in monetary units and need to be annualized over the time horizon of the project. Annualization is accounted for using a capital recovery factor (CRF) which can be seen below in Eq. 3.

$$CRF = \frac{i(1+i)^Y}{(1+i)^Y - 1}$$ E

Where $CRF$ is the capital recovery factor ($y^{-1}$), i is the real discount rate (%) and $Y$ is the project time horizon (yr).

Capital costs, Eq. 4, can be split into that of the energy storage container (i.e. battery packs, pressure vessels, etc), the cost of power converter systems (i.e. electrolysers, gas turbines, etc) and the balance of plant components (i.e. buildings, utility services, piping, etc). The cost of the storage container is assumed to be proportional to the size of its storage capacity and can be calculated using Eq. 5. The remaining costs of the power converter systems and balance of plant costs are assumed to be proportional to the power rating of the system.

$$C_I^T = C_{STOR} + C_{PCS} + C_{BoP} \qquad \text{Eq (4)}$$

Where $C_I^T$ is the total investment cost (£), $C_{STOR}$ is the cost of the storage vessel (£), $C_{PCS}$ is the power converter costs (£) and $C_{BoP}$ represents the balance of plant components cost (£).

$$C_{STOR} = c_e \frac{E}{\mu \cdot DoD_{max}} \qquad \text{Eq (5)}$$

In Eq. 5, $c_e$ is the specific cost of storage capacity ($\frac{£}{\text{kWh}}$), $E$ is the required energy (kWh), $\mu$ is the system's round-trip efficiency (%) and $DoD_{max}$ is the maximum depth of discharge of the technology (%). The required energy is divided by the round-trip efficiency and maximum depth of the discharge so as to ensure that the system is designed to be able to discharge this energy per cycle, given the efficiency losses and discharge constraints.

The operating and maintenance costs can be divided into fixed and variable categories. Where the fixed costs are independent of the usage of the system throughout its lifespan (Eq. 6).

$$C_{O\&M\_Fixed} = c_f \cdot L_m + \frac{d \cdot c_{el} \cdot \upsilon \cdot L_{el}}{24} \qquad \text{Eq (6)}$$

Where $c_f$ is the operating and fixed costs efficient $\left(\frac{£}{kW \cdot yr}\right)$, $L_m$ is the annualizing factor for maintenance and operating costs, $d$ is the number of operational days per year, $c_{el}$ is the electricity cost $\left(\frac{£}{kWh}\right)$, $\upsilon$ is the daily self-discharge ratio (%) and $L_{el}$ weights the annualizing factor for the costs associated with the electricity purchased.

Variable costs are those that depend on the quantity of usage of the ESS throughout its lifespan (Eq. 7). This includes the cost of purchasing electricity and also natural gas, such as in some compressed air energy storage (CAES) systems. Storing curtailed renewable energy will be important for future energy systems. These periods of negative pricing offer high-value potential for large storage systems, notably storage systems with high variable costs. However, price forecasts and volumes of future curtailed energy in the UK are largely unknown, except for in proprietary models. and are highly dependent on the capacity buildout to Net-Zero, localized cannibalization of the wind fleet and even the weather year experienced. Therefore, for this analysis, only historic wholesale electricity prices are considered.

$$C_{O\&M\_Var} = \left(\frac{c_{el}}{\mu} + \frac{r_{gas} L_{gas} c_{gas}}{10^3}\right) L_{el} \cdot h \cdot n \qquad \text{Eq (7)}$$

Where $C_{O\&M\_Var}$ is the variable cost of operation and maintenance $\left(\frac{£}{\mathrm{kW{\cdot}yr}}\right)$, $c_{gas}$ is the natural gas cost $\left(\frac{£}{GJ}\right)$, $r_{gas}$ is the gas consumption rate $\left(\frac{MJ}{MWh}\right)$, $L_{gas}$is the annualizing factor, $n$ is the annual cycles, $h$ is the discharge time $(hr)$.

Two important time frames to consider in the life-cycle cost analysis are the time horizon of the project (dependant on the storage application) and the lifetime of the components making up the ESS (dependant on the storage technology). It is critical to consider the aspect of time when evaluating energy storage systems on an equal basis as vastly different results can be generated if the project lifetime is not standardized and different storage technology lifetimes not accounted for. In order to ensure a fair comparison of system costs, the cost of any associated replacements over the specified project's time-horizon is included using Eq. 8. Here, $c_r$ is the replacement cost coefficient $\left(\frac{£}{kWh}\right)$, $k$ is the number of replacements required over the project lifetime and $L_r$ is the annualizing cost factor for replacement.

$$C_R = \left(\frac{c_r \cdot h}{\mu}\right) k \cdot L_r \qquad \text{Eq (8)}$$

Disposal and recycling of components once a technology’s lifespan has ended must also be considered in the overall cost calculation. The challenge comes in that recycling is not currently a widely utilized or documented practice in ESSs and it is not straightforward to determine credible cost estimates for each type of technology. Therefore end-of-life costs were not accounted for in the present cost model but were still integrated, to allow for any future refinement, in Eq. 9.

$$C_{EoL} = c_{EoL} \cdot L_m \qquad \text{Eq (9)}$$

Where $c_{EoL}$is the end of life cost coefficient $\left(\frac{£}{kWh}\right)$.

## 1.2 Revenue optimization model

The second part of this economic analysis is to quantify the annual revenue potential for each ESSs. This will aid in determining the profitability merit order of the different ESSs. As mentioned, there are multiple markets ESSs can participate in to generate revenue, with participation dependent on technology specifications. The primary sources of revenue in electricity markets include wholesale price arbitrage, capacity market payments and providing balancing and ancillary services (i.e. black start, short-term operating reserve) (Energy UK, 2017). The revenue streams considered in this report are those primarily concerned with large systems providing long-term storage with only price arbitrage and capacity market payments being considered. Hydrogen-based systems are also given the option to sell stored hydrogen, rather than electricity as an additional revenue stream. Capacity market payments are assumed to be an annual lump-sum payment per MWh with a de-rating factor. Revenue from price arbitrage was determined using a mixed-integer linear programming (MILP) model. This seeks to optimize a linear objective function, which is subject to one or more constraints. The objective function is set to maximize net annual operating profit from charging and discharging sequences, given perfect foresight of hourly UK 2019 wholesale electricity prices (NordPool, 2020).

Several constraints and functions needed to be defined for the MILP model. Most importantly, these include a function for calculating profit, storage capacity, charge level and creating binary variables that ensure charging and discharging are de-coupled and cannot happen simultaneously. The formulas for these constraints used can be seen in Eq. 10-14, with the output variables including charge level, net operating profit and

$$Profit_t = -Pwr_{ch,t} \cdot \left(P_{elec,t} + MC_{ch}\right) + Pwr_{dis,t} \cdot \left(P_{elec,t} - MC_{dis}\right) + Pw_{dis\,H_2,t}\left(P_{H_2} - MC_{dis}\right) \quad \text{Eq (10)}$$

charging and discharging at each hourly time step, respectively.

In Eq. 10, $Profit_t$ (£) is the net operating profit at a given time and is determined using the maximum charge and discharge rate, $Pwr_{ch,t}$ and $Pwr_{dis,t}$ $(kW)$, the price of electricity or hydrogen, $P_{elec,t}$ and $P_{H_2}$ $\left(\frac{£}{kWh}\right)$, and the marginal cost of charging, converting hydrogen to storable energy, and discharging, converting stored chemical energy to electricity, $MC_{ch}$ and $MC_{dis}$ $\left(\frac{£}{kWh}\right)$.

$$E_{storage} = \frac{E_{out}}{DOD_{max} \cdot \eta_d} \quad \text{Eq (11)}$$

Where $E_{storage}$ in Eq. 11 is the storage capacity (MWh), $E_{out}$ is the required energy volume specified (MWh), $\eta_d$ is the discharging efficiency (%) and $DOD_{max}$ is the maximum depth of discharge (%). In Eq. 12, $CL_t$ is the charge level at a given interval (MWh) and $\eta_c$ and $\eta_d$ is the charging and discharging efficiency (%).

$$CL_t = CL_{t-1} + Pwr_{ch,t} \cdot \eta_c - \frac{Pwr_{dis,t}}{\eta_d} \quad \text{Eq (12)}$$

$$Pwr_{ch,t} = \begin{cases} \leq 0 & if\ bin_{C,t} = 0 \\ \geq 0 & if\ bin_{C,t} = 1 \end{cases} \quad \text{Eq (13)}$$

The variable $bin_{C,t}$ determines if the system is charging or discharging. The objective function (Eq. 14) represents the total profit over time interval T which is in hourly intervals.

$$Profit_{total} = \sum_{t=0}^{T} Profit_t \quad \text{Eq (14)}$$

### 2.1 Literature Documents

Performance parameters have been amalgamated from literature,(Drury, Denholm, & Sioshansi, 2011; Dunn, Kamath, & Tarascon, 2011; Evans, Strezov, & Evans, 2012; International Renewable Energy Agency, 2017; Karellas & Tzouganatos, 2014; Moseley & Garche, 2014; Murrant & Radcliffe, 2018; Punys et al., 2013; Zakeri & Syri, 2015) as well as cost parameters.(Haugen, Paoli, Cullen, Cebon, & Boies, 2020; International Renewable Energy Agency, 2017; Mugyema, Botha, Kamper, Wang, & Sebitosi, 2023; Staffell, Green, Gross, & Green, 2021; Zakeri & Syri, 2015)

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