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Incomplete markets in risk and storage duration in future markets

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Abstract

Renewable energy sources (RES) are crucial for decarbonising the electricity grid and mitigating climate change. However, their variable and uncertain nature poses challenges to the reliable and efficient operation of energy systems. To effectively integrate renewable resources, flexible technologies are necessary. One flexible technology is storage. Whereas short-duration energy storage has been widely explored, long-duration energy storage (LDES) has not. LDES systems can operate across different timescales (e.g. hours, weeks, and even seasons) and support very large shares of renewables in the electricity mix.

Despite the value of LDES in highly decarbonized scenarios, there are technological and market challenges that prevent their deployment, especially because revenues uncertainty expose LDES investors to financial risks. To effectively hedge financial risks and consequently, improve LDES investment conditions, different financial mechanisms, such as long-term contracts, can be helpful. No prior research has investigated the integration of flexible energy storage technologies beyond batteries, particularly LDES, under market conditions where investors can partially hedge financial risks. However, previous research has shown that limited risk trading could lead to under-investment in equipment resilience.

Therefore, in this work, equilibrium models will be employed for generation capacity expansion planning with risk-averse market participants, aiming to determine whether incomplete risk trading instruments explain under-investments in LDES assets. The outcomes of this research will offer valuable insights to several stakeholders on long-term planning strategies.

Contents

List of Acronyms

ADMM Alternating Direction Method of Multipliers

BESS Battery Energy Storage Systems

CAES Compressed Air Energy Storage

CVaR Conditional Value at Risk

ESS Energy Storage Systems

GHG Greenhouse Gas Emissions

KKT Karush-Kuhn-Tucker

LDES Long Duration Energy Storage

MCP Mixed Complementarity Problem

MIP Mixed Integer Program

MIQCP Mixed Integer Quadratically Constrained Program

PHS Pumped Hydro Storage

RES Renewable Energy Sources

T&D Transmission and Distribution

VRE Variable Renewable Energy

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1
Introduction

The sustainable development targets defined by the Paris Agreement were set with the aspiration of reducing greenhouse gas emissions (GHG) in order to limit the rise of global warming temperature below 2°C (Conference of the Parties (UNFCCC) staff 2016). The current dependence of our world on fossil fuels, especially in the energy sector, underlines the need for a rapid and effective transformation that will lead to zero GHG emissions by 2050, compared to the 20 billion tonnes level back in 2020 (Schmidt & Staffell 2023, International Energy Agency (IEA) staff 2014).

In recent years, energy systems have experienced an upward shift in the deployment of variable, weather-dependent, renewable energy sources (RES). RES play a crucial role in decarbonising future power systems and mitigating climate change. The 2023 world energy outlook by International Energy Agency (IEA) staff (2023) projects that variable renewable energy (VRE) sources will reach 11 TW by 2030 and 28 TW by 2050. However, their variability and uncertainty pose major flexibility and supply challenges due to imbalances between the energy generated from them and load demand (International Energy Agency (IEA) staff 2011, Schmidt & Staffell 2023). Therefore, in order to ensure the reliable and efficient operation of energy systems, handling their inherent variability is utmost importance. A key solution to this problem is the integration of energy storage systems (ESS) (Schmidt & Staffell 2023). Although energy storage solutions, such as batteries, usually address the intermittency of RES and balances demand-supply variations, other technologies are required that go beyond the current battery capabilities, such as limited energy capacity and short discharge durations, and can operate over different timescales—from hours to weeks and seasons—(LDES Council staff 2024). Long-duration energy storage (LDES) have the ability to store energy for longer durations than conventional batteries and consequently, support even higher shares of VRE sources. These assets help accelerate the transition towards fully decarbonised, flexible, and sustainable net-zero carbon systems, as indicated in recent energy planning and policy reports (LDES Council staff 2024, LDES Council staff & McKinsey & Company staff 2021).

Nevertheless, there are many barriers to the deployment of LDES, mainly related to their high capital costs and long lead times from a technological perspective and revenue uncertainties from a market perspective. More specifically regarding the latter, energy trading in day-ahead and intraday markets, balancing markets and ancillary services are the major revenue streams of these technologies. LDES are essential for maintaining grid stability and flexibility by supporting renewable integration. However, these contributions are undervalued, insufficiently remunerated in current electricity markets, and not fully compensated through existing trading instruments. (Bassi et al. 2015, McNamara et al. 2022, Jones et al. 2016, Bowen et al. 2019, Schmidt & Staffell 2023).

Under the current market design, revenue uncertainties, combined with energy price volatility and lack of adequate spreads to support energy arbitrage, create financial risks for LDES investors. If these risks are not properly managed, they can significantly alter investments conditions. Therefore, financial solutions are needed to effectively trade risk and facilitate the deployment of LDES. Before proceeding further, it is important to define what is meant by current market design and, to an extent, market-based financial solutions. In reality, all markets are incomplete, which refers to the limited ability of market participants to hedge risks through a broad range of market-based or financial solutions. In simple words, the current electricity market design does not have the required amount or even different types of contracts to fully hedge investors' risks and aid in this transformation (Mays et al. 2019, Mays & Jenkins 2023, Ehrenmann & Smeers 2011, Dimanchev et al. 2024, Abada et al. 2017, Tirole 1999).

Undoubtedly, LDES technologies are capable of providing substantial system value, but their challenges coupled with the existing market structure raised a question that will be explored in this manuscript on whether incomplete risk trading instruments explain the under-investments in LDES assets.

In several studies in the past, there were concerns about the adjustments needed in the financial contracting of electricity markets, or broader market reforms to address their incompleteness and support an effective low carbon transition (Mays et al. 2019, 2022, Mays & Jenkins 2023, Aurora Energy Research staff 2022). Within this framework, the objective of this project is to confirm or reject the project's working hypothesis, providing insights for several stakeholders, such as policymakers, and to fill in the gap of knowledge quantifying the effects of incomplete contracting on under-investments in LDES technologies. To achieve this objective, the project will simulate a future system using stochastic equilibrium techniques under cases with varying perspectives on market incompleteness.

2
Background

This chapter is organized into four sections. Some sections provide useful background knowledge (Section 2.1, 2.2), while others review the literature to identify methodological approaches relevant for solving the research question and to explore market integration of LDES (Section 2.3, 2.4). More specifically, Section 2.1 introduces the different types of LDES technologies. Section 2.2 presents the theoretical background on markets and risk theory, while Section 2.3 reviews the literature to identify state-of-art approaches on risk and investments modelling that are needed to complete the project. Lastly, Section 2.4 identifies gaps in the topic of incomplete contracting and LDES investments in energy markets and refers to the contributions of this work.

2.1 LDES Technologies

This research is mainly focused on energy storage and especially on LDES assets to facilitate the decarbonisation of our energy systems with increasing shares of renewables. Based on LDES Council staff (2024), LDES are projected to scale to at least 8 TW by 2040 to support a net-zero energy system. For instance, decarbonising the UK is estimated to require approximately 400 TWh of LDES. This rapid increase is driven by the necessity to integrate vast amounts of RES and as a result ensure that there will be always enough electricity to meet demand –known as adequacy–, something is currently done by conventional generators. These technologies will provide the flexibility needed in future fully decarbosized systems enhancing grid reliability, resilience and energy security (LDES Council staff 2024, Sepulveda et al. 2021). Despite these advantages, one of their limitations is interannual variability due to fluctuations in energy stored and supplied across different years (Aurora Energy Research staff 2022, Electric Power Research Institute (EPRI) staff et al. 2024).

Generally, energy storage solutions are comprised of five distinct categories including chemical, thermal, mechanical, electrical and electrochemical (Schmidt & Staffell 2023). According to reports by LDES Council staff (2024), Electric Power Research Institute (EPRI) staff et al. (2024), Aurora Energy Research staff (2022), Department for Business & Energy & Industrial Strategy (BEIS) staff (2022), chemical and, to some extent, mechanical storage technologies are most suitable for LDES applications. While chemical storage technologies like hydrogen are still in early maturity stages, mechanical storage on the other hand, such as pumped hydro storage (PHS) and compressed air energy storage (CAES), are one of the most technologically mature and greatly deployed.

Starting with the former, hydrogen could be produced via electrolysis coupled with RES during low demand periods and stored into geological formations, tanks, metal hydrides or even chemical bonds. This conversion of electricity into hydrogen is called 'Power to gas', and it can be bilateral meaning that, when needed, hydrogen can be converted to electricity. Despite the attractiveness of hydrogen because of its high gravimetric density and independent sizing of power and energy capacity, it is in the early stages of development, with many challenges related to its low volumetric density, high capital costs of electrolyzers, infrastructure challenges and low round trip efficiency (Schmidt & Staffell 2023, Ball & Wietschel 2009).

Moving on to PHS, in which energy is stored by leveraging the height difference and gravity between two water reservoirs. Water is pumped to the higher reservoir when there is low demand and electricity surplus generated by RES and released to generate electricity through generators in periods with high demand. This technology is appealing due to its low specific energy capacity costs (<50 £/kWh), relatively high round trip efficiency and maturity. Already, there are more than 100 GW installed across the globe (Schmidt & Staffell 2023). An argument against this technology is the geographical limitations for future expansion, long build times, high upfront costs, low energy densities, and the socio-environmental impacts as it is described by (Papadakis et al. 2023).

Lastly, CAES uses geological formations or even tanks to store compressed air when there is excess electricity and then utilises it to turn a turbine and generate electricity when needed (Barbour & Pottie 2022). CAES solutions have low specific energy capacity costs, long lifetimes and low energy densities, similar to PHS, but they have low round trip efficiencies.

Currently, common barriers across all the aforementioned technologies include high up-front costs and geographical limitations, particularly for mechanical storage technologies. However, these can be developed at large scale with high energy capacities, making them ideal for LDES assets in future power systems. Worth noting that, LDES assets are not a specific technology, rather than a class of technologies that includes existing and emerging technologies with duration over six hours (Department for Energy Security & Net Zero staff 2024, Aurora Energy Research staff 2022, Electric Power Research Institute (EPRI) staff et al. 2024). In general, they are characterized from low annual life cycles, long discharge durations capable of providing hours to seasonal storage solutions and infrequent utilization.

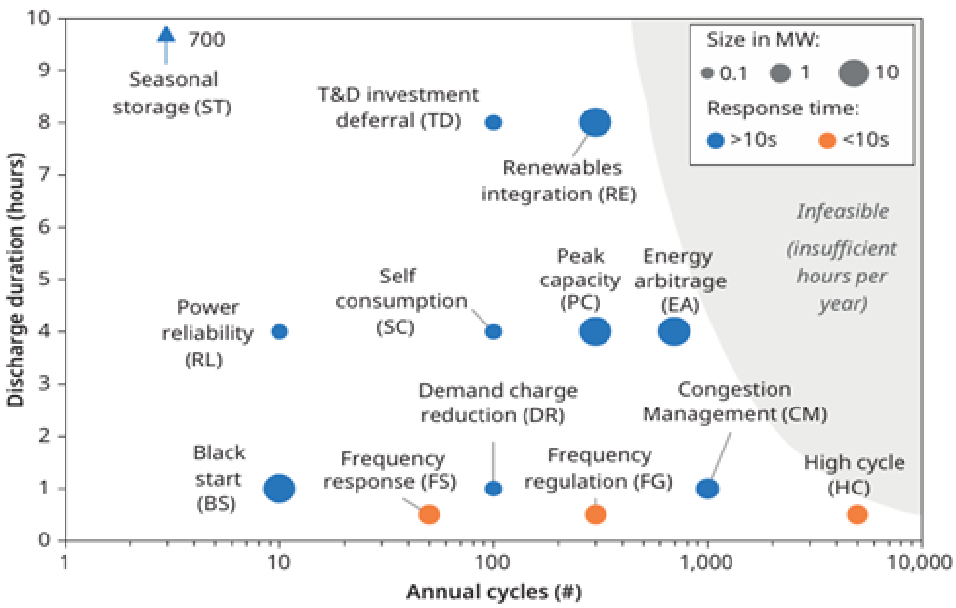

Figure 2.1: Applications of energy storage, adapted from Schmidt & Staffell (2023).

The benefits of LDES have been examined by a large number of existing studies in the broader literature towards power grid decarbonisation with high share of renewables. As shown in Figure 2.1, which depicts different energy storage applications based on discharge duration and annual cycles, LDES are suited for applications in the upper part of the graph (Dowling et al. 2020, Sepulveda et al. 2021). More specifically, seasonal storage, renewables integration and transmission and distribution (T&D) investments deferrals are some of the LDES applications, highlighting their contribution to system value in ensuring resource adequacy in future power systems. McNamara et al. (2022), LDES Council staff & McKinsey & Company staff (2021) acknowledged that LDES could shift renewable generation over time, maximising its economic value through long term energy arbitrage while enhancing resilience and system stability. As described by McNamara et al. (2022) curtailment of wind and solar can be avoided, maximising the utilization of existing assets. Furthermore, Cole et al. (2023) refer to the increasing peaking potential, which is the capability of energy storage to serve peak net demand in deep decarbonisation scenarios and therefore, replace “last mile” carbon-intense peaking plants. Moreover, McNamara et al. (2022), LDES Council staff & McKinsey & Company staff (2021), de Sisternes et al. (2016), Bloomberg New Energy Finance staff et al. (2018), Heuberger et al. (2017), Strbac et al. (2016, 2015), Pfenninger & Keirstead (2015) have shown that LDES can help manage congestion and defer T&D investments, reducing overall system’s costs and emissions.

Another important aspect is the market value of these technologies, which refers to their potential revenues from the services they provide. This has been partially explored by Brown et al. (2024), in which the authors focused on market pricing of systems with high shares of renewables and the impact of LDES assets. In systems with lots of zero marginal costs technologies and inelastic demand, price instability can occur due to demand-side unresponsiveness leading to many problems such as zero prices, price collapse, volatility and high scarcity prices. These issues could be addressed by introducing demand elasticity, while LDES can contribute to more stable pricing through their opportunity costs (Brown et al. 2024). Studies in Neumann et al. (2023), Aaslid et al. (2021) conclude that hydrogen as well as other LDES technologies will set the prices in future fossil free systems. Lastly, Mallapragada et al. (2023), Levin et al. (2023) underline that in future systems with high shares of VRE sources, LDES are expected to reduce the frequency of zero electricity prices.

2.2 Markets and Risk Theory

Considering the benefits discussed in the previous paragraphs, key questions arise on what actions are needed to facilitate the deployment of LDES technologies.

The liberalization of the power sector resulted in a riskier market environment, as market participants were exposed to uncertainties and risks that were previously borne by consumers through regulated pricing in vertically integrated natural monopolies (Ehrenmann & Smeers 2011). For instance, uncertainties in future fuel prices and in long-term electricity demand, due to the electrification of heat and transport sectors, result in a wide range of projections for revenue streams (Ehrenmann & Smeers 2011, Magill & Shafer 1991, Tirole 1999, Dimanchev et al. 2024, Radner 1970). In current electricity markets, where investors are typically risk-averse, these uncertainties hinder investments by increasing the cost of capital. Hence, the introduction of financial instruments, such as a wide range of contracts tailored to the profiles of different technologies, could enable a lower cost of capital by allowing risk sharing between market participants. This facilitates risk hedging, improves investment conditions, and supports the deployment of LDES technologies (Dimanchev et al. 2024, de Maere d'Aertrycke et al. 2017, Radner 1970).

However, current electricity markets are incomplete as evidenced from limited liquidity– such as low trading volumes, the absence of long-term forward and future markets, and lack of diverse financial contracts– failing to optimally hedge investors' risks (Tirole 1999). Without financial instruments, which can be viewed as a form of insurance, market participants are more reluctant to make future commitments (Tirole 1999, Magill & Shafer 1991, de Maere d'Aertrycke et al. 2017). Moreover, this market incompleteness is not addressed from the inadequate policies and regulations. It is very difficult to design, introduce, and procure these kinds of financial instruments, especially for long-term contracting, partly due to the interannual variability of LDES assets coupled with price volatility, which together enhance revenue uncertainty. Lastly, it is often up to the specific market structure and design, on what hedging instruments are available, which complicates it even more.

2.3 Modelling Risk, Investments, and Methodologies

After introducing the difficulty of solving the problems arising from market incompleteness, the purpose of this section is to provide a review of state-of-the art methodologies and approaches, that solve equilibrium problems with incomplete risk markets.

Electricity markets problems are commonly formulated as optimisation or equilibrium problems (Gabriel et al. 2013). On one hand, optimisation models are often structured through an objective function subject to equality and inequality constraints. On the other hand, equilibrium problems consist of several inter-linked optimisation problems, one for each market participant on its own objective function (Gabriel et al. 2013).

Predominantly, equilibrium problems are utilised for electricity markets modelling because of their capability to represent individual agents, essentially incorporating energy market relationships and interactions (Gabriel et al. 2013). In this study, equilibrium models will be used for generation capacity expansion planning with risk-averse market participants. Under the assumption of perfect competition between market participants which is not usually the case in real systems affected by market imperfections, equilibrium and optimisation problems are usually equivalent (Mays et al. 2019, Ehrenmann & Smeers 2011, Tirole 1999). When they do, it is equivalent to reformulate the equilibrium problem as an optimisation problem faced by a risk-averse central planner, who has in his possession all assets and aims to minimise total system costs, or equivalently, maximise social welfare (Mays et al. 2019, Dimanchev et al. 2024, Munoz et al. 2017).

In either optimisation or equilibrium problems, risk-averse behavior is commonly represented by the widely utilised Conditional Value at Risk (CVaR) function, which is a coherent risk measure (Tyrrell Rockafellar & Uryasev 1998, Ehrenmann & Smeers 2011). A large number of existing studies in broader literature have examined investment equilibria with risk-averse market participants (Mays et al. 2019, Ehrenmann & Smeers 2011, Mays et al. 2022, Mays & Jenkins 2023, Dimanchev et al. 2024, Abada et al. 2017, Kaminski et al. 2021, 2022). From these studies, three different groups were identified, each varying in its perspective on market incompleteness. The different classifications can be listed as follows: complete markets, fully incomplete markets (also known as missing markets) and partially complete markets.

In complete markets, investors can utilise financial instruments to fully hedge their risks among market participants (Munoz et al. 2017, Diaz et al. 2019, de Maere d'Aertrycke et al. 2017), for instance, through Arrow-Debreu securities defined for every possible outcome (Arrow & Debreu 1954) or through contracts that span the entire risk space (Abada et al. 2017). Their benefits lie in reduced complexity from a computational point of view, as they can often be reformulated as optimisation problems. This simplifies problem-solving and identifies effective long-term LDES investment planning strategies, giving more weight to worst-case scenarios. Worth noting, optimisation problems can be solved relatively easily due to their convexity and monotonicity (Abada et al. 2017).

Another category of market incompleteness is fully incomplete markets, where risk-averse market participants cannot hedge any of their risks due to absence of financial instruments (Dimanchev et al. 2024, Newbery 2016, Staum 2007, Radner 1970). In this case, the problem is non-monotone and non-convex, because there is no risk diversity due to uniformity in risk profiles of market participants (Abada et al. 2017, Ehrenmann & Smeers 2011). The nature of this equilibrium problem is no longer equivalent to that of a central planner optimisation problem. Therefore, as indicated by previous research studies (Abada et al. 2017, Dimanchev et al. 2024, Gabriel et al. 2013, Kaminski et al. 2021), this problem is commonly solved by deriving the Karush-Kuhn-Tucker (KKT) optimality conditions for each market participant and concatenating them to formulate a mixed complementarity problem (MCP) (Ehrenmann & Smeers 2011, Hoschle et al. 2018). This approach results in a non-linear system of equations which is commonly solved through PATH solver or other non-linear commercial solvers (Pineda et al. 2018, Dirkse & Ferris 1995). Another method used is to reformulate MCP/KKT conditions to mixed integer programs (MIP) using the big-M constraints approach (Fortuny-Amat & McCarl 1981). Although these methods perform well for small-scale problems, when a large number of scenarios are employed, which is the case of real-world energy markets, the computational burden is increased, and commercial solvers often fail to converge (Mays et al. 2019, Ehrenmann & Smeers 2011, Gérard et al. 2017, Dirkse & Ferris 1995, Boyd 2010).

Consequently, several methods, both algorithmic-iterative and non-iterative, are reported in the literature to solve large-scale problems and help in scaling generation expansion models. Starting with the algorithmic methods, Hoschle et al. (2018) decompose the problem to each individual market participant by presenting a decomposition alternating direction method of multipliers (ADMM) algorithm, in which prices are iteratively changed towards equilibrium. This ADMM algorithm was utilised by Kaminski et al. (2021, 2022) to solve generation capacity expansion problems under different market designs (e.g. energy-only markets and capacity markets). Furthermore, Mays et al. (2019) proposed another decomposition algorithm similar to ADMM, but it iteratively focuses on individual problems for each participant before considering the market as a whole. Expanding on that point, this algorithm finds a near-equilibrium solution by ensuring that investments and market outcomes are compatible in each iteration. The method by Mays et al. (2019) is more scalable than the ADMM one, because only investments are adjusted in each step, and it is solvable via the CPLEX commercial solver. However, convergence is not guaranteed for this method, unlike for the ADMM algorithm, as presented by Boyd (2010). Regarding the non-iterative method, Dimanchev et al. (2024) suggested a reformulation of the risk-averse equilibrium problem in the case of incomplete markets, providing computational benefits and a procedure to handle multiple equilibria. In this study, a primal-dual variant of the problem is derived. Then, KKT conditions were formulated, and commercial solvers (e.g. Gurobi) were utilised to solve this problem as a mixed integer quadratically constrained program (MIQCP). For all three methods, existence and multiple equilibria issues were addressed by Abada et al. (2017), although these challenges remain, especially for large scale systems.

Nevertheless, both above classifications, complete and fully incomplete markets, are considered as extreme cases, because in real-world energy markets limited contracts exist and thus risks can partially be hedged (Mays et al. 2019, 2022, Mays & Jenkins 2023, Tirole 1999, Shu & Mays 2023). Therefore, the third category of energy market incompleteness is partially incomplete markets, which is extremely difficult to mathematically represent and solve due to computational issues and limited methodological frameworks. Throughout the literature, the only contribution to solving these problems is presented by Mays & Jenkins (2023). They use the same iterative algorithm explained in the previous paragraph (Mays et al. 2019), but with a slight modification on including an inner loop for adjusting contract prices. In addition, in this study, each type of contract is offered by a different hedge provider. However, questions regarding the possibility of multiple equilibria and convergence challenges remain to be addressed.

2.4 Research Gaps and Contributions

As far as we know, no previous research has included LDES modelling in the case of incomplete markets (Ehrenmann & Smeers 2011, de Maere d'Aertrycke et al. 2017, Hoschle et al. 2018). Mays & Jenkins (2023), Dimanchev et al. (2024) have included battery energy storage system (BESS) investments in their equilibrium models, but the storage duration of these technologies was modelled in a simplified way. More specifically, Mays & Jenkins (2023) has formulated storage as a possible investing technology alongside with a revenue put contract representing the financial benefits of investing in battery storage.

Therefore, as the study in Dimanchev et al. (2024) indicated, one of the remaining challenges for all researchers in this domain is how to incorporate flexible energy storage technologies beyond batteries, such as LDES in the context of incomplete markets. This will enable us to explore the relationship between markets in risk and investment in LDES, which is the focus of this thesis project. Previous research has shown that risk-aversion among investors and incomplete risk trading can explain under-investment in resilience-enhancing technologies, such as weatherized gas-fueled power plants, in decentralized markets (Mays et al. 2022). Inspired by this, the working hypothesis of this project is that the same factors could explain under-investment in long-duration storage or sources of long-term flexibility in future decarbonised systems. In addition, different contracts can be explored and evaluated for their effectiveness to hedge the risks of LDES investors, although limited contract modelling is currently available in the literature and is not the main scope of this study (Mays et al. 2019). To accomplish these, methodological frameworks presented in Ehrenmann & Smeers (2011), Mays et al. (2019), Mays & Jenkins (2023), Dimanchev et al. (2024), Hoschle et al. (2018) and discussed in section 2.3, will be analyzed and further developed based on their limitations in LDES modelling.

Conclusions

Currently, increasing shares of RES are being integrated into our energy systems. These assets are pivotal in decarbonising future power systems and mitigating climate change. However, their variability and uncertainty pose major flexibility and supply challenges that must be addressed in order to ensure the reliable and efficient operation of energy systems. Although current energy storage solutions (e.g. batteries) could address these issues, other technologies, such as LDES, are needed that surpass battery capabilities and can operate over different timescales—from hours to weeks and seasons. In addition, LDES technologies could support even higher shares of RES and help in transitioning towards carbon-neutral, flexible systems.

Nonetheless, despite their benefits, several barriers hinder their deployment, associated with high capital costs and long lead times from a technological perspective, as well as revenues uncertainties from a market perspective. These uncertainties pose financial risks to LDES investors under the current market design. Therefore, financial instruments are needed to effectively hedge the risk and facilitate the deployment of LDES by improving investments conditions. In this context, no previous research has specifically explored LDES investment modelling under cases with different degrees of market incompleteness, including complete, fully incomplete and partially complete markets.

To explore these different groups in LDES investments, equilibrium models will be used in this research for generation capacity expansion planning modelling with risk-averse market participants. This approach will allow the exploration of the relationship between incomplete risk trading and investments in LDES. Addressing this issue will provide insights for several stakeholders, such as policymakers, regulators, energy investors and governments, on long-term planning strategies.

Finally, the next steps for the rest of the master thesis will focus on developing a two-stage stochastic expansion model, in which investments decisions will be taken in the first stage and operational decisions (e.g. economic dispatch) will be taken in the second stage. To do this, a system model will be constructed that includes one representative agent for each market participant, such as conventional generators, renewable energy sources (e.g. solar and wind), nuclear power, storage and consumers (demand side). Specifically for storage modelling, LDES necessitates a careful implementation to accurately reflect their real-world operation and distinguish them from short-duration energy storage technologies (e.g. batteries). Then, equilibrium techniques will be applied to simulate complete and fully incomplete markets scenarios. In the case of complete markets, equilibrium models will be formulated as optimisation models, as explained in Section 2.3. For fully incomplete markets, the ADMM algorithm presented by Hoschle et al. (2018) will be explored. Finally, if there is enough time, simulating partially complete markets using the algorithm described in Mays et al. (2019) is also of interest, although the exact modelling of LDES contracts is uncertain at this point.

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