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Enhancing Operations Management of Pumped Storage Power Stations by Partnering from the Perspective of Multi-Energy Complementarity

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Abstract: Driven by China's long-term energy transition strategies, the construction of large-scale clean energy power stations, such as wind, solar, and hydropower, is advancing rapidly. Consequently, as a green, low-carbon, and flexible storage power source, the adoption of pumped storage power stations is also rising significantly. Operations management is a significant factor that influences the performance of pumped storage power stations in various domains, including environmental protection, economic benefits, and social benefits. While existing studies have highlighted the importance of stakeholder partnering in operations management, a systematic exploration of the causal relationships between partnering, operations management, and the performance of pumped storage power stations—especially from a multi-energy complementarity perspective—remains untouched. This paper strives to shed light on the vital role of stakeholder partnering in augmenting the operations management and overall performance of pumped storage power stations, thereby contributing to China's dual carbon goals. A comprehensive conceptual model was developed by reviewing the relevant literature to empirically examine the causal relationships among partnering, operations management, and power station performance, which was validated using data from the Liaoning Qingyuan Pumped Storage Power Station, which is the largest of its kind in Northeast China. The findings suggest: (1) Effective partnering among stakeholders, particularly with grid companies, significantly influences the operations management of pumped storage power stations, with deficiencies in partnering mainly attributed to the lack of effective communication channels and problem-solving mechanisms. (2) The level of operations management in China's pumped storage power stations is relatively high, averaging a central score around 4.00 (out of a full score of 5) on operations management indicators. However, there is a need to concentrate on enhancing multi-energy complementarity coordination, digital management system development, and profitability. (3) Path analysis further unveils that partnering not only improves operations management but also boosts the performance of pumped storage power stations. These findings suggest a wide range of practical strategies for operations managers at pumped storage power stations to forge partnerships with stakeholders and integrate complementary resources, aiming to achieve excellence in performance.

Keywords: pumped storage power station; partnering; operations management; performance; multi-energy complementarity; path analysis; dual carbon goals

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1. Introduction

China proposed goals that carbon emissions will reach a peak by 2030 and achieve carbon neutrality by 2060 [1,2]. In recent years, to promote the achievement of dual carbon goals, China's demand for renewable energy has been continuously increasing. Clean energy power stations such as wind power, solar power, and hydropower have been rapidly established to alleviate the environmental pressure of CO_2 emissions from fossil fuels. With the establishment of a large number of clean energy power stations nationwide, there is an urgent need to establish long-duration energy storage stations to absorb the excess electricity produced by clean energy power stations and balance and adjust the power system [3]. Among all forms of energy storage, pumped storage is regarded as the most technically mature, and is suitable for large-scale development, serving as a green, low-carbon, clean, and flexible adjustable power source in the electrical system [4,5] pumped storage power stations, by absorbing clean energy sources such as wind power, solar power, and hydropower, and plays a crucial role in ensuring the safety and stability of power systems, optimizing the structure of power sources, and reducing greenhouse gases emissions [6–9]. Accelerating the construction of pumped storage power stations is an urgent requirement for building a new type of power system that is primarily based on new energy [10]. It is a critical support for ensuring the safe operation of the power system and a significant guarantee for the large-scale development of renewable energy [6,11–13]. Typically, the construction of pumped storage power stations is large-scale and has a long implementation period, serving as a “large-capacity power bank” in the power system [7]. It needs to be connected to the grid with clean energy power stations such as wind power and solar power, timely absorbing the electricity generated by these clean energy power stations, ensuring the stability and balance of the power system [11].

Due to the vulnerability of renewable energy sources such as wind and solar to natural weather changes, their independent generation is inconsistent and variable, making reliable electricity supply challenging. To address this, it is imperative to integrate pumped storage power stations with wind and solar energy, ensuring the stability of clean energy supplies and achieving multi-energy complementarity [14,15]. From this perspective, the operational management of pumped storage power stations involves a broader spectrum of stakeholders, beyond traditional grid companies and electricity consumers. It must also consider the demands of clean energy stations including wind, solar, and hydropower [3,6,11–13]. Pumped storage power stations partnering with stakeholders is a key to operations management success [16]. By fostering partnering, pumped storage power stations can more effectively obtain, integrate, and manage resources during their operation [17].

The initial purpose of constructing pumped storage power stations was to absorb excess electricity from the power system, ensuring system stability. With the substantial construction of clean energy stations, there is a need for a stable energy storage system to integrate renewable energy electricity [4,10,18]. As a clean and stable green energy storage station, pumped storage power stations have seen a rapid development [4,19]. The primary objective of building pumped storage power stations has shifted from absorbing excess electricity from the power system to absorbing surplus electricity from renewable energy stations [19,20]. Under the new circumstances, the operational objectives of pumped storage power stations have changed. It is necessary to reanalyze the operations management of pumped storage power stations from a multi-energy complementarity perspective.

Operations management can significantly influence the performance of pumped storage power stations, such as environmental protection, economic benefits, and social benefits, so operation management is crucial for pumped storage power stations [21]. From the perspective of multi-energy complementarity, the operations management of pumped storage power stations largely depends on the partnering among stakeholders between different types of renewable energy power stations and power grid companies; current research tends to advocate collaborative strategies to integrate the distinct expertise and requirements of stakeholders to achieve complementarity among different renewable energy power stations, aiming to reach the goal of decarbonizing the regional power grid [22,23]. Partnership is a long-term commitment between more organizations, aiming to maximize the effectiveness of each participant’s resources to achieve specific objectives, which is based on the trust of mutual assistance among stakeholders [24]. Partnering has been found to effectively encourage stakeholders to voice their opinions, enhancing operations management with each other [25]. While there is a consensus on the importance of partnering in operations management [25,26], there is limited research that systematically explains the causal relationship between partnering and the operations management of pumped storage power stations from the perspective of multi-energy complementarity, as well as how the performance of pumped storage power stations can be enhanced by partnering. Understanding the in-depth underlying causes to improve operations management of pumped storage power stations is crucial for integrating the resource optimization of all stakeholders involved in multi-energy complementarity [27,28]. Therefore, this study aims to establish and test a conceptual model, quantitatively investigating the causal relationships among partnership, operations management, and pumped storage power stations' performance. The model testing is based on the data collected from the largest pumped storage power station in the Chinese Northeast region—the Liaoning Qingyuan Pumped Storage Power Station.

The rest of this paper is organized as follows: Section 2 establishes a conceptual operations management model in pumped storage power stations under the perspective of multi-energy complementarity. Section 3 provides a literature review on the operations management of pumped storage power stations. Section 4 describes the research methodology, clarifying the research framework and empirical questions, and elaborates on the rationale behind choosing pumped storage power stations for an in-depth study. Section 5 details the survey results and analyses. Section 6 adopts path analysis to validate and interpret the relationships among partnering, operations management, and the performance of pumped storage stations. Section 7 exposes the contributions of this study. Section 8 concludes by discussing the limitations of the research findings and suggests future work.

2. Development of the Conceptual Operations Management Model

Renewable energy power stations primarily encompass clean energy sources such as solar, wind, and hydropower. The operation of pumped storage stations is aimed at optimizing the energy structure and facilitating a low-carbon transformation by harmonizing renewable resources within a region [11]. Considering the strong interconnection among different types of renewable energy power stations and pumped storage power stations and with power grid companies, it is imperative to view the operations management of pumped storage power stations from a multi-energy complementarity perspective, which involves various stakeholders [29]. These stakeholders include government, power grid companies, wind power stations, solar power stations, hydropower stations, pumped storage power stations, thermal power stations, and electricity consumers [30]. Pumped storage power stations partner with stakeholders and share relevant information during the operations management processes, which facilitates the integration of various types of renewable energy power stations into a cohesive "multi-energy complementarity" entity [3,11,22,31]. Thus, as depicted in Figure 1, a conceptual model has been formulated to delve into the causal relationships among partnering, operations management, and the performance of pumped storage power stations from a multi-energy complementarity standpoint. Specifically, partnering can enhance operations management and, in turn, operations management can mediate the relationship between partnering and the performance of pumped storage power stations. These relationships need to be quantified through subsequent empirical research.

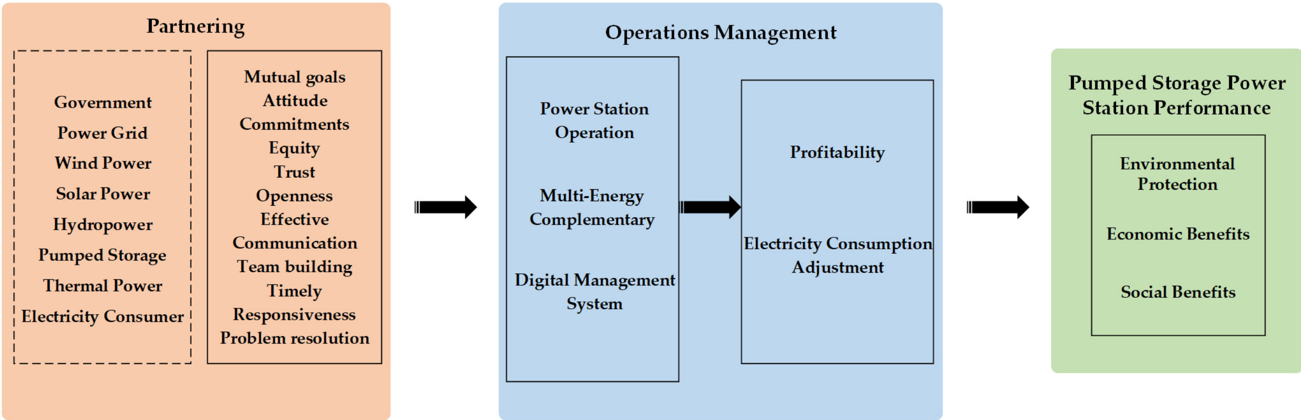

Figure 1. Conceptual operations management model in pumped storage power stations under the perspective of multi-energy complementarity.

3. Literature Review

As shown in Table 1, existing research on the operations management of pumped storage power stations in the context of multi-energy complementarity mainly focuses on theoretical analysis [32–39]. The primary concern is the maximization of renewable energy generation by pumped storage power stations in collaboration with renewable energy stations, aiming to alleviate power imbalances [32,34,36–39]. This entails an optimal resource allocation between clean energy stations and pumped storage power stations. Through algorithms, it has been proven that optimizing the use of pumped storage power stations, in conjunction with wind, solar, and hydro stations, can effectively mitigate fluctuations in renewable energy and simultaneously reduce the operational costs of renewable energy stations [32,33,36–39]. Furthermore, existing studies mainly concentrate on optimizing algorithms that simulate the multi-energy complementarity process of pumped storage power stations operating in tandem with renewable energy stations [32,37–39]. There is a noticeable lack of field research and analysis concerning the actual operational management situations of pumped storage power stations from a multi-energy complementarity perspective. There is also insufficient attention given to issues of misaligned interests arising from inadequate communication and collaboration with stakeholders during operations management. To effectively address existing challenges, operators of pumped storage power stations should adopt a partnering strategy. By examining the needs of each stakeholder, operators can gain a comprehensive understanding of factors related to operations within both the internal and external environment of the power station, which ensures that the actual operations management meets the interests of various stakeholders [40,41]. The critical success factors for partnering mainly include mutual goals, attitude, equity, commitments, trust, openness, team-building, effective communication, problem resolution, and timely responsiveness [24,42]. By the establishment of trust in partnering, participants of pumped storage power stations can establish connections with various stakeholders to promote open communication, thereby facilitating the effective integration of essential information into the station's operational processes [43]. Partnering with power grid companies helps facilitate the quick integration of the pow-er station with the power grid, allowing it to accept grid dispatch and transmit clean energy power through the power grid [11,22]. Partnering with different types of renewable energy power stations, through the compatibility and integration of technology and equipment, enables different types of renewable energy power stations and pumped storage power stations to work in tandem [31]. Taking the combination of pumped storage with wind and solar energy as an example, the power supply can be effectively balanced based on the real-time operating data of wind and solar power [13,22,30]. Furthermore, active communication with local communities and the government not only helps in understanding the potential social and environmental impacts of renewable energy stations, but also ensures that the station strictly adheres to relevant laws and regulations during its operation [21,23,31].

Table 1. Literature statistics related to operations management of pumped storage power stations.

Source	Research Object	Methodology Employed	Key Findings
Pattnaik et al., (2023) [32]	Optimal utilization of clean energy and its impact on hybrid power systems.	Algorithmic simulation	Advantage of incorporating Static synchronous compensator with Hybrid power system + Pumped hydro storage is elucidated.
Gao et al., (2022) [33]	Integrating abandoned coal mine storage with wind–solar power technology.	Algorithmic simulation	Effective mitigation of wind and solar power variation using abandoned mine reservoir.
Zhao et al., (2021) [34]	Minimization of operating cost for pumped storage power stations.	The cooperative game method	Optimized solution obtained shows an effective minimization of operating costs.
Yong et al., (2022) [35]	Integrating abandoned coal mine storage with wind–solar power technology.	Two-stage fuzzy evaluation model	The site selection issue of underground pumped storage power stations is studied.
Javed et al., (2020) [36]	The effectiveness of a hybrid pumped and battery storage system in improving off-grid renewable energy reliability and sustainability.	Algorithmic simulation	A hybrid pumped and battery storage is proposed for off-grid renewable energy systems.
Ghasemi et al., (2018) [37]	Maintaining a balance between generation and demand.	Algorithmic simulation	Pumped storage unit optimal scheduling and demand response implementation, improve economic and technical performance indexes.
Notton et al., (2017) [38]	Maximizing renewable generation and mitigating power imbalance.	Algorithmic simulation	Optimization of the hydro pumping storage operation using several reversible pumps in parallel.
Panda et al., (2020) [39]	Optimal generation scheduling and coordination among different hybrid power system configurations.	Algorithmic simulation	Modeling and evaluation of the optimal operation of three hybrid power systems.

4. Methodology

4.1. Research Framework

The research framework of this study is presented in Figure 2. The "Introduction" elaborates on the research background and objectives. Accordingly, the literature review and theoretical construction are accomplished in the "Development of the Conceptual Operations Management Model" section. To validate the model, tasks of theoretical testing include extracting empirical research questions from model development, data collection, data analysis, and result interpretation, which will be detailed subsequently.

4.2. Empirical Research Questions

The relevant themes appearing in the model (Figure 1) worth investigating have been translated into specific questions. What is the extent of the application of partnership in the operations management of pumped storage power stations? What is the current status of operations management in pumped storage power stations? What is the performance of pumped storage power stations? What are the relationships among the topics?

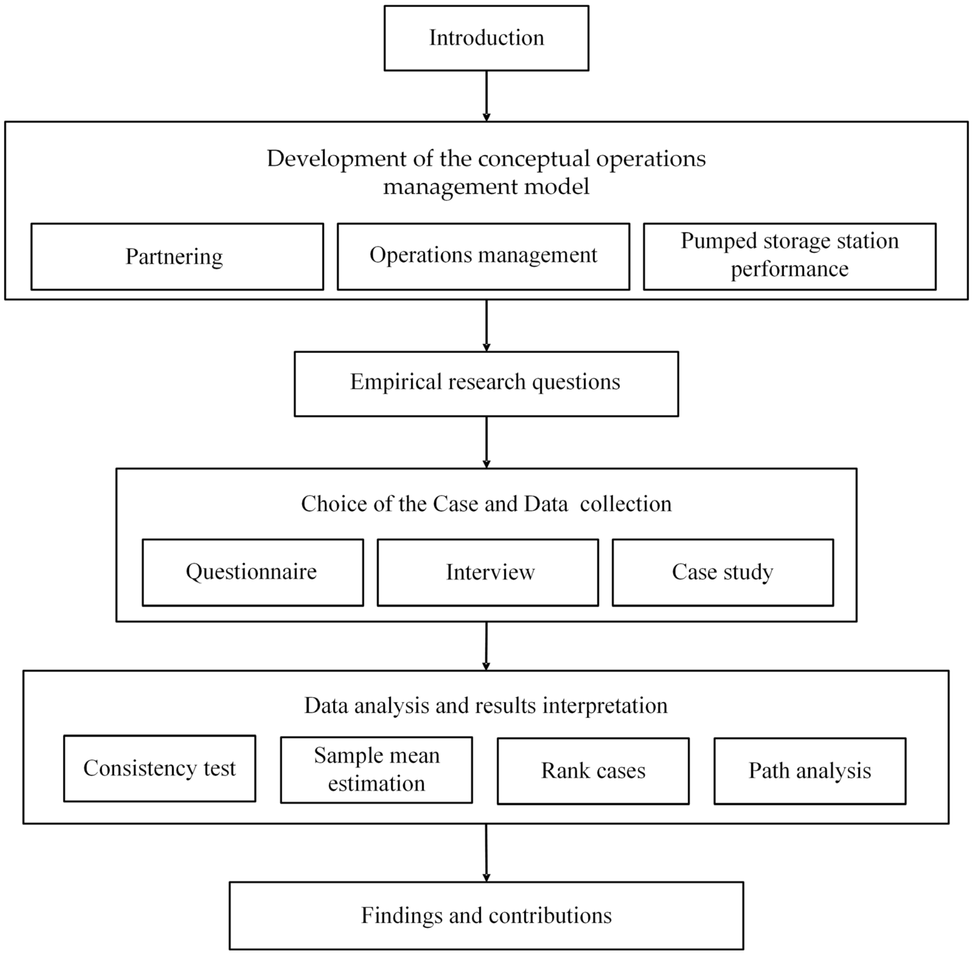

Figure 2. Research framework.

4.3. Choice of the Case of the Liaoning Qingyuan Pumped Storage Power Station

The importance of pumped storage power plants in multi-energy complementarity is considered [4–13]. Given that the Liaoning Qingyuan Pumped Storage Power Station is the largest pumped storage power station in the Northeast region of China and is one of 139 key projects in the latest initiative to rejuvenate China's old industrial base in the Northeast, this power station was chosen for an in-depth study. All data has been collected through on-site investigation at the Liaoning Qingyuan Pumped Storage Power Station This pumped storage power station plays a significant role in the utilization of clean energy in the Northeast region of China, the protection of the local ecological environment, and the promotion of economic benefits and social benefits.

4.4. Multiple Methods to Collect Data for the Case Study

In case studies, utilizing a mix of data collection methods can significantly bolster the reliability of analysis results as it allows for the validation and complementation of various sources of evidence [44,45]. This study employs questionnaires, interviews, and field investigations to gather both quantitative and qualitative data, all of which were obtained through on-site inspections at the Liaoning Qingyuan Pumped Storage Power Station. Building upon the literature reviewed, a conceptual model was formulated to better understand the operations management of pumped storage power stations from a multi-energy complementarity perspective (see Figure 1). The five-point Likert scale facilitated the acquisition of quantitative data concerning partnering, operations management, and the performance of pumped storage power stations.

The respondents were key management and technical personnel from the Liaoning Qingyuan Pumped Storage Power Station, including the owner, the general contractor (design–builder alliance), and consulting engineers. They all possess professional experience from various organizations involved in pumped storage power stations, with an average work experience of 8.07 years, ensuring that the data collected reliably reflect the situation of pumped storage power stations. This study adopted a fieldwork approach, ensuring that all questionnaires issued during the site visit were collected, with a total of 122 questionnaires received. After excluding invalid questionnaires or questionnaires with over 90% of the same numerical answers, a total of 105 valid questionnaires were analyzed.

During the on-site investigation, semi-structured interviews were conducted, with questionnaire content serving as the primary discussion points. A total of 41 technical and managerial experts in the field of pumped storage power stations participated, contributing in-depth qualitative data. These experts, holding notable positions within their respective units, provided valuable insights, enhancing the breadth and depth of the collected data. The interview data effectively complemented, verified, and interpreted the information gleaned from the questionnaire survey [46]. Moreover, a review of collected documents further elucidated processes integral to the operations management within pumped storage power stations. The amassed data were collectively employed to test and interpret the conceptual model of operations management under the lens of multi-energy complementarity (see Figure 1).

4.5. Data Analysis Techniques

The questionnaire results were analyzed using the Statistical Package for Social Science (SPSS 26.0). The statistical analysis methods used in this study included a consistency test, sample mean estimation, rank cases, and path analysis.

Cronbach's α is crucial for measuring internal consistency reliability [47] and can be calculated using the following formula [48]. The selection criteria for Cronbach's α are $0.7 \leq \alpha \leq 0.8$ (acceptable), $0.8 \leq \alpha \leq 0.9$ (good), and $\alpha \geq 0.9$ (excellent) [49]. In behavioral research, the mean is the primary method used to estimate the value of the population and measure the central tendency [50]. The sample mean of all indicators is used to estimate ratings and is arranged in descending order to understand the status of the survey topics. Path analysis based on linear regression was adopted, and the results were tested for significance levels that follow the typical statistical significance level of 0.05, with a level of 0.01 considered highly significant. Data from interviews and direct observations were used to further confirm and explain the cause–effect relationships established in Figure 1.

5. Survey Results and Analysis

5.1. Partnering

Interviewees were asked to evaluate 10 critical success factors for partnering, where 1 = strongly disagree and 5 = strongly agree. The results are shown in Table 2.

Table 2. Partnering among pumped storage power stations and stakeholders.

Indicators	Rating	Rank	Cronbach's α
Attitude	4.06	1	0.99
Equity	4.06	1	
Commitment	4.04	3	
Trust	4.03	4	
Openness	4.02	5	
Timely responsiveness	4.02	5	
Mutual goals	4.01	7	
Team building	4.01	7	
Effective communication	4.00	9	
Problem resolution	3.99	10	
Average	**4.02**		

As shown in Table 2, the average rating was 4.02, indicating that the participants of pumped storage power stations achieved a relatively high level by adopting partnering strategies to manage relationships with stakeholders. Attitude and equity obtained the highest rating (4.06) and commitment and trust ranked third (4.04) and fourth (4.03), respectively. This indicates that stakeholders maintain a positive attitude during the pumped storage power stations implementation and that being fair in dealings and honoring commitments among stakeholders are essential prerequisites for establishing trust [24]. This promotes trust among stakeholders during the operation of the power station, facilitating the smooth progress of station operations. It was noteworthy that problem resolution had the lowest rating (3.99). While trust is formed among the pumped storage power station's stakeholders, this does not necessarily ensure the establishment of a comprehensive problem-solving method and process. Interviews with the power station's operation managers confirmed that due to the lack of effective problem-solving methods and processes, when issues arise, managers cannot respond quickly, find it hard to accurately pinpoint the responsible party, and must spend significant time seeking solutions.

5.2. Operations Management

Respondents were asked to evaluate the following aspects related to the operations management of pumped storage power stations, mainly including power station operation, multi-energy complementarity, digital management system, profitability, and electricity consumption adjustment, where 1 = strongly disagree and 5 = strongly agree. The results are shown in Table 3.

Table 3. Pumped Storage Power Stations Operations Management.

Indicators	Rating	Rank	Cronbach's α
Power Station Operation			
There are appropriate pumped storage power stations' operation performance measures and incentives to promote the continuous improvement of operations management.	4.04	2	0.983
Using advanced technology and equipment to support efficient operation of pumped storage power stations.	4.02	3	
Multi-Energy Complementarity			
There is a suitable multi-energy complementarity governance to support pumped storage power stations' purchasing and selling of electricity via grids.	3.98	5	
Responsibilities and rights of multi-energy complementarity stakeholders are clearly defined, ensuring a fair sharing of the benefits generated from the pumped storage power station.	3.95	8	
Digital Management System			
The digital management system can monitor electricity consumption adjustment in real-time, promptly adjust the operation of the pumped storage power station, and optimize power dispatching.	3.96	7	
Integrated management of power generation, transmission, loading, and storage with the support of the digital system, enhancing the power system's ability to promptly respond to, dispatch, and coordinate diverse power sources.	3.92	9	
Electricity Consumption Adjustment			
Pumped storage power stations play a significant role in adjusting the local grid load and power consumption.	4.05	1	
Pumped storage power stations can play an important role in adjusting local wind and solar energy in the process of multi-energy complementarity.	4.02	3	
Profitability			
The local electricity market has a large demand to consume the green electricity produced by the wind, solar, water, storage power stations.	3.98	5	
There is a pricing mechanism suitable for clean energy transactions, which ensures reasonable returns on investment for pumped storage power stations.	3.91	10	
Average	**3.98**		

Figure 3 demonstrates that the foremost consideration factor, "Power Station Operation", ranks second with an average of 4.03. This underscores the significance of performance assessment, incentive mechanisms, and technological advancements in optimizing the operational efficiency of pumped storage power stations. Through incentive mechanisms, they can improve work efficiency and ensure the regular operation of the power station. At the same time, there is also a need to strengthen the focus on the modernization of technology and equipment, because advanced technology and equipment can not only enhance the operational efficiency of the power station but also reduce the failure rate and lower operating costs. Interviews with power station managers indicated that the existing performance evaluation system does not align with the power station's long-term interests. A whole life cycle cost perspective (covering engineering, procurement, construction, and operation) should be considered. For instance, to economize during construction, some stations utilized traditional technologies for crucial equipment, leading to frequent malfunctions during operations, particularly when transitioning between pumping and power generation. Additionally, in the pursuit of high profits, the early operational phase often saw stations pushing their load capacities to the maximum during peak demand, ignoring the equipment's economic and efficient operation, ultimately compromising long-term benefits despite short-term profit appearances.

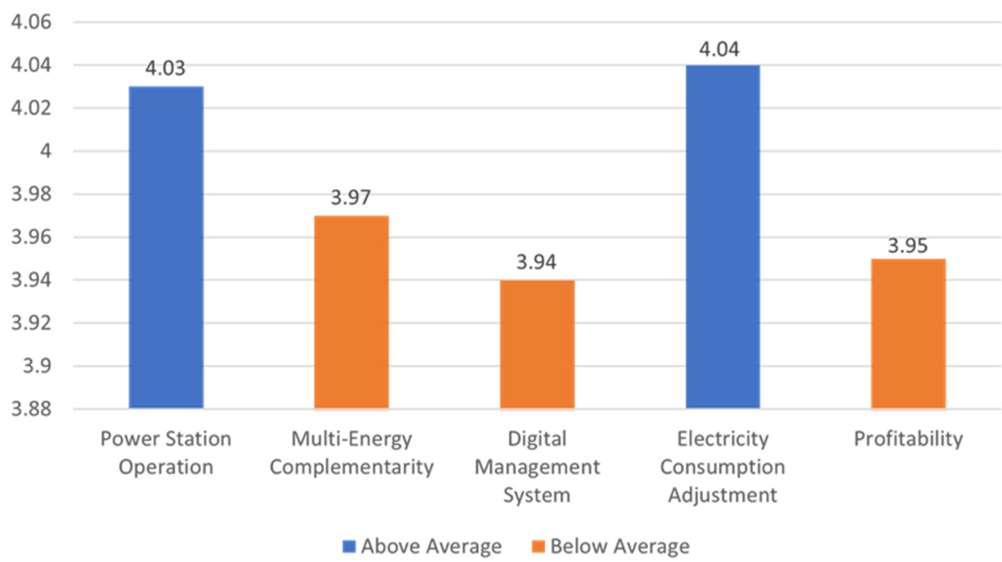

Figure 3. Rating of key indicators of Pumped Storage Power Stations Operations Management.

The second crucial factor in the operations management of pumped storage power stations, as shown by an average rating of 3.97 in Figure 3, is "Multi-Energy Complementarity", which shows the need to establish a matching mechanism for multi-energy operation, to standardize grid-connection procedures for clean energy, and to clarify rights and responsibilities among all participants. During operation, partnering with other power stations such as wind, solar, and thermal stations is vital for optimal energy distribution. A well-defined mechanism ensures stability in the power grid, especially during energy shortages. Moreover, as pumped storage power stations gain traction, standardizing grid connection with clean energy stations is indispensable to maintain stability and safety. In the multi-energy complementarity process, a clear delineation of responsibilities and rights among participants is essential to foster smooth partnerships and avert potential disputes. Interviews revealed that it is insufficient to solely focus on the operations management of pumped storage power stations, and there is also a need to emphasize complementarity and collaboration with other power stations of clean energy. To ensure the smooth implementation of multi-energy complementarity, pumped storage power stations, wind power stations, solar power stations, and grid companies have signed cooperative agreements, clarifying the rights and responsibilities of each party. The agreement stipulates quotas, prices, and other matters related to energy supply and demand, ensuring that the interests of all parties are protected and reducing obstacles to partnering due to the allocation of rights and responsibilities.

The factor "Digital Management System" was rated the lowest, with an average score of 3.94, as illustrated in Figure 3. This factor primarily encompasses the development and utilization of a power station's digital management system, which can monitor electricity supply and consumption in real-time. Additionally, the ability of the digital management system to integrate with grid companies for achieving coordinated management in multi-energy complementation is a crucial aspect. The built digital management system within the pumped storage power station needs to ensure real-time data provision concerning electricity supply and consumption during its operation. Through this digital system, the power station can achieve more accurate control over various equipment operations, reduce the chance of human errors, and subsequently enhance the operational efficiency and safety of the power station [22,31]. Interviews indicated a notable reliance on traditional operations management in pumped storage power stations, where monitoring of power supply and consumption data is carried out through manual observation and paper-based recording. This conventional approach not only dampens efficiency but is also prone to data delays and errors, especially during peak periods. The establishment of a digital management system facilitates real-time monitoring and forecasting of power supply and consumption, lowers communication costs with the grid company, and allows the power station to adjust its power supply based on the real-time demand of the grid, thereby achieving integrated management in multi-energy complementation.

The factor "Electricity Consumption Adjustment" secured the highest ranking from respondents, registering an average score of 4.04, as illustrated in Figure 3. This aspect primarily explores the capability of pumped storage power stations to exercise a vital regulatory role in managing local grid load and power consumption. Furthermore, within the scope of multi-energy complementarity, pumped storage power stations possess considerable regulatory potential for local wind and solar clean energy sources. Pumped storage power stations are pivotal within the power grid, ensuring stable voltage and frequency regulation, in addition to storing excess electricity which can later be redistributed based on the grid's demand at different times. Power grid companies heavily depend on pumped storage power stations to promptly respond to the grid's needs, thereby ensuring voltage and frequency stability. Simultaneously, power generation from wind and solar sources can be unstable due to external factors like weather conditions. Hence, pumped storage power stations are required to adjust and store the surplus electricity generated during high-yield periods from these clean energy sources. The symbiotic relationship between clean energy power stations and pumped storage power stations fosters a robust and efficient multi-energy complementarity system. During the interviews conducted, power station operators indicated that the primary role of pumped storage power stations during operation is to absorb and utilize the electricity generated from renewable energy power stations.

Lastly, the factor "Profitability" received the lowest average rating of 3.95, as reflected in Figure 3. This dimension primarily revolves around the substantial demand within the local electricity market and the establishment of a pricing mechanism conducive to clean energy transactions. A robust demand in the local electricity market signifies a strong market appetite to assimilate the electricity output from renewable energy power stations, which, in turn, bolsters the economic viability of pumped storage power stations. A well-calibrated clean energy pricing mechanism is crucial to ensure that, post the capital investment phase, the power station can garner a reasonable return during its operational tenure through electricity sales. If the electricity pricing is too low, or if there is not an appropriate pricing mechanism to highlight the value of pumped storage, it becomes challenging for pumped storage power stations to maintain stable operations over the long term. Conversations with the power station's operations management personnel revealed that there is currently a high demand for renewable energy in China, driving a nationwide momentum towards establishing renewable energy power stations. Being an energy storage station capable of absorbing renewable energy, pumped storage power stations have witnessed rapid development. However, the overall construction of the renewable energy pricing mechanism remains underdeveloped. Due to high initial investment costs, the overall price of renewable energy exceeds that of thermal power. The absence of a reasonable pricing mechanism renders renewable energy power stations, including pumped storage power stations, vulnerable to the issue of low returns.

5.3. Pumped Storage Power Stations' Performance

Respondents were asked to rate the environmental protection, economic benefits, and social benefits of pumped storage power stations on a scale of 1 to 5, where 1 = very poor and 5 = very good. The results are shown in Table 4.

Table 4. Pumped storage power stations' performance.

Indicators	Rating	Rank	Cronbach's α
Social benefits	4.27	1	0.960
Environmental protection	4.26	2	
Economic benefits	4.24	3	
Average	**4.26**		

As shown in Table 4, the performance scores for pumped storage power stations range from 4.24 to 4.27, indicating that the performance of pumped storage power stations is good. Pumped storage power stations can not only meet their own economic benefits through operations management but also generate positive societal benefits and contribute to environmental protection. After communicating with the power station participants, it was learned that due to the high demand for renewable energy power, pumped storage power stations can achieve good economic benefits in the power market through reasonable pricing mechanisms and operations management. Meanwhile, the construction and operation of pumped storage power stations have provided many employment opportunities for the residents, boosting the local economy. Moreover, if the pumped storage power station is completed, it will become a local tourist attraction, blending seamlessly with the natural scenery and providing new habitats for various fish, birds, and other wildlife.

6. Testing the Model

As depicted in Tables 2–4, the scale exhibits satisfactory internal consistency reliability, demonstrated by a minimum Cronbach's α of 0.960. To delve deeper into the relationships outlined in the conceptual model (refer to Figure 1), this study employed path analysis. Utilizing the mean ratings of each group (comprising 10 partnering indicators, 10 indicators pertinent to pumped storage power stations operations management, and 3 indicators for pumped storage power stations' performance) as variables, the path analysis was executed to validate the conceptual model. The regression coefficients for each path and the percentage of variance explained are represented by R^2 and summarized in Appendix A. The results confirm the cause–effect relationships established in the conceptual model, as illustrated in Figure 4.

The path analysis validates the significance of the pumped storage power station's operations management, progressing from partnering to operations management, ultimately impacting the renewable energy power station performance (see Figure 4). Partnering has a significant positive impact on operations management, thereby enhancing renewable energy power station performance, as shown below.

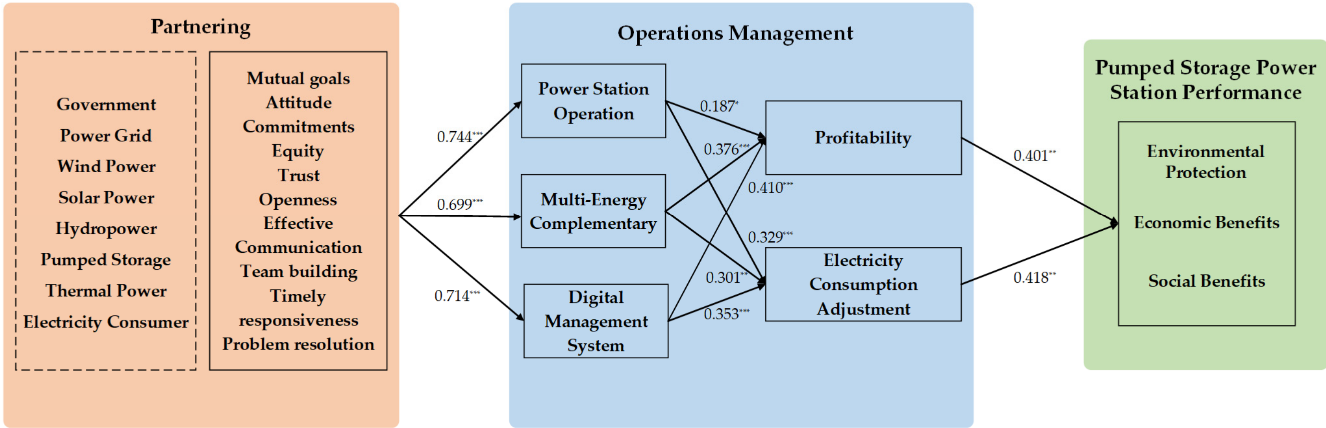

Figure 4. Relationships among partnering, operations management, and pumped storage power station performance. Note: *** = $p < 0.001$; ** = $p < 0.01$; * = $p < 0.05$.

6.1. Relationship between Partnering and Operations Management

As shown in Figure 4, partnering has significant impacts on the operations management of pumped storage power stations. The influence of partnering on power station operation is markedly illustrated, bearing a standardized regression coefficient of 0.744 ($p < 0.001$), multi-energy complementarity with a coefficient of 0.699 ($p < 0.001$), and digital management system with a coefficient of 0.714 ($p < 0.001$). Interviews and field observations confirmed that partnering enhances operations management, covering aspects like power station operation, multi-energy complementarity, and digital management system.

Firstly, partnering can effectively assist pumped storage power stations in achieving better power station operation under the perspective of multi-energy complementarity. In the perspective of multi-energy complementarity, the connection between pumped storage power stations and grid companies is tighter, necessitating a more flexible response to demand fluctuations rather than simply operating according to planned capacity. As confirmed through interviews, partnering enables pumped storage stations to become critical components that stabilize grids, reduce renewable energy interruptions, and boost clean energy integration.

Secondly, partnering can assist in building multi-energy complementarity among pumped storage stations, renewable power stations, grids, and consumers. This integration enables the optimal allocation of diverse resources like wind, solar, pumped storage, etc., for efficient clean energy utilization through interconnected management. Through partnering, wind energy can be used when abundant, while pumped storage balances supply when wind is low, reducing intermittency risks and maintaining stability. For instance, grid company investment in the Liaoning Qingyuan Pumped Storage Power Station enabled the rapid absorption and supply of electricity. A number of high-voltage transmission lines have been developed by the grid company, which helps achieve a rapid interconnection between pumped storage power stations and renewable energy power stations such as wind and solar. This multi-source integration leads to a robust, flexible system drawing on each energy's strengths. Ultimately, partnering facilitates optimal complementarity for maximized efficiency and stability.

Finally, partnering among stakeholders is essential for establishing digital management systems to handle the complex data flows in multi-energy complementarity processes. By fostering such partnerships, effective data sharing is enabled, aiding the station in more accurately forecasting power demand. This, in turn, optimizes power station operations, dispatch, and efficiency. A manager overseeing digitization highlighted that a grid company boasts extensive experience in creating digital management systems for pumped storage power stations. They provided a comprehensive digital management system construction plan for the Liaoning Qingyuan Pumped Storage Power Station, encompassing the development of data centers, cloud platforms, and the establishment of the

Internet of Things infrastructure. Upon completion of the digitization system, a seamless data sharing avenue between pumped storage power stations and grid companies was established. This realization of real-time data sharing and coordination showcases how partnering facilitates the digital management system operation in complex multi-energy complementarity processes.

6.2. Relationship between Operations Management

The connections between different factors of operations management can be seen in Figure 4. The operations management of pumped storage power stations mainly includes power station operation, multi-energy complementarity, digital management system, profitability, and electricity consumption adjustment. Among them, power station operation, multi-energy complementarity, and digital management system fall under the operations management approaches of pumped storage power stations. In contrast, profitability and electricity consumption adjustment represent the benefits and functions of the power station. The operations management approaches of the pumped storage power station impact its benefits and functions. The standardized regression coefficients of power station operation, multi-energy complementarity, and digital management system on profitability are 0.187 ($p < 0.05$), 0.376 ($p < 0.001$), and 0.410 ($p < 0.001$), respectively. The standardized regression coefficients of power station operation, multi-energy complementarity, and digital management system on electricity consumption adjustment are 0.329 ($p < 0.001$), 0.301 ($p < 0.01$), and 0.353 ($p < 0.001$), respectively. This verifies that the power station operation, multi-energy complementarity, and digital management system have a significant impact on both profitability and electricity consumption adjustment.

For a pumped storage power station to operate stably in the long term, achieving reasonable returns on investment is crucial. When it comes to power station operation, performance evaluations and incentive mechanisms are utilized to motivate station managers to adopt practices that enhance both efficiency and stability. By leveraging advanced technology and equipment, the overall efficiency of the station can be significantly improved, generating more electricity for market consumption, which, in turn, enhances returns on investment. Regarding multi-energy complementarity, pumped storage power stations attain a more stable electricity output by integrating different forms of energy, such as wind and solar power, ensuring consistent returns. During this process, the roles and responsibilities of all participating parties are clearly defined, minimizing managerial conflicts and ensuring efficient operations. This collaborative environment facilitates reaping benefits through energy complementarity. In the domain of digital management systems, these systems empower power station managers to monitor power supply and demand in real-time, enabling timely adjustments and optimizing power dispatch. Through the digital management system, integrated management of the power station, grid, load, and storage is achieved, enhancing the station's ability to respond to variations in diverse power sources like wind and solar power. This not only facilitates regional energy complementarity but also maximizes the station's profits. In conclusion, through continuous optimization of operations, partnerships with other clean energy power stations, and the advancement of digital management systems, pumped storage power stations can supply stable power to the market. The local market's high demand for renewable energy, coupled with favorable pricing mechanisms, ensures that these operational strategies yield substantial economic returns for pumped storage power stations.

From a multi-energy complementarity standpoint, the significant function of pumped storage power stations lies in their electricity consumption adjustment capabilities, which are indispensable for ensuring the long-term stable operation of the entire power system. In the realm of power station operation, performance assessments and incentive mechanisms are crucial to ensure the station operates at its optimal state. The employment of advanced technology and equipment empowers the station to operate more flexibly and efficiently, swiftly responding to sudden power demands, thus achieving effective electricity consumption adjustment. A coordinated multi-energy complementarity operational mechanism guarantees that the pumped storage power station can adjust its output based on the power supply from wind and solar power, thereby providing a stable electricity supply to the grid. Concurrently, a clear delineation of rights and responsibilities among the stakeholders in multi-energy complementarity safeguards the interests of all participants, aiding in better coordination of various resources to ensure the efficient operation of the power station. In the arena of digital management systems, constructing a digital operation system grounded on big data and cloud computing enables real-time adjustments to the station's operating status to meet the immediate demands of the grid, thus achieving the objectives of electricity consumption adjustment. Through comprehensive management of power station operations, the establishment of a multi-energy complementation mechanism, and advancements in the digital management system, pumped storage power stations can effectively adjust grid voltage, and store and release electrical energy. This not only ensures the stability and efficiency of the grid but also plays a crucial role in adjusting the local grid load and integrating wind and solar clean energy sources.

6.3. Impacts of Operations Management on Pumped Storage Station Performance

As shown in Figure 4, profitability, and electricity consumption adjustment in the operations management of pumped storage power stations significantly influences the performance of the power station. The standardized regression coefficients are 0.401 ($p < 0.01$) and 0.418 ($p < 0.01$), respectively. This confirms that the power station operation, multi-energy complementation, and digital management system ensure the station's revenue and its key role in electricity consumption adjustment, thereby having a significant impact on its performance.

By enhancing the operations management of pumped storage power stations, and promoting coordination with other renewable energy stations, as well as advancing digital management system construction, it is ensured that the pumped storage can yield stable returns and effectively fulfill its role in electricity consumption adjustment. Precise forecasting and scheduling facilitated by a digital management system ensures that pumped storage power stations release electricity when prices are high and conserve energy when prices are low. This strategy guarantees higher market profits, offering a more stable revenue stream for pumped storage power stations. The consistent performance in generating returns entices more investments into the pumped storage power sector. The construction and operation of pumped storage power stations have generated a significant number of job opportunities for local residents while also invigorating the development of related industries, imparting long-term economic benefits to the region. As renewable energy stations become increasingly prominent in the grid, public interest and support for renewable energy are burgeoning, cultivating a positive social atmosphere.

7. Discussion

7.1. Contributions to the Body of Knowledge

Stakeholder partnering plays a crucial role in the operations management of pumped storage power stations. While the influence of operations management on the performance of pumped storage stations has been explored, there exists a void in theoretical frameworks that meld stakeholder partnering to systematically tackle operations management issues. This research fills this gap and makes significant theoretical and practical contributions to the knowledge system, demonstrating how operations management activities in real-world pumped storage power stations occur. Firstly, this study established interdisciplinary connections in the areas of partnering, operations management, and pumped storage power stations' performance by developing a mediation model. Secondly, the field research on Liaoning Qingyuan Pumped Storage Power Station reveals that the focal points of operations management for pumped storage stations are the establishment of power station operation, multi-energy complementarity, and the digital management system for the stations. Thirdly, the causal relationships delineated in the conceptual model were authenticated, elucidating that partnering not only catalyzes operations management but also significantly enhances the performance of pumped storage stations through refined operations management. Fourthly, this study revealed that in the actual operation of pumped storage stations in China, issues pertaining to partnering among stakeholders emerge, primarily due to the absence of effective communication channels and problem-resolution methods.

7.2. Strategies for Improving Pumped Storage Power Stations Operations Management

1. Fostering partnering among stakeholders of pumped storage power stations for multi-energy complementarity.

Among the 10 key factors for partnering between stakeholders in pumped storage power stations, effective communication and problem resolution rank the lowest (see Table 1), which indicates that pumped storage power stations and stakeholders need to establish both formal and informal channels of communication that are effective. Additionally, comprehensive methods and processes for problem resolution should be developed and implemented effectively among stakeholders. To improve communication channels in the operations management of the power station, regular meetings can be organized to invite stakeholders to assess how to best coordinate pumped storage power stations for accommodating different types of renewable energy. At the same time, a specialized online platform can be developed through a digital management system to facilitate information sharing and communication among stakeholders. To improve methods and processes for problem resolution, standardized operating procedures can be established among stakeholders for regular issues. Additionally, a specialized problem-solving team can be formed among pumped storage power stations and stakeholders, responsible for handling emergent and complex problems.

2. Enhancing operations management capability by partnering in multi-energy complementarity.

The operations management capability of a pumped storage power station reflects the extent to which the station's managers achieve the performance objectives. This is closely related to the partnering between the pumped storage power station and other stakeholders such as clean energy power stations. Establishing open communication between the pumped storage power station and its stakeholders through partnering will help the station's operations managers clearly understand the needs of stakeholders. Furthermore, this open channel facilitates the effective utilization of shared information, technology, and expertise, which, in turn, enhances operational efficiency and performance.

3. Building multi-energy complementary mechanisms between pumped storage power stations and clean energy stations through the digital management system.

Multi-energy complementary coordination between pumped storage power stations and clean energy power stations can be facilitated through the digital management system. By deploying sensors and Internet of Things devices within the power station, real-time monitoring of electricity demand and supply can be achieved. A data center is established to analyze this data, employing machine learning or AI algorithms for demand forecasting. Based on demand forecasts and real-time data, the operation of the pumped storage power station can be dynamically adjusted. Further optimization of the electricity supply is achieved by integrating with smart grid systems. A real-time reporting and feedback function is set up on the mobile end within the digital management system to quickly respond to issues or faults that arise during operation.

4. Improve the operations management of pumped storage power stations from a full life-cycle perspective

Successful operations management must be considered as early as the planning and design phase of the power station. During the feasibility study and preliminary planning stage, the complementarity and integration requirements between multiple energy sources are considered, appropriate technologies are selected, and future operation and maintenance needs are considered; in the design phase, specific operating system selections and engineering designs are contemplated, with the integration of various energy types in mind, aiming for optimal efficiency and synergy during the operational stage; during the construction phase, operation and maintenance plans are formulated, operational personnel are trained, and suitable operations management systems are chosen.

8. Conclusions

8.1. Findings

In conclusion, the established mediation model (Figure 1) demonstrates the interrelationships among partnering, operations management, and the performance of pumped storage stations, substantiated by data from a Qingyuan pumped storage power station in Fushun City, Liaoning Province, Northeast China. Key insights include:

(1) Effective partnering, particularly with grid companies, significantly influences the operations management of pumped storage power stations. Through trust and fair collaboration, stakeholders contribute positively to the operation process, albeit existing gaps in communication and problem-resolution mechanisms warrant attention.

(2) The operations management level in China's pumped storage power stations is relatively high, with a central score around 4.00 on operations management indicators. It should be noted that the operations management of pumped storage power stations needs to focus on improvements in multi-energy complementarity coordination, digital management system construction, and profitability.

(3) Path analysis further reveals that partnering not only augments operations management but also elevates the performance of pumped storage power stations. Detailed assessment into operations management factors highlights the influential role of partnering in aspects such as power station operation, multi-energy complementarity, and digital management system, which, in turn, fortifies the station's profitability and electricity consumption adjustment, catalyzing overall performance enhancement.

8.2. Limitations and Future Research Directions

The findings of this study largely draw from experiences and data gathered from participants involved with the Liaoning Qingyuan Pumped Storage Power Station in China. While the insights herein are deemed extendable to other domestic and potentially international pumped storage stations, the reliance on a single station as the data source marks a limitation. Future research endeavors should aim to validate these insights through data garnered from diverse pumped storage stations worldwide.

The trajectory of future research, as indicated by this study's findings, will be significantly aimed at refining operations management within pumped storage power stations. The focal points should: (1) Establish robust partnerships among various stakeholders within pumped storage power stations, harnessing such partnerships to enhance the operations management of these stations. (2) Investigate methods to assimilate stakeholder needs into the operations management framework, aiming to cater to these needs by optimizing the operations management of pumped storage power stations. (3) Foster multi-energy complementarity between pumped storage power stations and different types of clean energy stations, underpinned by a robust digital management system.

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Appendix A

Table A1. Test of mediated relationships among conceptual model components.

Step	Predictors	Criteria	R	R^2	R_a^2	F	β	t
1	P	PSO	0.744	0.553	0.549	125.008	0.744 ***	11.184
2	P	MEC	0.699	0.489	0.484	96.523	0.699 ***	9.825
3	P	DMS	0.714	0.509	0.505	104.890	0.714 ***	10.242
4	PSO	PR	0.945	0.893	0.890	275.049	0.187 *	2.474
	MEC						0.376 ***	3.918
	DMS						0.410 ***	4.280
5	PSO	ECA	0.949	0.901	0.898	296.758	0.329 ***	4.530
	MEC						0.301 **	3.263
	DMS						0.353 ***	3.828
6	PR	PSPSP	0.798	0.637	0.630	86.977	0.401 **	2.895
	ECA						0.418 **	3.021

Note: R_a^2 = adjusted R^2; β = standardized regression coefficient; P = Partnering; PSO = Power Station Operation; MEC = Multi-Energy Complementarity; DMS = Digital Management System; PR = Profitability; ECA = Electricity Consumption Adjustment; PSPSP = Pumped Storage Power Station Performance; *** = $p < 0.001$, ** = $p < 0.01$, * = $p < 0.05$.

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