Compressed Air Energy Storage in Abandoned Coal Mines: A Survey

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Abstract

This survey explores the utilization of Compressed Air Energy Storage (CAES) in abandoned coal mines, emphasizing its role in integrating renewable energy sources into power systems. By leveraging the geological stability and airtight properties of these subterranean formations, CAES offers a promising solution to the intermittency challenges of renewable energy, such as wind and solar power. The study highlights the Bilinear Cavern Model (BCM) as a pivotal tool in optimizing the thermodynamic processes within CAES systems, minimizing energy losses and maximizing recovery rates. This model, along with advanced scheduling and power flow techniques, enhances the operational efficiency and economic viability of CAES, supporting its integration into large-scale power systems. Furthermore, the strategic repurposing of abandoned coal mines aligns with broader energy transition goals, providing a sustainable method of underground energy storage that capitalizes on existing infrastructure. By facilitating the storage of excess energy during low demand and its release during peak periods, CAES not only stabilizes the power grid but also promotes the broader adoption of renewable technologies. The survey concludes that the technological advancements and modeling innovations discussed significantly enhance the potential of CAES in abandoned coal mines as a sustainable energy storage solution, contributing to a resilient and cleaner energy future.

1 Introduction

1.1 Concept of Compressed Air Energy Storage (CAES)

Compressed Air Energy Storage (CAES) is a pivotal technology for large-scale electrical energy storage, essential for integrating renewable energy sources into modern power systems [1]. CAES operates by compressing air with surplus electrical energy during low-demand periods, storing it in subterranean formations such as caverns or abandoned mines. When energy demand peaks, the stored air is released and expanded to drive turbines, generating electricity.

This technology effectively mitigates the intermittency and variability of renewable sources like wind and solar power. By absorbing excess energy and releasing it as needed, CAES enhances the operational flexibility of power systems [2]. As the share of wind and other renewables increases, CAES becomes increasingly vital for maintaining a stable and reliable electricity supply, thereby promoting the broader adoption of renewable energy technologies.

1.2 Relevance of CAES in Renewable Energy Integration

The integration of CAES systems is crucial for facilitating the adoption of renewable energy sources, particularly those with intermittent outputs, such as wind and solar power. CAES addresses the uncertainties of wind generation by providing a reliable storage solution that buffers energy supply fluctuations and stabilizes the grid [2]. By storing excess energy during low-demand periods and

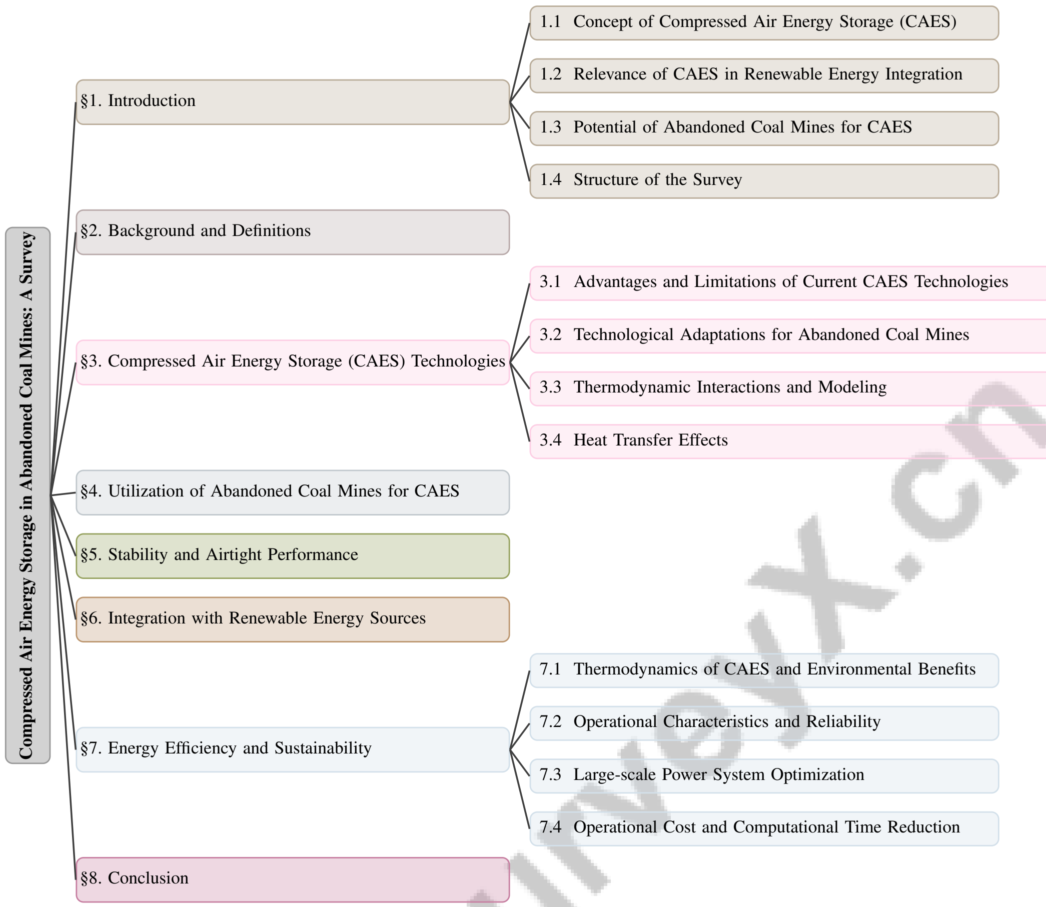

Figure 1: chapter structure

releasing it during peak times, CAES ensures a continuous, stable power supply, enhancing the reliability of renewable systems. Additionally, CAES supports the co-optimization of energy and reserve markets, delivering both energy storage and ancillary services that bolster grid stability and efficiency [2]. This dual functionality not only balances supply and demand but also facilitates higher levels of renewable energy integration, fostering a cleaner and more sustainable energy future.

1.3 Potential of Abandoned Coal Mines for CAES

Utilizing abandoned coal mines for CAES presents a promising opportunity to enhance energy storage capabilities while repurposing existing infrastructure. These subterranean formations offer several advantages for CAES applications. The geological stability of abandoned coal mines provides a robust environment capable of withstanding the pressures associated with compressed air storage [1], reducing the risk of structural failure and ensuring long-term reliability.

Moreover, the airtight nature of these mines is crucial for maintaining CAES efficiency. Their ability to contain compressed air with minimal leakage optimizes energy recovery during discharge cycles. Abandoned coal mines, with their naturally sealed environments, enhance the overall energy efficiency of the storage process [1].

Additionally, the geographical distribution of abandoned coal mines aligns well with regions of high energy demand, particularly those transitioning from coal-based generation to renewables. This proximity can minimize transmission losses and facilitate efficient integration with the existing grid. Repurposing these mines for CAES also contributes to environmental sustainability by giving new life to sites that would otherwise remain unused or require extensive rehabilitation [2].

Strategically repurposing abandoned coal mines for CAES not only leverages their geological features to enhance large-scale energy storage but also plays a crucial role in integrating renewable sources,

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such as wind power, into the grid. This approach aligns with the broader objectives of energy transition and sustainable infrastructure development, offering a viable solution to challenges in energy storage efficiency and market optimization while supporting a shift towards a cleaner energy landscape [2, 3].

1.4 Structure of the Survey

This survey systematically analyzes CAES in the context of utilizing abandoned coal mines. Following the introduction, Section 2 provides background and definitions, offering an overview of key concepts such as CAES, characteristics of abandoned coal mines, and their relevance to renewable energy and underground storage. Section 3 explores various CAES technologies, examining their principles, advantages, and limitations, with a focus on adaptations for abandoned coal mines, including discussions on thermodynamic interactions and heat transfer effects.

Section 4 evaluates the potential of abandoned coal mines for CAES, highlighting their suitability based on geological stability and airtight performance, and introduces the Bilinear Cavern Model (BCM) for site assessment. Section 5 addresses essential factors influencing the stability and airtight performance of CAES systems, emphasizing the importance of accurate cavern modeling for effective operation. Section 6 investigates the synergistic integration of CAES with renewable energy sources, focusing on advanced optimization methodologies such as the Two-Stage Stochastic Day-Ahead Scheduling Model, which accommodates wind power uncertainties, and the Two-Level Linearized AC Optimal Power Flow approach, designed for computational efficiency in CAES applications [1, 2, 3].

In Section 7, the survey discusses energy efficiency and sustainability, covering the thermodynamics of CAES, environmental benefits, operational characteristics, and strategies for large-scale power system optimization, including methods to reduce operational costs and computational time. Finally, Section 8 concludes the survey by summarizing key findings and reinforcing the potential of utilizing abandoned coal mines for CAES as a sustainable energy storage solution.The following sections are organized as shown in Figure 1.

2 Background and Definitions

2.1 Renewable Energy and Underground Storage

The integration of renewable energy sources, notably wind and solar, is vital for achieving a sustainable energy transition. However, the inherent variability and intermittency of these sources necessitate robust energy storage solutions to stabilize power supply and manage fluctuations [2]. Compressed Air Energy Storage (CAES) emerges as a viable solution, leveraging subterranean formations, such as abandoned coal mines, which offer geological stability and airtight conditions essential for efficient energy storage [1]. These underground spaces allow for the storage of surplus energy during low-demand periods and its release during peak demand, thereby enhancing grid stability and facilitating the integration of renewables.

Moreover, CAES systems contribute to grid reliability and the co-optimization of energy and reserve markets by providing ancillary services that bolster grid efficiency [2]. The strategic utilization of underground storage solutions like CAES addresses the limitations of renewable energy sources and supports the development of a resilient and sustainable energy infrastructure.

3 Compressed Air Energy Storage (CAES) Technologies

CAES technologies have become pivotal in developing advanced energy storage solutions, particularly through the repurposing of abandoned coal mines. These systems, which include components such as compressors, expanders, caverns, and motor/generator sets, are crucial for large-scale electricity storage, thereby facilitating the integration of renewable energy sources like wind power into electrical grids. Innovations such as the bilinear cavern model have improved CAES efficiency by addressing thermodynamic complexities, optimizing power systems, and enhancing market responsiveness alongside variable renewable energy sources [1, 2, 3]. Table 1 presents a comprehensive overview of the methods utilized to address thermodynamic interactions and heat transfer effects within Compressed Air Energy Storage (CAES) systems, emphasizing the roles of the Bilinear Cavern Model and

Category	Feature	Method
Thermodynamic Interactions and Modeling	Thermodynamic Modeling	TL-LAC-OPF[2]
Heat Transfer Effects	Thermodynamic Efficiency Enhancement	BCM[1], BCM[3]

Table 1: Summary of Methods for Thermodynamic Interactions and Heat Transfer Effects in Compressed Air Energy Storage (CAES) Systems. This table categorizes the features and methods employed to enhance thermodynamic efficiency and model interactions within CAES technologies, specifically focusing on the Bilinear Cavern Model (BCM) and the two-level linearized AC optimal power flow (TL-LAC-OPF). The methods highlighted demonstrate advancements in modeling techniques that optimize CAES performance and facilitate the integration of renewable energy sources.

advanced power flow modeling techniques. Additionally, Table 2 offers a detailed comparison of the methods employed in Compressed Air Energy Storage (CAES) systems, focusing on thermodynamic interactions, technological adaptations for abandoned coal mines, and the advantages and limitations of current technologies.

As illustrated in **??**, the hierarchical structure of Compressed Air Energy Storage (CAES) technologies highlights both the advantages and limitations of current systems. This figure delineates the technological adaptations for abandoned coal mines, the thermodynamic interactions and modeling involved, and the effects of heat transfer. It particularly emphasizes the role of the Bilinear Cavern Model and advanced power flow modeling in optimizing CAES performance and integrating renewable energy sources. While CAES offers significant storage potential, it also presents challenges and opportunities within geological formations previously used for coal extraction. Evaluating the advantages and limitations of current systems is essential for assessing the feasibility of CAES implementations, leading to a nuanced understanding of this innovative approach's benefits and drawbacks.

3.1 Advantages and Limitations of Current CAES Technologies

CAES technologies offer substantial benefits and limitations impacting their use, especially in abandoned coal mines. A key advantage is their capability for large-scale energy storage, crucial for balancing supply and demand in grids with high renewable energy integration. The stable and airtight geological formations of abandoned coal mines enhance CAES efficiency and reliability [1]. However, challenges such as substantial capital investment and complex infrastructure requirements hinder widespread adoption. The complexity of CAES technology, including specialized components like compressors and expanders, complicates implementation and may deter investors despite its benefits for energy storage and grid stability [2, 3]. Thermodynamic losses during air compression and expansion also affect energy recovery rates.

Recent advancements like the bilinear cavern model address these limitations by reducing computational complexity while maintaining accuracy, making it suitable for real-time energy management [1]. The model shows high accuracy, with an error margin of about 0.12

3.2 Technological Adaptations for Abandoned Coal Mines

Adapting CAES technologies for abandoned coal mines requires a tailored approach considering these environments' unique characteristics. The Bilinear Cavern Model (BCM) is pivotal in this adaptation, integrating the ideal gas law and the first law of thermodynamics to account for specific underground storage conditions [3]. This model optimizes CAES performance by accurately simulating thermodynamic processes and heat transfer effects during air compression and expansion.

Incorporating the BCM into CAES design and operation in abandoned coal mines allows precise monitoring and control of thermodynamic conditions, enhancing energy storage efficiency and reliability [1, 2, 3]. This integration improves CAES performance, enabling better optimization in energy and reserve markets while accommodating renewable energy sources' variability. Addressing site-specific challenges, such as structural integrity and airtight performance, is essential. The BCM enhances thermodynamic interactions evaluation within CAES systems by capturing temperature and pressure variations, simplifying computational challenges, and facilitating renewable energy sources' effective incorporation into power systems [1, 3].

Technological adaptations of CAES for abandoned coal mines, supported by advanced modeling techniques like the BCM, are crucial for maximizing these sites' potential as energy storage solutions.

These adaptations improve operational efficiency by simplifying complex thermodynamic processes, facilitating the sustainable repurposing of existing infrastructure, and enhancing renewable energy sources' integration into power systems, supporting a more reliable and efficient energy market [1, 2, 3].

3.3 Thermodynamic Interactions and Modeling

Analyzing thermodynamic interactions and modeling is crucial for optimizing CAES systems, particularly in abandoned coal mines. The Bilinear Cavern Model provides a framework for understanding thermodynamic relationships of air pressure and temperature during charging and discharging [1]. This model uses linear approximations to simulate complex interactions within the storage cavern, facilitating accurate predictions of system behavior under varying conditions.

The BCM's characterization of thermodynamic relationships—integrating the first law of thermodynamics and the ideal gas law—plays a key role in optimizing CAES performance, enhancing operational efficiency, and facilitating renewable energy sources' integration into power grids [1, 2, 3]. By accurately modeling air pressure and temperature changes, operators can optimize compression and expansion cycles, minimizing energy losses and maximizing recovery. This is crucial in subterranean environments, where maintaining thermal balance is challenging due to geological formations.

Additionally, integrating advanced power flow modeling techniques further enhances CAES efficiency. The two-level linearized AC optimal power flow (TL-LAC-OPF) approach effectively captures CAES operational characteristics, reducing artificial losses and improving market reliability [2]. This approach co-optimizes energy and reserve markets, ensuring CAES systems contribute to grid stability and efficiency while supporting renewable energy integration.

Sophisticated thermodynamic modeling techniques, like the BCM and TL-LAC-OPF, are essential for maximizing CAES systems' potential in abandoned coal mines. These models improve CAES systems' operational efficiency by accurately representing cavern behavior during charging and discharging, facilitating renewable energy sources' integration into the grid. They support sustainable infrastructure repurposing, meeting energy transition objectives while fostering a resilient energy future. By incorporating thermodynamic principles and optimizing computational approaches, these models enhance market decision-making in energy and reserve markets while aligning with broader sustainability goals [1, 2, 3].

3.4 Heat Transfer Effects

Heat transfer effects are crucial in determining CAES systems' overall efficiency and performance, especially when utilizing subterranean formations like abandoned coal mines. During compression, air is pressurized and heated, while it cools during expansion as it drives turbines [1]. Managing these thermal dynamics is essential, as improper handling can lead to significant energy losses and reduced efficiency.

As illustrated in Figure 2, the key aspects of heat transfer effects in Compressed Air Energy Storage (CAES) systems are highlighted, focusing on thermal dynamics, the Bilinear Cavern Model (BCM), and advanced heat management strategies. The BCM integrates thermodynamic principles to model and mitigate thermal effects. By simulating heat exchange processes within the storage cavern, the BCM optimizes thermal conditions, ensuring minimal energy dissipation during compression and expansion [3]. This model is effective in subterranean environments, where geological formations influence thermal stability.

Advanced heat management strategies, like thermal energy recovery systems, capture and reuse heat generated during compression, enhancing energy recovery rates. These strategies boost CAES systems' thermodynamic efficiency by employing an accurate bilinear cavern model that optimizes charging and discharging, lowering operational costs through reduced reliance on additional heating or cooling resources, and facilitating renewable energy sources' integration into power systems [1, 2, 3].

Considering heat transfer effects in CAES operations is essential for maximizing energy efficiency and ensuring reliable performance in abandoned coal mines. By employing advanced modeling techniques, like the bilinear cavern model that accounts for thermodynamic processes and heat

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transfer, along with effective heat management strategies, CAES systems can enhance efficiency. This supports renewable energy sources' sustainable integration, like wind power, into the power grid by enabling more effective energy storage and optimization in electricity markets [1, 2, 3].

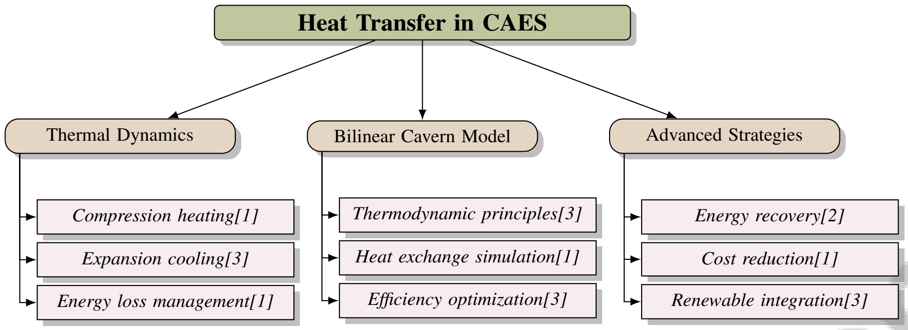

Figure 2: This figure illustrates the key aspects of heat transfer effects in Compressed Air Energy Storage (CAES) systems, focusing on thermal dynamics, the Bilinear Cavern Model, and advanced heat management strategies.

Feature	Advantages and Limitations of Current CAES Technologies	Technological Adaptations for Abandoned Coal Mines	Thermodynamic Interactions and Modeling
Efficiency Improvement	Large-scale Storage	Enhanced Reliability	Operational Efficiency
Modeling Technique	Bilinear Cavern Model	Bilinear Cavern Model	Two-level Linearized AC
Renewable Integration	Grid Balancing	Market Optimization	Grid Stability

Table 2: This table provides a comparative analysis of current Compressed Air Energy Storage (CAES) technologies, highlighting their advantages and limitations, technological adaptations for use in abandoned coal mines, and the thermodynamic interactions and modeling techniques involved. The table emphasizes the role of the Bilinear Cavern Model and advanced modeling techniques in enhancing operational efficiency and integrating renewable energy sources into power systems.

4 Utilization of Abandoned Coal Mines for CAES

4.1 Bilinear Cavern Model (BCM)

Benchmark	Size	Domain	Task Format	Metric

Table 3: Table illustrating the key characteristics of representative benchmarks, including their size, domain, task format, and evaluation metric. This table serves as a reference for understanding the scope and applicability of different benchmarks within the context of the Bilinear Cavern Model (BCM) for Compressed Air Energy Storage (CAES).

The Bilinear Cavern Model (BCM) is pivotal in assessing the feasibility of using abandoned coal mines for Compressed Air Energy Storage (CAES). This model simplifies complex cavern processes while maintaining accuracy, making it highly suitable for optimization tasks [1]. By modeling the charging and discharging cycles, the BCM provides a comprehensive framework for evaluating subterranean environments in CAES applications [3]. Table 3 provides a detailed overview of representative benchmarks relevant to the Bilinear Cavern Model (BCM), highlighting their size, domain, task format, and metric.

The BCM integrates essential thermodynamic principles, enabling precise simulations of air pressure and temperature dynamics within storage caverns. This capability is critical for optimizing CAES operational efficiency, as it identifies optimal thermodynamic conditions for energy storage and retrieval, thus enhancing renewable energy integration into power systems and facilitating energy and reserve market participation [1, 2, 3]. The model effectively captures interactions between air compression, expansion, and heat transfer, minimizing energy losses and improving overall energy recovery rates.

Utilizing the BCM allows for detailed evaluations of the geological and structural characteristics of abandoned coal mines, essential for determining their suitability for CAES operations. It analyzes temperature and pressure variations during charging and discharging, incorporating thermodynamic principles and heat transfer dynamics. This leads to a more accurate and computationally efficient integration into power system optimization, ultimately enhancing large-scale energy storage potential and the incorporation of renewable sources into electric power systems [1, 2, 3]. The BCM not only supports the strategic repurposing of existing infrastructure but also aligns with broader energy transition goals and sustainable development. Its application fosters the integration of renewable energy into the power grid, contributing to a more resilient and sustainable energy future.

5 Stability and Airtight Performance

5.1 Stability and Airtight Performance

The stability and airtight performance of storage caverns are crucial for the successful deployment of Compressed Air Energy Storage (CAES) systems, particularly in repurposed abandoned coal mines. Geological stability is essential to ensure the caverns can withstand the high pressures of compressed air storage, maintaining structural integrity over time and facilitating reliable energy storage and retrieval. This reliability is vital for integrating renewable energy into power grids. Advanced cavern models, such as the bilinear model, enhance simulation accuracy of temperature and pressure variations, supporting both operational efficiency and safety in CAES facilities [1, 2, 3]. Preventing cavern collapse or deformation is critical to avoid operational failures and safety risks.

Airtight performance is equally critical for optimizing CAES efficiency, as it influences thermodynamic properties and heat transfer dynamics during energy charging and discharging [1, 2, 3]. The ability to contain compressed air with minimal leakage is pivotal for maximizing energy recovery during discharge cycles. Abandoned coal mines, with their naturally sealed environments, inherently reduce air loss, thereby enhancing storage efficiency. Effective airtight performance ensures stored energy is preserved until needed, maximizing system reliability.

Thermodynamic behavior within CAES caverns is significantly influenced by heat transfer processes, often overlooked in simpler models [3]. Accurate thermal dynamic modeling is essential for optimizing operational conditions and minimizing energy losses. By incorporating heat transfer effects, advanced models provide a comprehensive understanding of cavern interactions, leading to improved design and operation of CAES facilities.

6 Integration with Renewable Energy Sources

6.1 Two-Stage Stochastic Day-Ahead Scheduling Model

Integrating Compressed Air Energy Storage (CAES) systems with renewable energy, particularly wind power, requires sophisticated scheduling models to manage the inherent variability and uncertainty of renewable sources. The Two-Stage Stochastic Day-Ahead Scheduling Model leverages a linearized AC optimal power flow (LAC-OPF) framework to optimize energy and reserve markets while accommodating the stochastic nature of wind power. The incorporation of an accurate bilinear cavern model for CAES enhances computational feasibility by effectively capturing the thermodynamic processes of energy storage and retrieval, thereby improving the reliability and efficiency of energy management systems [1, 2, 3].

This model employs stochastic programming techniques to address the uncertainties of renewable energy outputs, facilitating reliable scheduling of energy storage and dispatch activities. By integrating the Bilinear Cavern Model, the Two-Stage Stochastic Scheduling framework significantly improves computational efficiency and accuracy, making it suitable for large-scale power system optimization [1]. It optimizes energy operations by accurately simulating thermodynamic processes within CAES caverns, minimizing losses, and maximizing recovery rates. This enhances CAES operational efficiency and provides a reliable buffer against supply fluctuations, supporting the broader integration of renewable energy.

Additionally, the Two-Stage Stochastic Day-Ahead Scheduling Model, combined with the Bilinear Cavern Model, enables the co-optimization of energy and reserve markets, ensuring that CAES systems effectively contribute to grid stability and efficiency [3]. This model promotes the seamless

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integration of renewable energy into the power grid, fostering a sustainable and resilient energy future.

6.2 Two-Level Linearized AC Optimal Power Flow

The Two-Level Linearized AC Optimal Power Flow (TL-LAC-OPF) model is an advanced optimization technique designed to enhance power flow management in systems incorporating CAES. This model addresses the complexities of integrating CAES into the power grid, particularly in optimizing electricity flow while maintaining system reliability and efficiency. By employing a linearized approach, the TL-LAC-OPF model reduces computational complexity without compromising the accuracy of power flow predictions, making it ideal for real-time energy management applications [2].

The TL-LAC-OPF model's two-level structure facilitates the co-optimization of energy production and reserve allocation, ensuring CAES systems can deliver both energy storage and ancillary services to support grid stability. The first level optimizes the dispatch of energy resources, including CAES, to meet demand while minimizing operational costs. The second level focuses on grid reliability by managing reserve requirements and adjusting power flows to accommodate fluctuations in renewable energy generation [2].

Integrating the TL-LAC-OPF model with advanced thermodynamic modeling techniques, such as the Bilinear Cavern Model, provides operators with a comprehensive understanding of CAES system interactions. This integration enhances operational efficiency by optimizing energy storage and retrieval conditions, minimizing energy losses, and improving recovery rates through effective management of thermodynamic variables like temperature and pressure during charging and discharging processes. Furthermore, the model's adaptability offers a realistic representation of CAES performance in power system optimization, facilitating better integration of renewable energy sources and mitigating computational challenges typical of traditional non-linear models [1, 2, 3]. Ultimately, the TL-LAC-OPF model supports dynamic interactions between CAES and the power grid, promoting a sustainable and resilient energy infrastructure.

7 Energy Efficiency and Sustainability

7.1 Thermodynamics of CAES and Environmental Benefits

The thermodynamic efficiency of Compressed Air Energy Storage (CAES) systems, especially within abandoned coal mines, is critical for enhancing energy storage and environmental sustainability. Utilizing advanced modeling techniques like the Bilinear Cavern Model allows for precise representation of thermodynamic behaviors, optimizing compression and expansion cycles to minimize energy losses and maximize recovery rates [3]. This optimization is essential for maintaining high operational efficiency in complex subterranean environments, balancing accuracy and computational efficiency, thus enabling CAES systems to reflect detailed thermodynamic characteristics without incurring excessive costs [3]. By reducing energy losses and enhancing recovery rates, CAES systems significantly lower the carbon footprint associated with energy storage, aligning with broader environmental objectives.

Integrating thermodynamic characteristics into market operations reduces operational costs and improves scheduling accuracy, ensuring CAES systems deliver reliable energy storage and ancillary services, facilitating the integration of renewable energy sources [2]. The environmental benefits of CAES in abandoned coal mines are twofold: they sustainably repurpose existing infrastructure and enhance the efficiency and reliability of renewable energy integration. The potential of CAES systems to significantly improve the integration of renewable energy sources, such as wind power, while reducing greenhouse gas emissions and reliance on fossil fuels, underscores their viability as a sustainable solution for large-scale energy storage [1, 2, 3]. By leveraging advanced modeling techniques and operational optimization, CAES systems can play a crucial role in fostering a resilient and sustainable energy future.

7.2 Operational Characteristics and Reliability

The operational characteristics and reliability of Compressed Air Energy Storage (CAES) systems are crucial for their effectiveness as a sustainable energy storage solution, particularly in abandoned coal mines. CAES systems offer large-scale energy storage, essential for balancing supply and demand in grids with significant renewable energy integration. The geological formations of abandoned coal mines provide a stable, naturally airtight environment, ideal for maintaining CAES efficiency and reliability [1]. Advanced modeling techniques, such as the Bilinear Cavern Model, enhance CAES reliability by accurately simulating thermodynamic processes within storage caverns, allowing precise control and monitoring of storage conditions, optimizing compression and expansion cycles to minimize energy losses [3]. Accurate predictions of system behavior under varying operational conditions ensure consistent and reliable energy output, even amid fluctuating renewable energy generation.

Integrating CAES systems with advanced power flow optimization techniques, like the Two-Level Linearized AC Optimal Power Flow (TL-LAC-OPF) model, bolsters operational reliability by ensuring efficient power flow management and grid stability [2]. This integration enables CAES systems to provide both energy storage and ancillary services, supporting grid stability while facilitating the broader integration of renewable energy sources.

7.3 Large-scale Power System Optimization

Optimizing large-scale power systems that incorporate Compressed Air Energy Storage (CAES) is crucial for enhancing the efficiency and reliability of energy grids with substantial renewable energy integration. Advanced modeling techniques, such as the Bilinear Cavern Model (BCM), accurately simulate thermodynamic processes within CAES systems, facilitating simulations of air compression and expansion cycles to identify optimal operational conditions that minimize energy losses and maximize recovery rates [3]. In conjunction with thermodynamic modeling, sophisticated power flow optimization techniques, such as the Two-Level Linearized AC Optimal Power Flow (TL-LAC-OPF) model, manage the complexities of large-scale power systems, reducing computational complexity while maintaining accuracy, enabling real-time applications in energy management [2]. By co-optimizing energy production and reserve allocation, this model ensures CAES systems provide both energy storage and ancillary services, enhancing grid stability and efficiency.

The integration of stochastic scheduling models, such as the Two-Stage Stochastic Day-Ahead Scheduling Model, enhances the optimization of large-scale power systems by addressing the variability and uncertainty inherent in renewable energy sources [1]. This model employs stochastic programming techniques to optimize CAES operations within the power grid, serving as a reliable buffer against supply fluctuations and facilitating seamless renewable energy integration. A multi-faceted approach integrating advanced thermodynamic modeling, power flow optimization techniques, and stochastic scheduling methods improves operational efficiency and reliability of CAES systems while supporting the broader integration of renewable energy sources, fostering a more sustainable and resilient energy infrastructure [1, 2, 3].

7.4 Operational Cost and Computational Time Reduction

Reducing operational costs and computational time in Compressed Air Energy Storage (CAES) operations is essential for enhancing the economic viability and efficiency of these systems, particularly in abandoned coal mines. A primary strategy for cost reduction involves optimizing thermodynamic processes within CAES systems to minimize energy losses and improve recovery rates. The Bilinear Cavern Model (BCM) is instrumental in this context, offering a detailed and accurate representation of thermodynamic interactions during air compression and expansion cycles [3]. By employing linear approximations, the BCM reduces computational complexity while ensuring high accuracy, making it suitable for real-time energy management applications [1].

Integrating advanced power flow optimization techniques, such as the Two-Level Linearized AC Optimal Power Flow (TL-LAC-OPF) model, contributes to operational cost reduction by ensuring efficient energy flow management within the grid, capturing CAES operational characteristics, reducing artificial losses, and enhancing market reliability [2]. By optimizing energy resource dispatch and managing reserve requirements, the TL-LAC-OPF model enhances CAES operational efficiency, thereby lowering costs.

The implementation of stochastic scheduling models, like the Two-Stage Stochastic Day-Ahead Scheduling Model, further reduces computational time by leveraging stochastic programming techniques to optimize CAES operations under uncertainty [2]. This model accommodates the variability of renewable energy sources, ensuring CAES systems can reliably provide energy storage and ancillary services while minimizing computational demands. The reduction of operational costs and computational time in CAES operations is achieved through advanced thermodynamic modeling with a bilinear cavern model that accurately simulates temperature and pressure variations during charging and discharging, alongside power flow optimization techniques like the TL-LAC-OPF that minimize binary variables to alleviate computational burdens, and stochastic scheduling methods that effectively manage the uncertainties of wind power generation. These strategies enhance the economic feasibility of CAES systems while supporting their integration into the power grid, promoting a more sustainable and resilient energy infrastructure [1, 2, 3].

8 Conclusion

Compressed Air Energy Storage (CAES) emerges as a transformative technology in the realm of sustainable energy, significantly enhancing the adaptability and resilience of power systems. The strategic utilization of abandoned coal mines for CAES offers an innovative approach to addressing the challenges posed by the intermittent nature of renewable energy sources such as wind and solar. These subterranean structures provide the necessary geological stability and airtight environments essential for efficient energy storage and retrieval, thus ensuring a reliable power supply during peak demand periods. This capability not only fortifies grid stability but also accelerates the transition towards renewable energy adoption, fostering a more sustainable energy landscape.

The integration of advanced modeling techniques, notably the Bilinear Cavern Model, plays a pivotal role in optimizing the operational efficiency of CAES systems. By enhancing the thermodynamic performance and minimizing energy losses, these models contribute to the economic feasibility of CAES projects, reducing both operational costs and computational demands. The repurposing of abandoned coal mines for CAES not only aligns with global energy transition objectives but also leverages existing infrastructure to provide a viable and sustainable energy storage solution. This approach underscores the potential of CAES in driving forward a cleaner and more efficient energy future.

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