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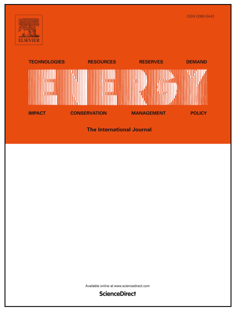

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Multi-mode operation of a Liquid Air Energy Storage (LAES) plant providing energy arbitrage and reserve services – Analysis of optimal scheduling and sizing through MILP modelling with integrated thermodynamic performance

Andrea Vecchi [a,*], James Naughton [b], Yongliang Li [a], Pierluigi Mancarella [b,c], Adriano Sciacovelli [a,†]

[a] Birmingham Centre for Energy Storage, School of Chemical Engineering, University of Birmingham, Birmingham B15 2TT, UK

[b] Department of Electrical and Electronic Engineering, The University of Melbourne, Parkville, Victoria, 3010, Australia

[c] School of Electrical and Electronic Engineering, University of Manchester, Manchester, M13 9PL, UK

[*] Corresponding author, e-mail: axv863@student.bham.ac.uk

[†] Corresponding author, e-mail: a.sciacovelli@bham.ac.uk

Abstract

Energy storage competitiveness is ubiquitously associated with both its technical and economic performance. This work investigates such complex techno-economic interplay in the case of Liquid Air Energy Storage (LAES), with the aim to address the following key aspects: (i) LAES optimal scheduling and how this is affected by LAES thermodynamic performance (ii) the effect of LAES sizing on its profitability and performance (iii) overall techno-economic assessment of LAES multi-mode operation when providing energy and reserve services. To address these aspects, a Mixed Integer Linear Programming-based optimisation tool has been developed to simulate LAES operation throughout a year while including detailed thermodynamic constraints, thus allowing an accurate performance estimation. The results demonstrate that considering LAES thermodynamic performance in the optimisation ensures a feasible dispatch profile thus avoiding loss of revenues, especially for the multi-mode cases. However, while operation with arbitrage and a portfolio of reserve services is financially promising, it also deteriorates LAES roundtrip efficiency; therefore, a techno-economic balance should be sought. In terms of design, the possibility of independently sizing LAES charge and discharge power is key for tailoring the plant to the specific operating mode. Furthermore, storage energy capacities greater than 2-3 hours do not significantly increase LAES profitability under the market conditions considered.

Highlights

- LAES multi-mode operation for energy arbitrage and reserve services is assessed
- A novel MILP optimisation including LAES thermodynamic constraints is formulated
- Against traditional models we get 10% lower revenues, but feasible dispatch profile
- Multi-mode operation may allow payback time below 20 years
- LAES power sizing allows optimal design which depends on the operating strategy

Keywords

Liquid Air Energy Storage; Mixed Integer Linear Programming; thermodynamic performance; reserve services; techno-economic assessment; energy storage

Nomenclature

Indices	
i	Reserve services, from 1 to I
n	Points used in the piecewise approximation, from 1 to N
t	Time periods, from 1 to T
Parameters	
C^{MAX}	Maximum power input to liquefaction [MW]
D^{MAX}	Maximum power output from PRU [MW]
D^{min}	Minimum power output from PRU [MW]

K^{MAX}	Maximum storage capacity [ton]
$S_{t,i}$	Reserve commitment [MW]
X_n	x-points for piecewise approximation [-]
Y_n	y-points for piecewise approximation [tonh^{-1}]
$x_{t,i}^S$	Reserve status [-]
x_t^S	Overall reserve status [-]
π_i^{ava}	Availability fee [£MW^{-1}h^{-1}]
π_i^{pos}	Positional fee [£h^{-1}]
π_i^{util}	Utilisation fee [£MWh^{-1}]
π_t^{el}	Wholesale electricity price [£MWh^{-1}]
ρ_i	Reserve call probability [-]
τ_i	Nominal reserve call duration [h]
Δt	Timestep [h]
γ	Rated liquefier conversion efficiency [MWhton^{-1}]
δ	Rated PRU conversion efficiency [MWhton^{-1}]
Variables	
$\boldsymbol{D_t}$	Discharge power output [MW]
$\boldsymbol{K_t}$	Liquid air inventory in the tank [ton]
$\boldsymbol{LAE_t}$	Liquid air expenditure [tonh^{-1}]
$\boldsymbol{x_t^C}$	Charge status [-]
$\boldsymbol{x_t^D}$	Discharge status [-]
$\boldsymbol{\alpha_{n,t}}$	Auxiliary variable [-]
$\boldsymbol{\psi_{n,t}}$	Piecewise interval identifier [-]
Other symbols	
$\dot{W}_{out}$	Power output [kW]
$\dot{m}_{LA}$	Liquid air mass flow rate [kgs^{-1}]
$T_{in,j}$	Turbine inlet temperature [K]
c_p	Specific heat capacity [kJkg^{-1}K^{-1}]
w_P	Pumping work [kJkg^{-1}]
$w_{T,j}$	Turbine specific work [kJkg^{-1}]
$\Pi_{T,j}$	Turbine expansion ratio [-]
η_M	Mechanical efficiency [-]
η_{RT}	Roundtrip efficiency [%]
$\eta_{T,j}$	Turbine isentropic efficiency [-]
χ_C	Liquefaction sub-system cost [M£]
χ_D	PRU sub-system cost [M£]
χ_K	Storage tanks cost [M£]
$CAPEX$	Capital expenditure [M£]
PBT	Payback time [y]
Rev	Revenues [M£y^{-1}]
k	Isentropic exponent [-]
ξ	Power indicator [-]

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1. **Introduction**

In an attempt to contain the global temperature rise within 1.5°C, major changes are expected to reshape the way we produce, transmit and consume electricity [1]. A transition towards renewable energy sources is regarded as crucial for a future low-carbon energy sector. However, increased grid flexibility is required to accommodate large amounts of intrinsically fluctuating generation [2]; Electric Energy Storage (EES), by compensating for mismatches between supply and demand, is recognized as a key technology enabling such flexibility. For this reason, it is believed EES will play a pivotal role in ensuring secure and uninterrupted power to future, low-carbon, energy systems [3].
Liquid Air Energy Storage (LAES) is an emerging bulk storage solution (i.e. involving power output in the range of tens to hundreds of MW and capacity from MWh to GWh [4]), in the field of thermo-mechanical technologies. This solution is technically comparable with large-scale alternatives (e.g. Pumped Hydro or Compressed Air Energy Storage), while also offering some key advantages. LAES relies on the principle of storing energy as cryogenic air in liquid state, which can easily be contained in near-ambient pressure vessels [5]. This feature removes geographical constraints [6] and ensures an energy density at least one order of magnitude higher than competing solutions (typical values for Pumped Hydro and Compressed Air Energy Storage are 0.5-1.5 Wh/L and 3-6 Wh/L, respectively, while LAES can achieve 100-200 Wh/L [7,8]). Furthermore, LAES is flexible, modular and based on well-understood components, thus showing potential for a rapid deployment.
LAES can support the operation of energy grids through the provision of a portfolio of functions and services, which, in well-structured energy markets, allows the storage operator to access multiple streams of revenues. Energy arbitrage, with load shifting from high to low price electricity, is the simplest and most investigated function that LAES can provide [9,10]. However, energy arbitrage by means of LAES operation is commonly studied in isolation. For example, Khani and Zadeh [11] studied the optimal dispatching of LAES in the Ontario electricity market for arbitrage purposes only. They found that LAES economic feasibility is limited in absence of further subsidies, as revenues only stem from energy price differentials between charging and discharging periods. Other studies with similar conclusions were also carried out [12,13]. However, these papers did not consider that LAES is also capable of providing ancillary services upon the request from the grid operator [14,15]. More specifically, the ability of LAES to rapidly modulate its power output enables it to support grid operation through services which require response times in the order of few hundreds of seconds to several minutes. In the UK context, these services are Fast Reserve (FR) and Short Term Operating Reserve (STOR).
Provision of multiple services gives opportunity to significantly increase revenues for energy storage assets, such as LAES plants. However, a series of challenges – currently marginally addressed – need to be overcome to access such opportunity. This requires consideration of: (i) the interaction between service requirements (e.g. minimum committed capacity) and thermodynamic performance of LAES; (ii) prioritization of services/markets; (iii) a multi-market optimal dispatch modelling methodology capable of adequately capturing LAES thermodynamic performance; (iv) the selection of LAES plant size (i.e. rated power input and output) when providing a portfolio of services.

Little has been done so far to address such considerations in a coherent and unified manner. A portion of existing studies partially addresses some of the challenges mentioned above, thus only marginally capturing the interaction between the various drivers. For example, Kalavani *et al*. [16] studied the stochastic scheduling of a 50 MW LAES to mitigate wind variability, without considering the effects of alternative sizes. Recently, Legrand *et al.* [10] assessed the link between LAES size and its economic value for future developments of the Spanish grid. However, arbitrage alone and a constant value for the roundtrip efficiency were considered in the analysis. Xie *et al.* [17] proposed an optimal design for LAES through use of a genetic algorithm. Most notably, this study is one of the few attempts to study the optimal provision of a portfolio of services via LAES. An *ad-hoc* algorithm for the coordination of arbitrage and STOR is developed, but the oversimplified black-box storage modelling does not capture accurately the thermodynamic behaviour of LAES. This is however crucial, since a precise representation of technology performance is paramount in order to ensure meaningful techno-economic results. This aspect is partially addressed in [18], where Zhang *et al*. investigated the possibility of a coupled air separation unit with cryogenic storage to operate in energy and reserve markets through a Mixed Integer Linear Programming (MILP) optimization. Regression curves were used for capturing the behaviour of the air separation unit, without a direct and explicit link to the underlying thermodynamic behaviour of the power generation section.

This paper covers the gaps in the literature discussed above, and in particular the lack of a coherent modelling framework to simultaneously capture LAES thermodynamics, provision of a portfolio of services and optimal dispatching of LAES. A MILP-based optimal dispatch problem for LAES is formulated, considering a portfolio of the three most suitable services for LAES: energy arbitrage, FR and STOR. By surpassing the current modelling limitations, the paper demonstrates how: (i) LAES variations in thermodynamic performance affect the provision of services; (ii) the thermodynamic performance must be properly accounted for when evaluating the optimal dispatching of LAES plant; (iii) the techno-economic viability and optimal capacity of LAES plant is impacted by provision of services. A graphical summary describing the landscape for the present paper is shown in Figure 1.

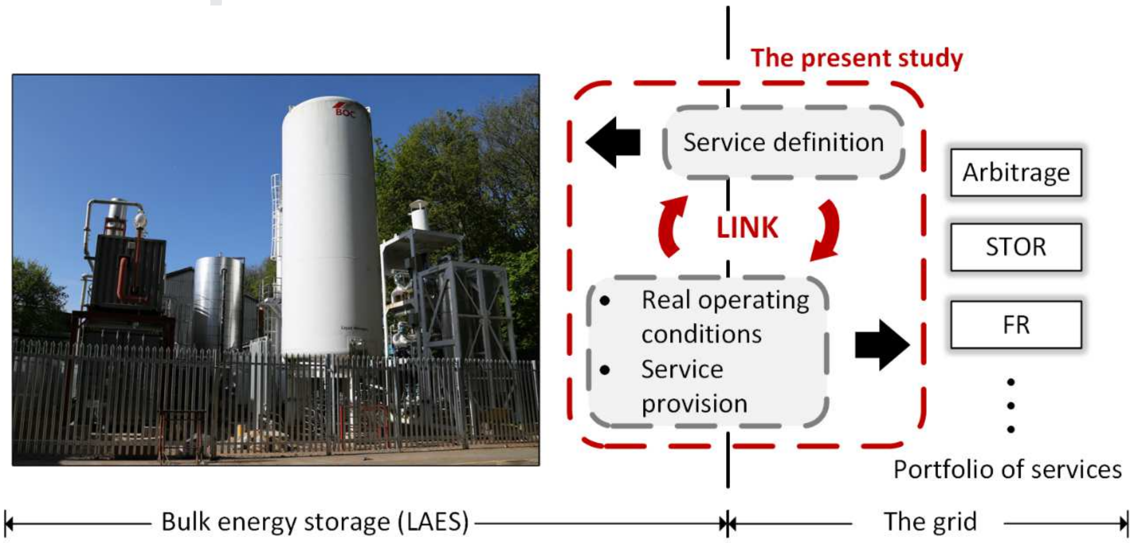

Figure 1: Liquid air energy storage operated as part of the grid – mutual links discussed in the present paper

2. **Proposed Modelling Framework**

The development of the unique modelling framework presented in this work is driven by the need to consider multiple aspects of LAES operation as part of the grid in a coherent and synergic manner. As a consequence, LAES thermodynamics, balancing services specifications and optimal storage dispatching are the building blocks for the developed methodology; they are brought together into the formulation of a LAES-centric MILP optimal dispatch problem. The schematic in Figure 2 gives an overall perspective on the framework adopted and the interactions between the key building blocks; further explanation for each one of these is provided individually in the following subsections.

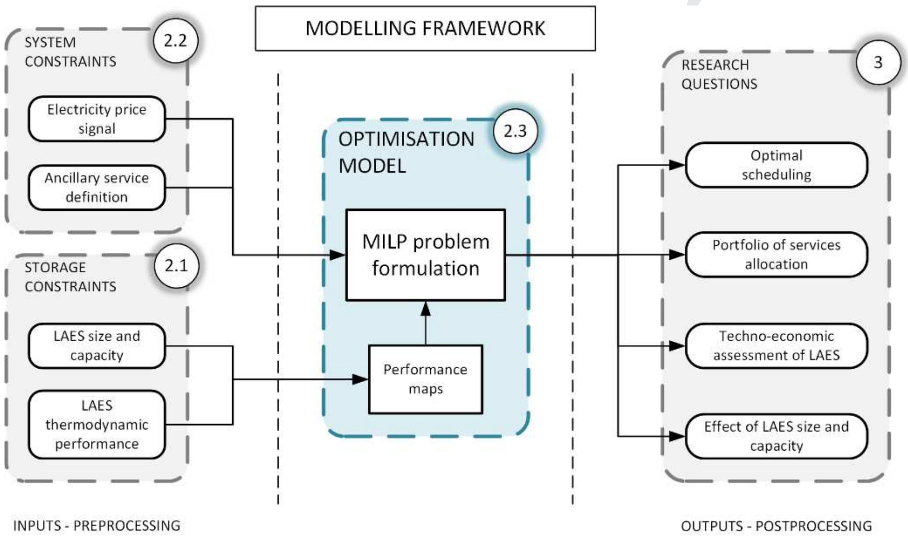

Figure 2: Mind map of the developed modelling framework

The MILP problem definition is central to the approach presented: it was used to optimise the yearly storage dispatch. The formulation was tailored to enforce the constraints associated with provision of reserve services as well as the variability of the electricity prices. The dynamic thermodynamic performance of LAES, together with plant size specification, was captured through performance maps. These were embedded within the MILP problem through a suitable piecewise formulation. Finally, the model was run according to the proposed case studies, to answer the research questions listed in Figure 2. Section 3 details the case studies and the associated results. Discussion on the techno-economic assessment of the optimal LAES scheduling and the effects of plant sizing is addressed in section 4.

2.1 LAES thermodynamics

This study focusses on a standalone LAES plant, which operates as a reversible thermodynamic cycle [19,20]. During the charging phase, off-peak electricity is used to drive a multi-stage intercooled compression train. Ambient air is pressurised to supercritical conditions and further cooled by heat exchange in a multi-stream cold box and/or expansion, eventually entering the two-phase dome. The liquid phase is then separated and stored. During LAES discharging, liquid air is used as the working fluid of a Rankine power cycle, in the power recovery unit (PRU). It is first pressurised by cryogenic pumps, evaporated and finally expanded in a multi-stage expansion train with intermediate reheating; the electricity generated is fed back into the grid. Along the process, thermal energy is generated in the form of compression heat and evaporation cold and studies have shown that effective harnessing of these streams is greatly beneficial to plant performance [21–23]. Therefore, the LAES layout comprises of additional hot and cold recycle loops coupling charging and discharging sub-processes. Thermal energy storage is necessary here, since the difference in time between periods when thermal streams are made available and utilised must be bridged. A simplified sketch of the described LAES system is shown in Figure 3, alongside qualitative thermodynamic cycles for the charging and discharging phase.

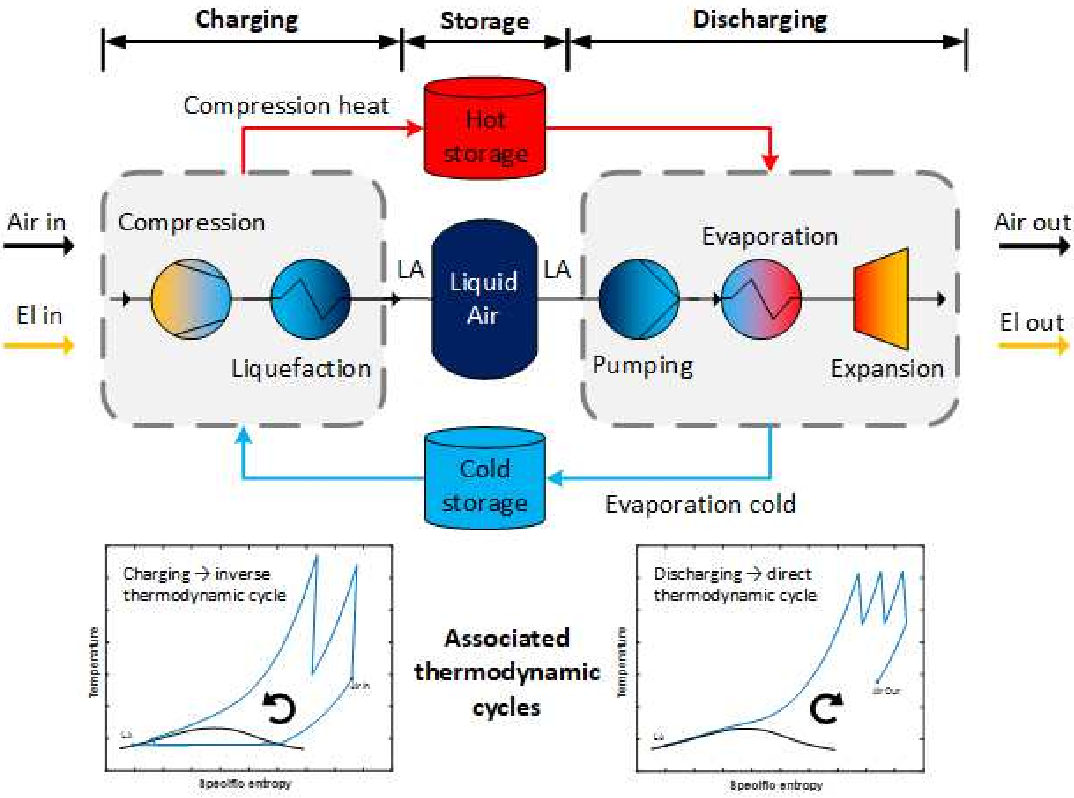

Figure 3: Conceptual drawing of a standalone LAES system and associated thermodynamic cycles for charging and discharging

LAES power output during discharge, $\dot{W}_{out}$, may be estimated based on the specific work $w_{T,j}$ generated by each single turbine stage, by safely neglecting the modest pumping work w_P associated with compression of liquid air:

$$\dot{W}_{out} = \eta_M \dot{m}_{LA} \left(\sum_j w_{T,j} - w_P \right) \approx \eta_M \dot{m}_{LA} \sum_j w_{T,j} \qquad 2.1$$

In equation 2.1, a mechanical conversion efficiency, η_M, may be considered and $\dot{m}_{LA}$ represents the mass flow rate of liquid air flowing through the system. Turbine power output is computed knowing the thermodynamic conditions of air at the turbine inlet (temperature $T_{in,j}$ and specific heat capacity c_p), together with turbine characteristic parameters, namely isentropic efficiency, $\eta_{T,j}$ and expansion ratio, $\Pi_{T,j}$.

$$w_{T,j} = \eta_{T,j} c_p T_{in,j} \left(\Pi_{T,j}^{\frac{k-1}{k}} - 1 \right) \quad 2.2$$

Due to external constraints limiting the delivered power or the intrinsic dynamic behaviour of some components (e.g. packed bed cold storage), off-design conditions may arise along the LAES process. Turbine isentropic efficiency and expansion ratios vary accordingly, following the typical off-design characteristic equations or maps, which can be found for example in [24]. These maps were embedded in a validated numerical model for LAES, considering rated and off-design conditions in the PRU. The model comprises energy, mass and momentum conservation for each component, alongside off-design characteristic equations for turbines, heat exchangers and cryogenic pumps. It is presented in detail as part of a further paper [25], and here it was used to correlate LAES thermodynamic performance to the generation level (i.e. the delivered power output, relative to plant rated value), as presented in Figure 4.

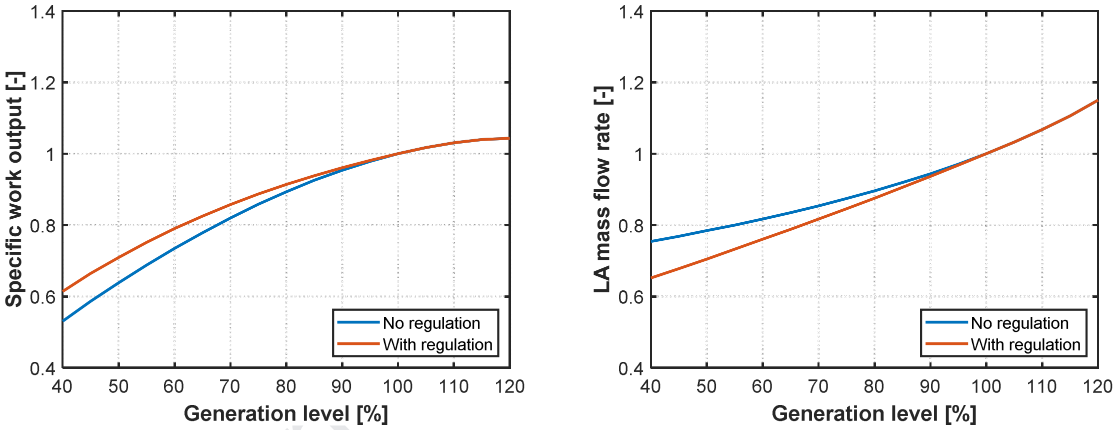

Figure 4: LAES thermodynamic characteristics in the power recovery unit, as a function of plant generation level

The graphs capture a performance detriment in the specific work output when running the PRU at part-load. Efficiencies and expansion ratios in the turbine stages decay, leading to poor LAES performance. Therefore, the mass flow rate consumption varies with the generation level in a nonlinear fashion. A suitable regulation strategy may be considered for part-load operation (i.e. generation level below 100%). This consists in controlling turbine inlet pressure by means of throttle valves, in order to maintain it at rated values and limit off-design inefficiencies, as explained in [25]. Even implementing such regulation strategy, the impact of off-design conditions can be partially mitigated, but not fully avoided (see Figure 4). To account for this inherent link between LAES generation level and its technical performance, a higher liquid air expenditure when running at part-load was accounted for in the MILP, as a major thermodynamic constraint to LAES operation.

2.2 Grid balancing services

Reserve services allow the grid to cope with sudden variations in both electricity generation and demand, avoiding power shortages by ensuring that grid frequency is maintained within safety thresholds. As explained in Figure 5, different ancillary services assist the energy system operator during different instances of frequency stabilisation. They can be classified according to their respective timeframes, which represent the primary criterion defining generation and storage units that are suitable for their provision.

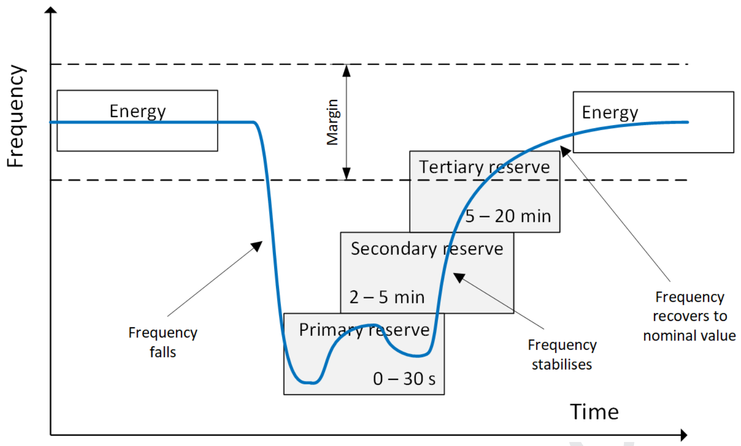

Figure 5: Frequency control ancillary services supporting the grid in the event of a frequency drop

In the case of LAES, typical sizes and ramp-up capability led to considering two major reserve services in the UK market, namely STOR and FR [14,15]. Both the schemes support grid operation with the delivery of active power to the system in response to an electronic dispatch call from National Grid [26]. STOR providers must be available within selected STOR windows that vary throughout the year, generally with a morning and an evening window. Representative values for the season 2016/2017 were used in the present analysis [27]. For FR, tendered windows are between 6:00 and 23:00 during weekdays and between 7:00 and 23:00 at weekends [28]. The service-dependent technical requirements to be met by STOR and FR providers, as well as the respective remuneration schemes are reported in Table 1. They include an availability fee (£/MW/h), payed for the periods the unit is made available, a positional fee (£/h), paid upon call by the operator, and a utilisation fee (£/MWh), for the energy provided following a delivery instruction.

At present, the simultaneous provision of these reserve services within the same tendered window is not allowed in the UK electricity market [29,30]. However, this option would not pose any issue from the technical point of view, provided the cumulative power level committed remains within the feasible generation level for the plant, and sufficient energy is stored to provide the services. Therefore, the concurrent provision of STOR and FR is also contemplated in the present paper, in order to inform on the associated potential economic benefits.

Table 1: Technical specifications and revenue schemes for STOR and FR services in the UK market [27,28]

	STOR	FR
Technical specifications	• Minimum commitment: 3 MW • Response time: < 240 min • Sustained period: > 2 hours • Delivery capability: > 3 times a week	• Minimum commitment: 25 MW • Response time: < 2 min • Sustained period: > 15 min • Ramp-up rate: > 25 MW/min
Revenue scheme	• Availability fee [£/MW/h]: 3.30-6.10 • Positional fee [£/h]: n.a. • Utilisation fee [£/MWh]: 147-155	• Availability fee [£/h]: 175-380 • Positional fee [£/h]: 0-320 • Utilisation fee [£/MWh]: 100-115

In addition to the provision of reserve, the typical strategy of storage operation entails taking advantage of differences in electricity price by charging at low price, while discharging at high price (arbitrage). For the current study, the operation of LAES according to different commitments to arbitrage and reserve services was considered (see section 3). Constraints on available power and energy were formulated as part of the MILP optimisation proposed, to ensure that all services could be provided, if called.

2.3 MILP problem formulation

The MILP problem used to optimise the LAES dispatch profile is presented in this section. Of particular note is the inclusion of LAES thermodynamics within the model, discussed in section 2.3.3, which enabled characterisation of the key interactions between service requirements and provision.

2.3.1 Optimisation variables and inputs

The decision variables for the optimisation (denoted here by bold fonts) define the dispatch profile for the LAES plant. They are associated with the power exchanged between storage and the grid, liquid air expenditure and LAES state of charge (SoC), i.e. liquid air inventory within the storage tank, as summarised in Table 2. It is worth noting that LAES was here assumed to be always charged with rated power input, in agreement with the common practice for gas liquefaction processes not to incur in excessive energy losses. Therefore, the binary variable $\boldsymbol{x_t^C}$ was sufficient to fully characterise the power input to the plant.

Table 2: Optimisation variables of the MILP optimisation problem

Symbol	Definition	Type	Units
$\boldsymbol{D_t}$	Discharge power output	Continuous	[MW]
$\boldsymbol{x_t^D}$	Discharge status	Binary	[-]
$\boldsymbol{x_t^C}$	Charge status	Binary	[-]
$\boldsymbol{K_t}$	Liquid air inventory in the tank	Continuous	[ton]
$\boldsymbol{LAE_t}$	Liquid air expenditure	Continuous	[ton/h]
$\boldsymbol{\psi_{n,t}}$	Piecewise interval identifier	Binary	[-]
$\boldsymbol{\alpha_{n,t}}$	Auxiliary variable	Continuous	[-]

Additional parameters are required to fully formulate the MILP problem. They characterise grid constraints (e.g. electricity price signal, typical reserve call duration, probability, etc.) and storage constraints (e.g. rated conversion efficiencies or minimum level for the LAES power output). They are gathered in Table 3. Further parameters completing the formulation of the optimisation are discussed throughout the section.

Table 3: Input parameters to the MILP optimisation problem

Symbol	Definition	Value	Units	Reference
π_t^{el}	Wholesale electricity price (year 2017)	Time-varying	[£/MWh]	[31]
π_{STOR}^{ava}	STOR availability fee	4.25	[£/MW/h]	[27]
π_{STOR}^{util}	STOR utilisation fee	150	[£/MWh]	[27]

π_{STOR}^{pos}	STOR positional fee	0	[£/h]	[27]
ρ_{STOR}	STOR call probability	2.9	[%]	[27]
τ_{STOR}	Nominal STOR call duration	1.5	[h]	[27]
π_{FR}^{ava}	FR availability fee	210	[£/h]	[28]
π_{FR}^{util}	FR utilisation fee	100	[£/MWh]	[28]
π_{FR}^{pos}	FR positional fee	90	[£/h]	[28]
ρ_{FR}	FR call probability	5	[%]	[28]
τ_{FR}	Nominal FR call duration	0.5	[h]	[28]
γ	Rated liquefier conversion efficiency	0.219*	[MWh/ton]	Model
δ	Rated PRU conversion efficiency	0.131*	[MWh/ton]	Model
D^{min}	Minimum power output from PRU	$0.4D^{MAX}$	[MW]	Model
D^{MAX}	Maximum power output from PRU	Multiple	[MW]	See section 3
C^{MAX}	Maximum power input to liquefaction	Multiple	[MW]	See section 3
K^{MAX}	Maximum storage capacity	Multiple	[ton]	See section 3

* These values are consistent with a rated roundtrip efficiency of 60% for LAES [12,17].

2.3.2 Objective function

The optimal LAES dispatch profile maximises the coordinated provision of arbitrage and the reserve services described in section 2.2. Equation 2.3 presents the mathematical formulation of the objective function, which comprises four contribution: (1) revenue from arbitrage, driven by variations in price signal π_t^{el} with hourly granularity; (2) availability revenue from reserve i; (3) utilisation revenue from reserve i and (4) positional revenue from reserve i.

$$Max \sum_{t=1}^{T}\left[\underbrace{\left(\boldsymbol{D_t} - C^{MAX}\boldsymbol{x_t^C}\right)\pi_t^{el}}_{1} + \sum_{i=1}^{I}\left(\underbrace{S_{t,i}\pi_i^{ava}}_{2} + \underbrace{\rho_i S_{t,i}\pi_i^{util}}_{3} + \underbrace{\rho_i x_{t,i}^{S}\pi_i^{pos}}_{4}\right)\right]\cdot\Delta t \qquad 2.3$$

Earnings from reserve market participation were evaluated using the parameters $S_{t,i}$ and $x_{t,i}^S$. $S_{t,i}$ was defined as a timeseries whose elements equal the committed power level to reserve service i within its respective window, while being null elsewhere; an analogous concept was used for the binary parameter $x_{t,i}^S$. The inherently stochastic nature of reserve services was accounted in equation 2.3 by the term ρ_i, which weights the revenue from a reserve call. ρ_i represents a call probability as the ratio between the average yearly period when reserve was delivered and the total duration of the availability window.

2.3.3 LAES thermodynamic characteristics

Section 2.1 demonstrated that LAES thermodynamic performance is intrinsically linked to its delivered power output. Therefore, the conversion efficiency of the PRU, δ, cannot be treated as a fixed parameter, and should be treated as an optimisation variable (i.e. $\boldsymbol{\delta_t} = \delta(\boldsymbol{D_t})$). This dependency was presented in Figure 4 and is clearly nonlinear, thus requiring an *ad-hoc* mathematical treatment to maintain the linearity of the optimisation.

The value $\boldsymbol{D_t/\delta_t}$ represents the instantaneous liquid air expenditure in each specific timestep. For simplicity in the linearization of the problem, this term was substituted by the variable $\boldsymbol{LAE_t} = \boldsymbol{D_t/\delta_t}$, which captures in a unique variable the inherent connection between power output and conversion efficiency. Characteristic curves extracted from the thermodynamic model were used to express this nonlinear dependency and, as illustrated in Figure 6, a piecewise linear approximation of the characteristics was defined in order to maintain the linearity of the MILP framework [32].

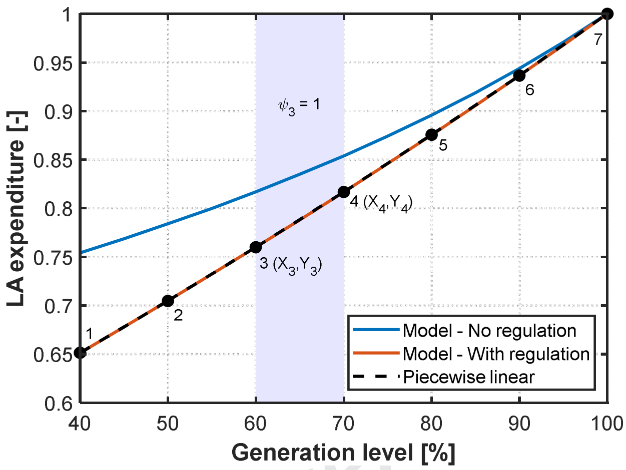

Figure 6: Characteristic liquid air expenditure for LAES, as a function on the generation level, and its piecewise approximation. LAE values have been normalised to the value referring to rated conditions

The feasible region of the generation level was subdivided into $N-1$ contiguous intervals and $N-1$ binary variables $\boldsymbol{\psi_{n,t}}$ were defined accordingly, each one mapping to one of the six piecewise intervals used for the problem specification, as illustrated in Figure 6. During LAES discharge at any given time, the amount of liquid air expenditure is constrained within at most one single interval:

$$\sum_{n=1}^{N-1} \boldsymbol{\psi_{n,t}} \leq \boldsymbol{x_t^D} \quad 2.4$$

By knowing the values of liquid air expenditure Y and generation level X at the extremes of the relevant interval along the characteristic curve, a unique operating point for each timestep was finally determined as a linear combination of these values, through the definition of the auxiliary set of variables $\boldsymbol{\alpha_{n,t}}$:

$$\begin{cases} \boldsymbol{\alpha_{n,t}} \leq \boldsymbol{\psi_{n-1,t}} + \boldsymbol{\psi_{n,t}} \\ \boldsymbol{\alpha_{1,t}} \leq \boldsymbol{\psi_{1,t}} \\ \boldsymbol{\alpha_{N,t}} \leq \boldsymbol{\psi_{N-1,t}} \end{cases} \quad 2.5$$

$$\sum_{n=1}^{N} \boldsymbol{\alpha_{n,t}} = 1 \quad 2.6$$

$$\boldsymbol{LAE_t} \geq \sum_{n=1}^{N} \boldsymbol{\alpha_{n,t}} Y_n \quad 2.7$$

$$\boldsymbol{D_t} \leq \sum_{n=1}^{N} \boldsymbol{\alpha_{n,t}} X_n \qquad 2.8$$

For $\boldsymbol{LAE_t}$ and $\boldsymbol{D_t}$ to lie on the thermodynamic characteristic curve, equations 2.7 and 2.8 would need to satisfy their associated equality constraints. However, the objective function was formulated in such a way that the optimisation would drive these constraints to be binding and thus they were relaxed to inequalities to assist with the solution convergence.

2.3.4 LAES dispatch constraints

Constraints considering the technical as well as the electrical side of LAES operation are listed in the equations below. Limitations associated with LAES power and capacity, mass (and thus energy) stored within the liquid air tank and storage cyclability over a periodic horizon of one week were specified as follows:

$$\boldsymbol{x_t^D} D^{min} \leq \boldsymbol{D_t} \leq \boldsymbol{x_t^D} D^{MAX} \qquad 2.9$$

$$\boldsymbol{K_t} = \boldsymbol{K_{t-1}} + \left[\frac{\boldsymbol{x_{t-1}^C} C^{MAX}}{\gamma} - \boldsymbol{LAE_{t-1}} \right] \cdot \Delta t \qquad 2.10$$

$$0 \leq \boldsymbol{K_t} \leq K^{MAX} \qquad 2.11$$

$$K_0 = K_{0+168\beta} = 0.5 K^{MAX} \qquad 2.12$$

where β is an integer number, denoting each single week. The choice of a weekly margin allows to benefit from longer planning horizons (for example exploiting price differentials between weekdays and weekends) yet giving confidence on the accuracy of the hourly electricity price profile supplied to the model and thus on the estimated revenues. Above one week, point (i.e. hourly) price predictions ahead are typically substituted by price distributions over future periods [33].

Model consistency against a real-time reserve call was ensured following a robust optimisation approach [34]. Thus, additional constraints were used to enforce the restrictions introduced by participation in the different reserve services. First, a cap on the LAES power output was imposed when inside the availability window (equation 2.13), to enable a power turn-up in case of a reserve call. Second, a minimum level in the liquid air tank was enforced (see equation 2.14), which is needed to fulfil service provision, should this be requested by the grid operator. These two constraints ensured the predicted dispatch profile for LAES could accommodate a real-time reserve call at any time.

$$\boldsymbol{D_t} + \sum_{i=1}^{I} S_{t,i} \leq D^{MAX} \qquad 2.13$$

$$0 \leq \boldsymbol{K_t} - \boldsymbol{LAE_t} - \frac{\sum_{i=1}^{I} S_{t,i}\, \tau_i}{\delta} \Delta t \leq K^{MAX} \qquad 2.14$$

Since cryogenic air liquefaction should be operated at its rated conditions [13], LAES charging was restricted to be operated outside of the reserve windows, excluding the possibility of a reserve call which would enforce a power modulation while charging:

$$\boldsymbol{x_t^C} + x_t^S \leq 1 \quad 2.15$$

Here, x_t^S is as a binary parameter which assumes the unit value when at least one of the $S_{t,i}$ is non-zero, indicating a reserve availability window.

3. Case Studies and Results

The model described in section 2.3 was compiled in MATLAB, while the solution was achieved through the optimiser Gurobi 8.1.1 [35], with a 0.5% relative gap as stop criterion for the iterations. Different model runs were conceived to address specific studies with the inclusion of thermodynamic constraints within the MILP optimisation, and in particular:

- *Optimal LAES scheduling*: how the technical performance of LAES, and consequently its optimal dispatch profile, varies when considering plant thermodynamic limitations
- *Optimal LAES sizing*: how plant sizing may affect LAES performance and economic value and what design guidelines can be followed depending on the services to be supplied
- *LAES multi-mode operation*: how providing a portfolio of balancing services to the grid impacts on LAES technical performance and on the final economic value for the plant

Figure 7 summarizes the set of model runs performed in this work, and for each run presents the specific aspects considered and the strategy adopted. Each run will consider a number of case studies, referring individually to a given set of storage services, from Case 0, only arbitrage, to Case 3, complete portfolio of services. The cases are detailed in Table 4, where values are expressed as a percentage of the rated power D^{MAX} to allow generalisation throughout model runs where LAES size is one of the aspects to be investigated. The design parameters for each of the runs are summarised below.

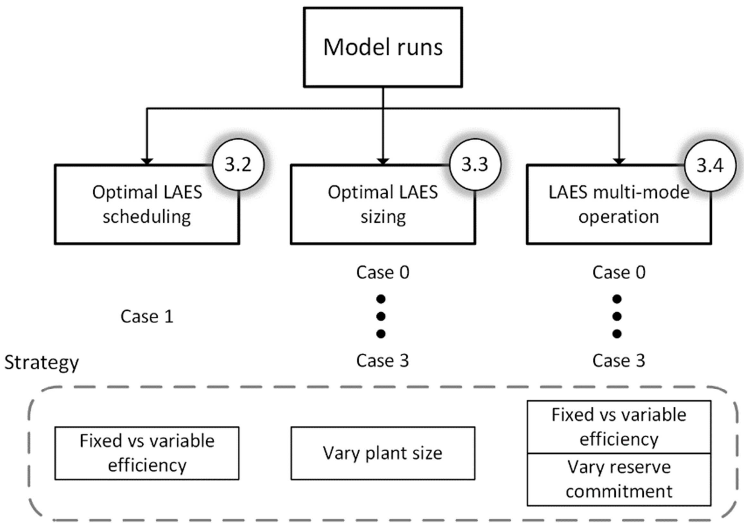

Figure 7: Overview of the model runs performed, with associated case studies and strategy

Table 4: Summary of the considered case studies. Values of committed power are expressed as percentages of D^{MAX}

Case Study		Arbitrage		STOR		Fast Reserve
Case 0	✓	100%				
Case 1	✓	90%	✓	10%		
Case 2	✓	75%			✓	25%
Case 3	✓	65%	✓	10%	✓	25%

Optimal LAES scheduling

A reference plant of 200 MW power output, 100 MW input and 3 hours of rated discharge capacity (600 MWh) was considered for these runs. Outcomes from the full MILP model integrating the LAES thermodynamic characteristics (real approach) were compared with those obtained if a fixed conversion efficiency was considered (ideal approach). Results from one-week operation according to arbitrage and STOR (Case 1) are discussed in section 3.2.

Optimal LAES sizing

For this analysis, a range of LAES sizing options was explored for each of the four cases of Table 4. The design parameters were identified as plant power output D^{MAX}, power input C^{MAX} and capacity K^{MAX}. The effect from each of them was then assessed by independently varying one parameter at a time within the design space defined in Table 5, and running the model for one-year operation; results are presented in section 3.3.

Table 5: Selected design space for the LAES plant

Design parameter	Symbol	Range	Increment step
PRU power output	D^{MAX}	100 MW - 300 MW	50 MW
Liquefaction power input	C^{MAX}	$0.1D^{MAX}$ - D^{MAX}	$0.1D^{MAX}$
Storage tank capacity	K^{MAX}	2 h - 10 h	1 h

LAES multi-mode operation

Based on the outcomes from the sizing study, a LAES plant of 200 MW output, 40 MW input (20% D^{MAX}) and 3 hours discharge capacity was chosen as a versatile solution to serve the four cases of Table 4. In section 3.4, techno-economic results from the model are assessed for such a plant over a one-year operation.

3.1 Economic and performance indicators

To quantify the economic performance of LAES, a static payback time (PBT) was chosen as the economic metrics in this study:

$$PBT = \frac{CAPEX}{Rev} \quad 3.1$$

where $CAPEX$ represents the capital cost associated with LAES plant and Rev is the yearly revenue from LAES participation in energy and reserve markets, i.e. the value of the MILP objective function. Costs were based on the supply chain quotes indicated by Highview Power Ltd for a 10 MW plant [5], and scaled up with a 0.6 exponent and a learning rate assuming 17.5% cost reduction for a double number of units [36]. These equations have the advantage of accounting independently for the cost contribution from each of the three LAES sub-systems: power recovery unit χ_D, liquefaction χ_C and storage tanks χ_K:

$$\chi_D = 5653\left(\frac{D^{MAX}}{10}\right)^{0.6} \quad 3.2$$

$$\chi_C = 11406\left(\frac{C^{MAX}}{4}\right)^{0.6} \quad 3.3$$

$$\chi_K = 1778\left(\frac{K^{MAX}}{86}\right)^{0.6} \quad 3.4$$

$$CAPEX = \chi_D + \chi_C + \chi_K \quad 3.5$$

D^{MAX} and C^{MAX} are expressed in MW and K^{MAX} in MWh. Cost is expressed in 2012 k$. The conversion to 2017 k£ was performed by adopting a proportionality factor 1.47, which accounts for the average USD-GBP exchange rate in year 2012 [37] and UK inflation rates between years 2012 and 2017, from the Office of National Statistics [38]. The accuracy of the costing approach was tested by comparing its predictions with results available in the literature for a variety of LAES plants [9,12,17], showing a satisfactory agreement within $\pm$6%.
Concerning the technical performance of LAES, plant roundtrip efficiency, η_{RT}, was computed as the ratio between the energy output and input, over the entire operating horizon:

$$\eta_{RT} = \frac{\sum_t \boldsymbol{D_t}\Delta t}{\sum_t C^{MAX}\boldsymbol{x_t^C}\Delta t} \quad 3.6$$

The parameter ξ defines the instantaneous discharge of the LAES as a function of its maximum discharge capability. Its value was computed only for situations when the power output is nonzero (i.e. LAES is discharging), and used to link plant scheduling with its roundtrip efficiency:

$$\xi = \frac{\boldsymbol{D_t}}{D^{MAX}} \qquad \forall\, t : \boldsymbol{x_t^D} \neq 0 \quad 3.7$$

3.2 Optimal LAES scheduling

The optimal weekly dispatch for LAES, when operating according to Case 1 (arbitrage + STOR) is presented here to highlight the key variations originating from the inclusion of thermodynamic constraints within the optimisation framework. Figure 8 refers to the ideal case (i.e. the first-order assumption of constant roundtrip efficiency widely adopted in the literature [11,12,16]), while results in Figure 10 account for the thermodynamic characteristics. The shaded area represents weekly reserve windows.

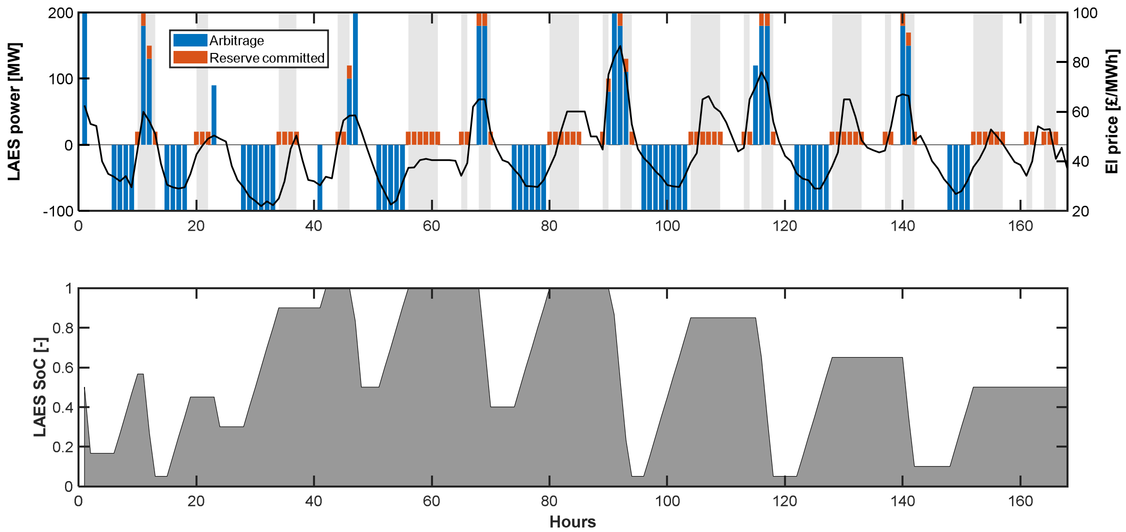

Figure 8: One-week LAES dispatch when providing arbitrage and STOR. Constant conversion efficiency case

In both cases, LAES is charged preferentially during periods of low electricity price, while discharged at peak times. When discharging, 100% power output is preferred, but within the reserve windows only a portion of LAES power output can be devoted to arbitrage. In the likely event of availability windows coinciding with the highest electricity prices, part-load discharging is imposed on the LAES due to the constraints associated with reserve provision. Additionally, a minimum air level (SoC) has to be guaranteed within the reserve windows to ensure service deliverability, further limiting the possibility of rated discharge.

As the scheduling in Figure 8 is ideal, reduced performance at off-design conditions is not accounted for, which could lead to an optimistic and unfeasible dispatch profile. To verify this, a corrected solution was computed, meaning the real variations of LAES conversion efficiency with the generation level (i.e. the characteristic curve in Figure 6) were used to compute the actual LAES SoC from the storage schedule of Figure 8. Results are presented as a dashed line in the bottom plot of Figure 9 (Corrected – Unfeasible). Clearly, the ideal scheduling is not feasible, as the LAES SoC would drop below 0 multiple times. This is because, during part-load operation, off-design conditions reduce the specific work output from the PRU (see the top plot of Figure 9); therefore, more air than expected is necessary for sustaining the given power output, leading to a sharper decrease in LAES SoC.

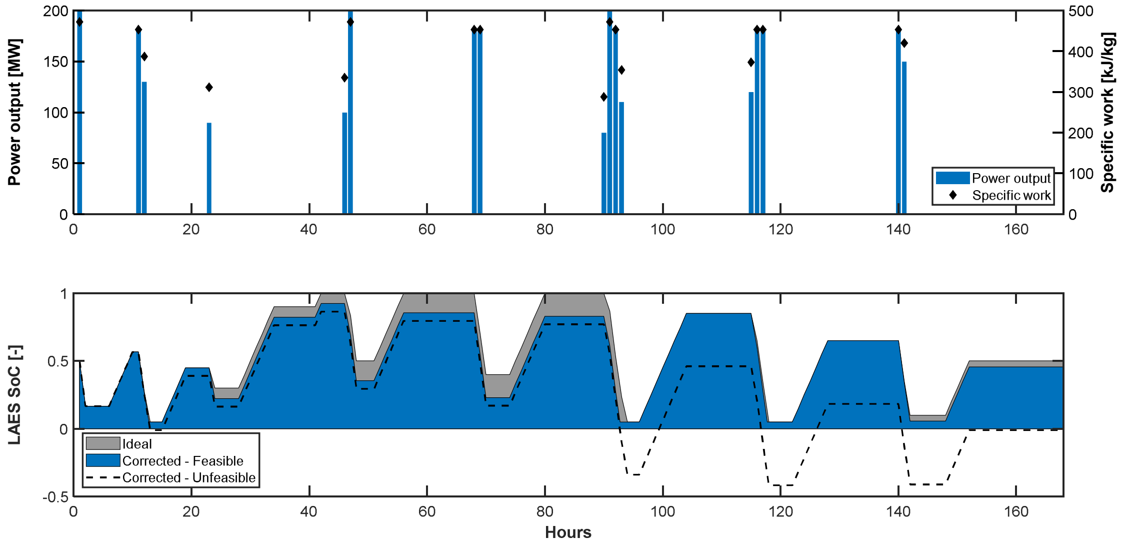

Figure 9: Corrected LAES dispatch by a posteriori accounting for thermodynamic characteristics

The major consequence of not accounting for thermodynamic characteristics within the optimisation is a dispatch profile which is not feasible, a posteriori. By sustaining LAES power output for a shorter period, the model constraints can still be satisfied, and the scheduling fulfilled by LAES (resulting in the Corrected – Feasible area in Figure 9, for LAES SoC). However, this means 3 out of the total 17 power generation instances cannot be fully sustained for the entire 1h timestep. This causes loss of revenues, potentially incurring in penalty payments and, more importantly, reduced contribution of LAES to grid stability. Also, LAES roundtrip efficiency would be 54.7% in this case: a 10% reduction of the nominal value 60%.

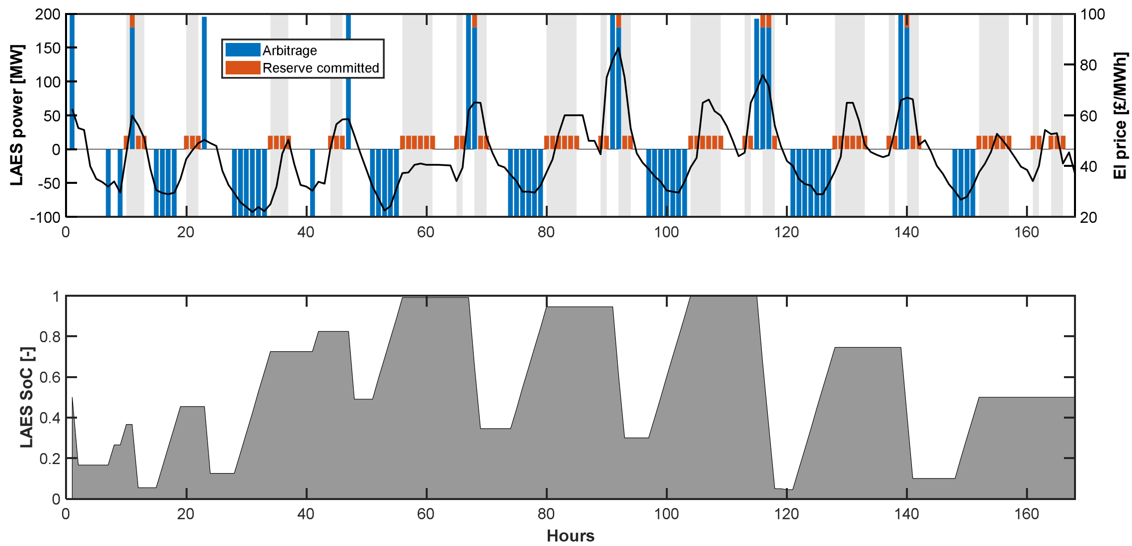

Figure 10: One-week LAES dispatch profile when providing arbitrage and STOR. Variable conversion efficiency case

When thermodynamic characteristics are accounted properly in the MILP framework (Figure 10), the optimal scheduling would require shorter LAES discharge periods but higher power output. The optimisation seeks to discharge preferentially at nominal condition, as can be inferred by the comparison of the average $\boldsymbol{D_t}$ values presented in Table 6**.** Discharging hours decrease from 17 to

13, but this allows the LAES to run at full power output during the highest electricity price peaks. The variations of LAES SoC suggest that the plant is providing inter-day arbitrage, capitalising on the largest energy price differentials. This highlights the importance of modelling large-scale storage over extended periods [11], in contrast with the typical patterns for technologies such as batteries [39]. The computed roundtrip efficiency for the real case is 58.64%, which is higher than the value referring to the feasible corrected dispatch. This demonstrates that a truly optimal scheduling can be achieved only by including the thermodynamic characteristics of LAES *within* the optimisation, as opposed to the re-elaboration of an ideal, unfeasible scheduling profile. Detailed discussion is provided section 4.1.

Table 6: Scheduling and performance metrics for the ideal and real weekly dispatch optimisation

Metrics	**Model run**	
	Ideal	**Real**
Discharging hours [h]	17	13
Average sell price [£/MWh]	67.36	67.5
Average power output [MW]	155.2	189.9
Energy output [MWh]	2639	2468
Charging hours [h]	44	42
Average buy price [£/MWh]	30.39	30.2
Energy input [MWh]	4400	4200
LAES roundtrip efficiency, η_{RT} [%]	60	58.6
Number of equivalent cycles [-]	4.4	4.11

3.3 Optimal LAES sizing

In the following, we refer to optimal sizing as the process of choosing storage design based on the outcomes from the sensitivity-type of analysis carried out on the rating of each LAES sub-system: liquefaction, PRU and tank capacity. This approach is meant to shed a light on the complex relationship between system design, portfolio of services to be provided and techno-economic performance, as opposed to identifying a unique optimized LAES size as outcome from a formal optimisation problem.

Figure 11 captures the effect of each independent design parameter on LAES payback time, as a function of the considered operating strategy. On the left-hand axes, PBT values are plotted; they have been normalised to the PBT of the reference 200 MW, 100 MW input and 600 MWh LAES, which lies sufficiently in the middle of the design space. On the right-hand axes, the sensitivity of PBT to the relevant design parameter is reported as $\partial PBT/\partial x$, where x is the design parameter. Each row in Figure 11 captures the individual effect of one of the design parameters. From the top row downwards: PRU power output, liquefaction power input and storage capacity.

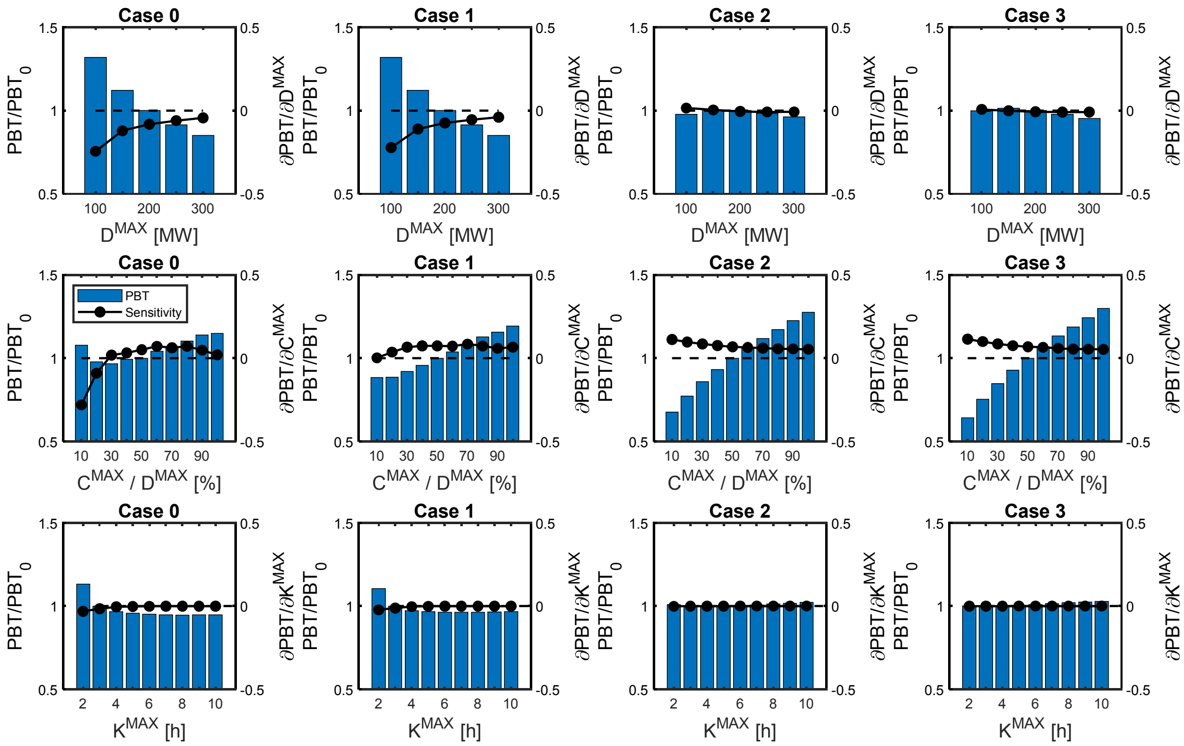

Figure 11: Independent impact of LAES design parameters on its profitability, for different operating modes. Row 1: PRU power output; row 2: liquefaction power input; row 3: storage tank capacity

Minimum PBT is determined by the ratio between the CAPEX associated with the selected design and the cash inflows from LAES operation. This latter value is determined by the specific dispatch profile for the plant – which clearly depends on the operating mode – as well as the revenue scheme.

When dealing with power sizing, larger PRU generally leads to better economic results (see first row of Figure 11). This is expected for cases heavily relying on arbitrage (Case 0 and Case 1), since costs increase with exponent 0.6, while arbitrage revenues are proportional to the PRU size, D^{MAX} (doubling D^{MAX} yields a double revenue). The behaviour is different when the share of reserve revenues is high (Case 2 and Case 3). At small PRU values (below 150 MW), the constant availability fee represents the main source of income, in such a way that the increase in revenues for larger PRU is not enough to offset the increase in CAPEX. For PRU above 150 MW, the increase in revenue is mainly driven by the utilisation fee, outpacing the CAPEX increase.

Considering liquefaction size (second row in Figure 11), an optimum value minimising PBT is found for Case 0 when the liquefier rating is 30% of the PRU. Because of the high share of CAPEX associated with the liquefier (in the range of 60%-70%) this is the most important parameter to minimise. However, this optimum value is relevant for arbitrage alone. When reserve is added, it provides additional revenues, which are little influenced by the liquefier rating, C^{MAX}. Therefore, the optimum is displaced progressively towards smaller values of C^{MAX}, and eventually below the lower limit considered for the current analysis.

Looking at capacity sizing (i.e. choosing the optimal energy storage capacity for given values of charging and discharging rated power), Figure 11 demonstrates how the storage tank size, K^{MAX}, is in general the least sensitive factor. This is no surprise, since the share associated with the tank is marginal with respect to plant costs, at less than 10% of the total CAPEX. Apart from relatively small storage capacities (2 hours of rated discharge or less), the predicted PBT displays only minor improvements for each additional hour of storage, with negligible influence of the operating mode. In general, outcomes show that the optimal decision on LAES sizing for minimising the investment payback time should ultimately be tailored to the specific operating mode, especially concerning the choice of the rated power input and output. However, for the assessment of LAES multi-mode operation, a single plant design is desirable. A 200 MW LAES featuring 40 MW liquefaction (20% D^{MAX}) and 3 hours of storage capacity was thus identified as a versatile solution yielding close-to-optimal PBT value for all the case studies. Further elaboration around sizing aspects is part of the Discussion section, where LAES size is also related to scheduling and thermodynamic performance metrics.

3.4 LAES multi-mode operation

The techno-economic results obtained from the MILP model for the individuated 200 MW LAES plant are presented here. Figure 12 shows the existing correlation between LAES operating mode and its technical performance, as captured by roundtrip efficiency η_{RT} and the power indicator ξ.

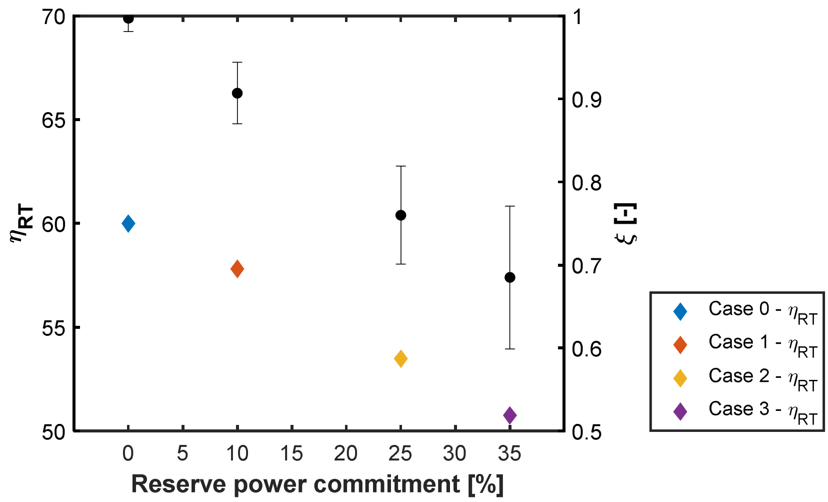

Figure 12: Link between operating mode and LAES plant technical performance

It demonstrates that the value of roundtrip efficiency over the whole year can change significantly (variation of up to 17% of nominal efficiency – from 60% to about 50% η_{RT}) when committing generation capacity to reserve services. While for Case 0 (arbitrage alone) LAES is mostly run around the rated generation level ($\xi \approx 1$), the larger the commitment to reserve, the larger the deviation from the rated power output, with associated off-design losses. Also, the values of the power indicator ξ become more distributed, meaning higher variability of LAES generation levels.

The more services that the LAES is providing, the more likely it is to operate at off-design conditions. This results in lower conversion efficiency and a reduced power exchange between LAES and the grid. However, LAES can benefit from more favourable differentials between average buy and sell prices and, on top of this, additional revenue schemes from reserve. The financial viability for the multi-mode operation is confirmed in Figure 13, which shows a breakdown of the yearly revenues for the reference plant, as a function of the operating mode and of the modelling approach. It demonstrates that committing power to reserve is economically justified by higher earnings, despite poorer plant efficiency. Multi-mode cases are found to be significantly more profitable than arbitrage alone, in agreement with what was highlighted in [40].

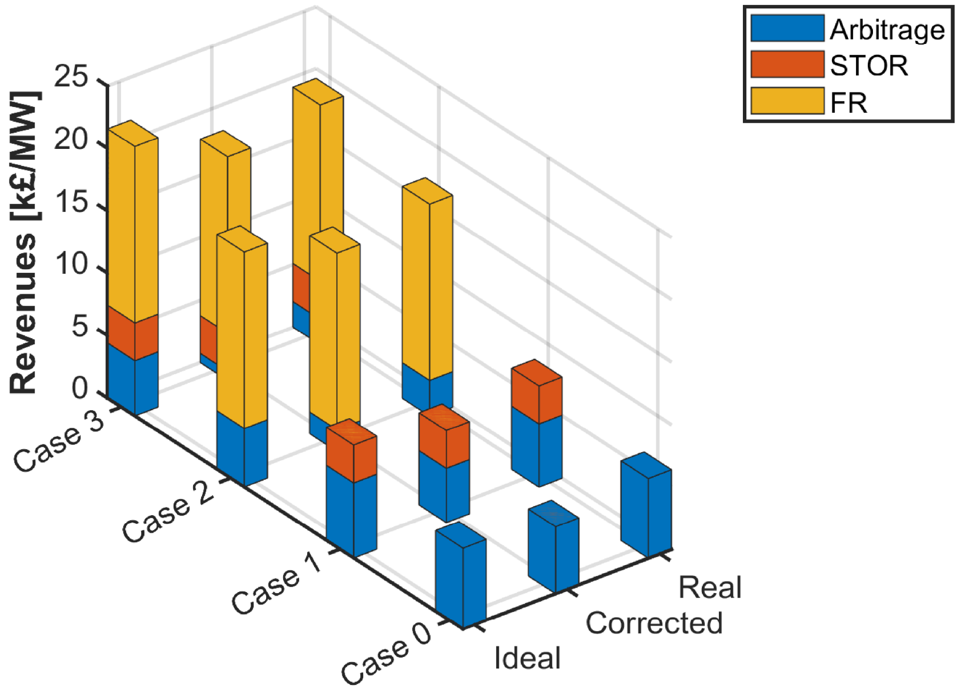

Figure 13: Yearly revenues for LAES as a function of the modelling approach, for the four selected operating modes

When multi-mode operation is based on arbitrage and STOR (Case 1), the former accounts for the majority of revenue; this agrees with the findings in [17]. In Case 2 and 3, on the contrary, earnings from FR provide the most significant source of income. The share of revenue provided by arbitrage decreases progressively: from 62% in Case 1 to 17% in Case 2 and down to only 11% in Case 3. This is due to the availability of additional revenue streams as well as to the lower conversion efficiency of LAES when committing power to reserve, as shown previously in Figure 12.

4. Discussion

Results presented so far confirm the unique capability of the developed model to provide an optimal dispatch profile, leading to more accurate estimations of LAES techno-economic value than traditional models based on constant efficiency. In this section, further discussion is given on the link between LAES scheduling, size and operation, which can only be captured thanks to the developed modelling framework.

4.1 Financial impact of accurate thermodynamic modelling

Based on the values in Figure 13, Table 7 compares the revenue from the ideal, constant efficiency model with revenues from both the a posteriori correction and the realistic MILP model. One can see that the correction of the ideal scheduling profile yields a significant reduction in the revenues. This is due to an infeasible profile which forces the storage to discharge for shorter timespans in order to comply with the constraints. Being able to capture LAES behaviour within the optimisation ensures the computation of a truly optimal and feasible scheduling profile. This is crucial, as it improves LAES profitability.

Table 7: Predicted variation of LAES economic value with respect to the constant conversion efficiency case

	Lost revenue - Corrected		Lost revenue - Real	
	[k£/MWh]	[%]	[k£/MWh]	[%]
Case 0	1.12	17%	0.11	2%
Case 1	1.67	18%	0.95	10%
Case 2	2.94	16%	1.84	10%
Case 3	3.67	17%	2.36	11%

Revenues from the realistic model display 2% reduction with respect to constant conversion efficiency for arbitrage alone (Case 0), while this value increases up to 11% for Case 3 (complete portfolio of services). This suggests an accurate modelling of LAES is necessary for multi-mode operation, in agreement with the conclusions drawn for a compressed air energy storage plant in [41]. The more services LAES is providing, the more revenue is lost for the corrected case, due to frequent off-design discharge (see section 3.4). Misevaluation of storage performance in these conditions would lead to a major impact on LAES financial viability.

4.2 Design guidelines for LAES

A key technological benefit of LAES is the possibility to design a plant in such a way that rated power for charging process and for the discharging process can be selected independently [10,12,17]. This feature of LAES is especially relevant for enabling a tailored design for specific operating strategies, as described in section 3.3.

The case providing arbitrage alone is the most sensitive to LAES power sizing (in terms of both liquefaction input and PRU output), showing the need for a careful design choice which is driven by the case-dependent fluctuations of electricity prices. When increasing the participation to reserve services, the dependency of PBT on power sizing progressively reduces. A larger portion of the revenues can be accessed via service commitment rather than energy dispatch, with the latter being primarily affected by LAES size. The final choice of D^{MAX} and C^{MAX} in these cases is likely to be driven by the technical limitations associated with the integration of LAES with the grid and its infrastructure (e.g. network constraints), rather than storage-centric considerations.

When considering storage capacity K^{MAX}, limited improvement of PBT is predicted for LAES capacities above 2-3 hours of rated discharge. This contradicts the typically guidelines for thermo-mechanical storage, deriving from a purely economic assessment of the low costs per unit kWh associated with these technologies [4,36]. However, different conclusions arise when technical considerations as well as storage dispatch are considered. Reserve services involve power delivery for relatively short periods and are unaffected by capacity specifications. Hence, every extra hour of added capacity yields progressively limited improvement on plant profitability if LAES power rating is not increased accordingly. As an example, Figure 14 shows how around 15% of tank capacity is not used for Case 1, when tank size is 6 h, as opposed to Figure 10, where tank size is 3 h and is fully utilised. LAES capacity reduction has also the added benefit of containing the land area required by the installation, which is greatly dependent on dimensions for liquid air and cold storage tanks [6].

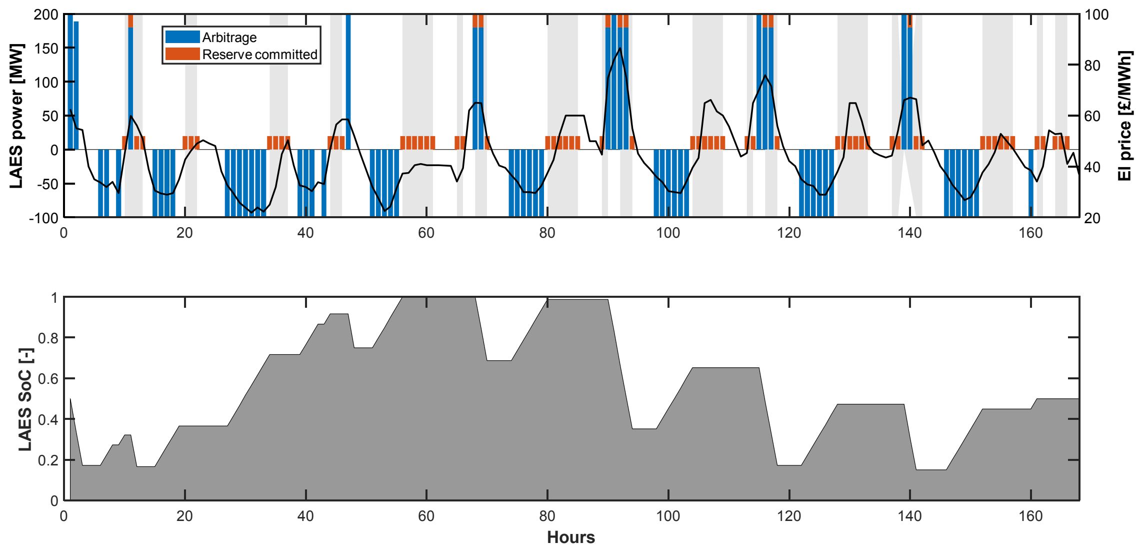

Figure 14: One-week LAES dispatch when providing arbitrage and STOR. 6 hours tank capacity

The tank capacity has the biggest impact on the thermodynamic performance of the LAES. Table 8 shows how larger tanks correspond to a better roundtrip efficiency. Due to the increased LAES capacity, it becomes less likely that the constraints involving a minimum SoC are binding. This in turns reduces the likelihood of LAES part-load discharging due to capacity constraints and it is reflected by the average values of the power indicator ξ being closer to the ideal value 1. Together with higher LAES thermodynamic efficiency, the total number of charging and discharging instances over the year increases, creating a compounding effect that leads to higher total revenues. However, once a critical amount of storage is established, additional capacity has very little effect economically, except to match the associated increase in CAPEX. The critical amount to be ensured is 4-5 hours if operating arbitrage alone, while only 2-3 hours are sufficient if simultaneous reserve is considered.

Table 8: Scheduling and performance metrics for LAES, as a function of the storage capacity

Case	K^{MAX} [h]	Discharging hours [h]	Off-design hours [h]	Power indicator, $\bar{\xi}$ [-]	Charging hours [h]	LAES roundtrip efficiency, η_{RT} [%]
0	2	532	150	0.99	1774	59.4
	6	676	76	1.00	2238	60.0
	10	686	60	1.00	2258	60.0
1	2	448	404	0.89	1396	57.1
	6	592	536	0.91	1848	58.2
	10	620	556	0.91	1924	58.6
2	2	334	324	0.76	952	53.1
	6	380	366	0.76	1068	54.0
	10	382	366	0.76	1062	54.7
3	2	266	258	0.68	716	50.8
	6	306	296	0.68	814	51.3
	10	308	292	0.68	808	52.1

4.3 Effect of reserve market participation

Focus is now given to the role reserve commitment plays in defining the financial viability of LAES. Figure 15 shows plant roundtrip efficiency as a function of the committed power to STOR and FR. The same amount of capacity annexed for FR has higher impact on performance than STOR. This can be explained through the larger availability window associated with FR, which limits the LAES to part-load discharge over longer periods. The power indicator ξ varies from 0.78 to 0.71 if 30% is devoted to STOR or FR, respectively.

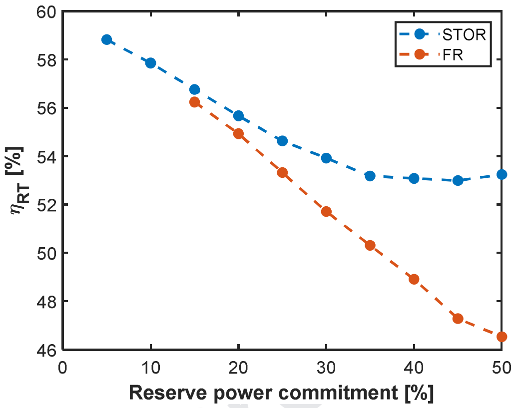

Figure 15: LAES roundtrip efficiency for different levels of power commitment to STOR and FR

Additionally, the larger is the power commitment, the greater the difference between the two considered reserve services. This is because more power is needed to ensure reserve deliverability and LAES is restricted to discharge at lower value, but for longer periods. Services requiring larger availability windows are further penalised (for example FR with respect to STOR), because price peaks are now more likely to coincide with availability windows. A reduced roundtrip efficiency limits the accessible profit from arbitrage, and a techno-economic trade-off must be achieved to maximise revenues. Figure 16 illustrates the economic impact of different choices in reserve power commitment.

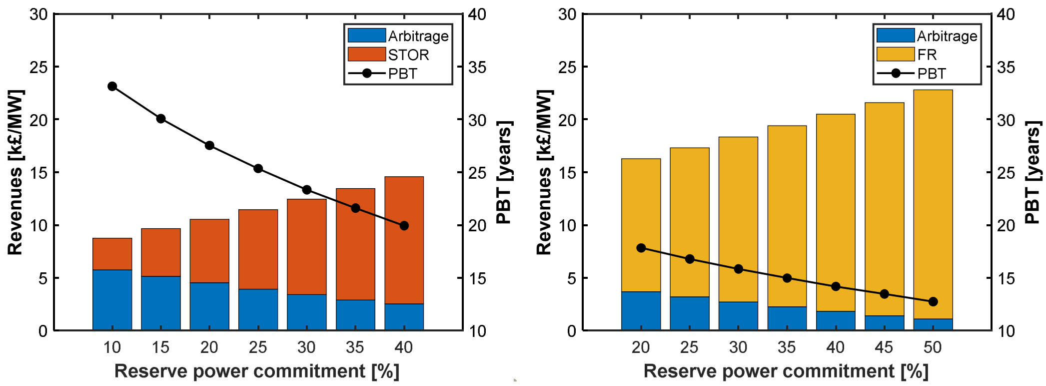

Figure 16: Yearly revenues for different levels of power commitment to reserve: STOR (left) and FR (right)

Higher revenues from increased reserve market participation are obtained, despite worse technical performance for LAES. Therefore, the most profitable approach could be to allocate more power into reserve services and possibility solely provide reserve services. Payback time drops from 33 to 23 years if 30% instead of only 10% of the rated output is committed to STOR; for FR, figures change from 18 to 14 years, when committing 40% instead of 20%. However, LAES scheduling

would in this case be mostly subject to the real-time calls from the grid operator, making it challenging to achieve meaningful predictions for the dispatch profile.
The possibility of supplying reserve alongside arbitrage drastically changes the dispatch pattern of LAES. Additional constraints to storage operation are introduced, resulting at times in competition between energy and reserve service. This is more significant for higher power commitment but enable the storage operator to benefit from higher profits. At lower commitment levels, revenues from FR are significantly higher than those from STOR, while the difference decreases as the commitment levels increase. In this case, the possibility to bid in different reserve markets could be particularly suitable. Ultimately, diversifying over a portfolio of revenue streams is necessary to decrease the risks associated with the variable profitability of ancillary services over the markets and the seasons. Therefore, a balanced power commitment should be sought.

5. **Conclusions**

This paper aimed at modelling and assessing the interdependence between the technical and economic performance of a LAES plant providing energy arbitrage and reserve services in the UK electricity market. For the first time, this was achieved by including realistic thermodynamic characteristics and constraints of LAES into a MILP framework, to optimise storage scheduling and dispatching against a portfolio of market services. The main conclusion can be summarised as follows:

- Storage thermodynamic limitations alter its optimal dispatching schedule: regardless of the operating mode, the plant will be run over fewer cycles but at higher power output, thus getting closer to rated conditions.
- Guidelines for plant optimal sizing depend fundamentally on the operating mode as well as the potential revenues that can be accrued (based on electricity price profile and reserve remuneration schemes). While for arbitrage only liquefier ratings as small as 30% of the PRU seem to provide the best solution, in multi-mode operation an ideal plant features a large PRU, a small liquefier (10% or lower than the PRU), and energy capacity in the range of 2-3 hours of rated discharge.
- LAES thermodynamic performance, as measured by η_{RT}, is negatively affected by multi-mode operation, with variations up to 10 points for the cases explored. Additionally, for a same level of reserve power commitment reserve services characterised by longer duration windows are likely to impact more on LAES technical performance.
- In multi-mode cases considering energy arbitrage alongside STOR and/or FR, worse LAES thermodynamic performance is economically more than compensated by larger revenues, meaning provision of a portfolio of services rather than traditional arbitrage-only operation should be sought by the storage operator. However, the higher the power committed to reserve services, the more it is crucial to model the variations of storage conversion efficiency for avoiding situations of unfeasible scheduling and missed revenues (up to about 2 k£/MW per year).

These conclusions all point towards the importance of ensuring high LAES flexibility to cope with a more and more diversified portfolio of energy and reserve services to be provided, whilst including thermodynamic constraints within optimisation models for better techno-economic assessment. The methodology presented here provides a relevant tool for predicting LAES value and potential in such a context and has additional utility, as it could be extended to a broad range of thermo-mechanical storage technologies.

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Highlights

- LAES multi-mode operation for energy arbitrage and reserve services is assessed
- A novel MILP optimisation including LAES thermodynamic constraints is formulated
- Against traditional models we get 10% lower revenues, but feasible dispatch profile
- Multi-mode operation may allow payback time below 20 years
- LAES power sizing allows optimal design which depends on the operating strategy

CRediT authorship contribution statement

Andrea Vecchi: Conceptualization, Methodology, Software, Formal Analysis, Writing – Original Draft, Writing – Review & Editing, Visualization **James Naughton:** Conceptualization, Methodology, Writing – Original Draft, Writing – Review & Editing, **Yongliang Li:** Supervision **Pierluigi Mancarella:** Supervision**,** Conceptualization, Writing – Review & Editing, Funding acquisition **Adriano Sciacovelli:** Conceptualization, Methodology, Supervision, Writing – Review & Editing, Funding acquisition

Declaration of interests

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

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: