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Assessment of Self-Dispatch Strategy in a Concentrating Solar Power System: Impact Analysis on the Chilean Spot Electricity Market

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Abstract. This study investigates the technical and economic impacts of self-dispatch strategies on Concentrated Solar Power (CSP) plants in Chile's spot electricity market. The PySAM simulation tool was used to model three dispatch scenarios—Marginal Cost-Responsive Dispatch, Daytime Mandated Dispatch, and Continuous Base Load Dispatch—to assess their effects on energy production, load factors, and financial outcomes at the Crucero and Cardones substations. The findings indicate that the Marginal Cost-Responsive Dispatch strategy optimizes revenue by aligning energy generation with periods of higher market prices. This strategy mitigates the adverse financial impacts of zero-marginal-cost periods, which undermine the viability of more rigid approaches like Daytime Mandated Dispatch. Economic analysis shows that only the Marginal Cost-Responsive Dispatch consistently covers annualized capital expenditures (CAPEX), particularly at lower CAPEX levels. In contrast, the alternative scenarios fail to achieve financial sustainability due to forced generation during low-value periods. Consequently, these results underscore the crucial role of dispatch flexibility in enhancing the economic performance of CSP plants. The study suggests that market regulations should be revised to encourage strategies that enable CSP plants to dynamically respond to market conditions, supporting the broader integration of CSP technology into Chile's energy market. Such adjustments are crucial for advancing the country's decarbonization goals. Future research should focus on further developing advanced self-dispatch algorithms and hybrid CSP systems to optimize economic outcomes in increasingly dynamic market environments.

Keywords: Self-Dispatch, Central Dispatch, Marginal Cost, Thermal Energy Storage (TES), TES Dispatch Control, k-Means Clustering, Chilean Electricity Market, Economic Viability

1. Introduction

1.1 Background

In the evolving landscape of Chile's centralized electricity market, a unique set of challenges has emerged, predominantly influenced by the non-self-dispatch nature of utility-scale generators and the market's neutral stance on energy sources. The market operates on a marginal cost principle, which, due to increased renewable energy penetration, often leads to zero marginal cost in the spot market. This scenario poses substantial financial challenges for generation companies, especially those unable to cover their minimal operational costs, thereby facing the risk of bankruptcy. The impact is particularly severe on Concentrated Solar Power (CSP) systems, which are inherently dispatchable and most beneficial when deployed during peak pricing hours that align with their business model.

Chile, despite having some of the highest levels of Direct Normal Irradiance (DNI) in the world and thus ideal conditions for CSP development, faces significant hurdles due to the lack of market incentives. The centralized system in Chile, coordinated by the National Electricity Coordinator (CEN), enforces dispatch rules that prioritize the lowest marginal cost resources without considering the strategic value of dispatchable generation. This presents a significant challenge for CSP operators, as they may be dispatched in a manner that does not align with peak pricing periods, potentially leading to suboptimal financial performance.

To address these challenges, two distinct dispatch approaches are considered: the standard market dispatch scenario and the strategic self-dispatch scenario. The standard market dispatch scenario adheres to the centralized market's dispatch rules, potentially resulting in suboptimal financial outcomes for CSP plants. Conversely, the strategic self-dispatch scenario allows CSP operators to autonomously manage their dispatch based on market signals—specifically, by modulating energy output according to real-time marginal price levels—and operational constraints such as thermal storage availability and turbine ramping limits. This approach leverages the inherent dispatchability of CSP technology, enabling operators to maximize revenue by aligning electricity generation with periods of high market prices. This strategic approach not only enhances the economic viability of CSP plants but also contributes to greater grid stability and reliability by supplying firm renewable generation during periods of high demand and reduced variable renewable output.

In this context, while CSP technology offers significant advantages by enabling the management of concentrated solar energy during daylight hours to generate electricity when it is most needed, these benefits cannot be fully realized without strategic dispatch and appropriate market incentives. Without these measures, CSP will fail to address the issues of zero marginal cost and energy curtailment, thereby hindering progress toward Chile's official decarbonization target of achieving carbon neutrality by 2050. Therefore, optimizing CSP dispatch is essential to overcoming these economic and operational challenges in the electricity market and supporting the country's transition to a low-carbon energy system.

1.2 Objective

This paper aims to evaluate the technical and economic impacts of allowing CSP plants to autonomously dispatch power during periods of high market prices, assessing how this strategy can optimize their performance and integration into Chile's spot electricity market.

2. Methodology

2.1 Data Collection

Marginal cost data for 2023 was collected from the National Electrical Coordinator [1], specifically focusing on the primary nodes of the National Electric System. In parallel, solar irradiance data was obtained from the Solar Explorer of the Ministry of Energy using Typical Meteorological Year (TMY) datasets [2]. These datasets were integral for modeling and analyzing the performance of CSP plants under various dispatch scenarios.

2.2 Simulation Framework

2.2.1 PySAM Package Overview

The simulation tool employed in this study was the PySAM (Python for System Advisor Model) package, developed by the National Renewable Energy Laboratory (NREL) [3]. PySAM is a robust and versatile software package that facilitates detailed simulations of renewable energy systems, including CSP technologies. It provides comprehensive tools for system design, performance prediction, and economic analysis, making it an indispensable resource for modeling and optimizing CSP plant operations.

An in-house Python code was developed to complement PySAM and address the specific needs of this study. This custom code was designed to integrate seamlessly with the PySAM framework, allowing for the implementation of a tailored dispatch matrix and advanced clustering algorithms, as detailed in subsequent sections. This integration enabled the simulation framework to accurately model and evaluate various dispatch strategies, thereby enhancing the overall analytical depth and precision of the study.

2.2.2 CSP Plant Design Specifications

This study focuses on a stand-alone CSP plant utilizing a power tower configuration, designed to optimize the operational efficiency of two critical substations within Chile's National Electrical System (SEN): Crucero and Cardones. These substations are essential for maintaining the stability and reliability of the national grid and are strategically situated in northern Chile, a region with significant potential for solar energy utilization.

The Crucero Substation, located in the Atacama region, is a pivotal component of the SEN, playing a crucial role in the distribution and transmission of electricity across northern Chile. This substation is particularly important for supporting the mining industry, a major contributor to the national economy. Similarly, the Cardones Substation, situated in the Atacama Desert, serves as a key node within the SEN, ensuring the reliable transmission of electricity generated from renewable energy sources, such as solar and wind, to central regions of Chile. The Cardones Substation is vital for integrating renewable energy into the national grid. The Atacama Desert, being one of the sunniest places on Earth, provides optimal conditions for solar energy generation.

The CSP plant is designed with a gross turbine output of 111 MWe and a gross-to-net conversion factor of 0.9, yielding a nominal capacity of 100 MWe. Based on the study by Zurita et al. [4], the plant incorporates a Thermal Energy Storage (TES) system with an 8-hour storage capacity and a solar multiple of 2. These parameters were selected to maximize the alignment of power generation with periods of peak demand, enhancing both the operational and economic performance of the plant. Specific adjustments to the TES dispatch control matrix were made to improve operational accuracy and ensure optimal performance at both the Crucero and Cardones substations.

2.2.3 TES Dispatch Control

The TES dispatch control methodology employed in this study extends the conventional approach implemented in PySAM, based on the System Advisor Model (SAM)'s default dispatch matrix. SAM’s method utilizes monthly average daily values to determine the timing and quantity of energy released from storage to the power block. While useful for basic modeling, this approach oversimplifies operational dynamics by neglecting daily and seasonal variations in solar resource availability.

To address these limitations and enhance simulation accuracy, the methodology introduces a refined TES dispatch control strategy. The base dispatch matrix in SAM segments the year into nine distinct periods, each associated with specific turbine output fractions and schedules. These periods, averaged over the month, do not adequately reflect the variability in solar irradiance and market conditions, leading to a simplistic and less accurate simulation model.

To improve upon this, a modified dispatch matrix was developed, segmenting each day into nine distinct periods for the entire year. This finer temporal resolution enables more precise simulations of energy dispatch, capturing variations in solar irradiance and market conditions across different times of day and seasons. This improvement ensures that energy release from TES aligns with market price signals and operational needs, enabling strategic self-dispatch during high-price periods.

Furthermore, to optimize the segmentation of dispatch periods, the methodology applied k-Means Clustering, a machine learning technique available in scikit-learn [5]. This approach dynamically adjusts dispatch periods by clustering similar days, thereby improving the granularity and responsiveness of the dispatch strategy. Through the iterative simulation of hundreds of scenarios, this refinement offers a comprehensive evaluation of the CSP plant's dispatch performance over a full year. These improvements enhance the robustness and applicability of the methodology for assessing the dynamic operation of CSP plants, providing valuable insights for future energy management strategies and optimizing revenue generation based on spot market marginal costs.

To comprehensively assess the operational performance and economic viability of the CSP plant, three distinct scenarios were analyzed, namely:

- **Scenario 1: Self-Dispatch (Cost-Responsive Dispatch):**

In this scenario, the CSP plant operates in response to short-term marginal cost fluctuations in the electricity market. The plant dynamically adjusts its power output to align with market signals, ensuring optimal economic performance.

- **Scenario 2: Daytime Mandated Dispatch (Daytime Operation):**

This scenario investigates the performance of the CSP plant when its output is forcibly injected into the grid between 6 AM and 6 PM. This operational mode ensures a consistent power supply during peak daylight hours, which is critical for meeting daytime electricity demand and stabilizing grid operations.

- **Scenario 3: Base Load Dispatch (Unrestricted Injection):**

In the base load scenario, the CSP plant operates without any dispatch restrictions, injecting power continuously as generated. This mode simulates a steady-state operation, providing a benchmark for the plant's maximum potential output and efficiency.

The Daytime Mandated and Continuous Base Load scenarios represent centralized dispatch strategies, while Marginal Cost-Responsive Dispatch is a self-dispatch strategy driven by the plant owner's objective to optimize revenue through market price signals.

2.3 Evaluation Metrics

The primary metric assessed in this study is the total energy generated, reflecting the CSP plant's electricity output under three distinct dispatch strategies: Marginal Cost-Responsive Dispatch, Daytime Mandated Dispatch, and Continuous Base Load Dispatch. This metric is crucial for evaluating the plant's productivity and its ability to supply electricity to the spot market, directly influencing its revenue-generating potential.

In addition to energy generation, revenue from electricity sales serves as a critical financial metric. This is determined by multiplying the energy dispatched by the corresponding spot market prices, focusing exclusively on marginal energy costs. By excluding ancillary costs and capacity payments, this metric provides an accurate measure of the financial returns from electricity generation for each dispatch strategy.

To evaluate the economic viability of the CSP plant, projected revenues under each dispatch strategy are compared against the annualized capital expenditure (CAPEX). The CAPEX is derived from specific capital cost scenarios—3250 USD/kWe, 5078 USD/kWe, and 7254 USD/kWe—based on data from the study "The Role of Energy Storage in Chile's Energy Transition Process and the Factors Influencing its Development" conducted by the Energy Center of the University of Chile and Fraunhofer Chile Research [6]. The annualized CAPEX is calculated over a 30-year lifespan with a 7% discount rate, offering a clear perspective on the financial sustainability of the plant.

3. Results and Discussion

3.1 Technical Performance

The technical performance of CSP plants at Crucero and Cardones was analyzed across three scenarios, focusing on how dispatch strategies affect energy production, load factors, and annual operating hours.

Figure 1 provides a seasonal comparison of gross turbine electrical output and marginal cost profiles for both substations. The results indicate that the CSP plants are strategically dispatched during periods of elevated marginal cost, rather than maximizing output solely at midday. This strategy is evident in generation peaks that coincide with early morning and late afternoon price surges across both summer and winter seasons. While the turbine's gross electrical output is defined as 111 MWe, some simulated values slightly exceed this level. These exceedances reflect transient operating conditions modeled in PySAM, where the plant may briefly generate above its nominal output under optimal solar and thermal conditions, particularly when thermal energy storage is fully charged. Additionally, negative output values appear during periods of low or no irradiance, representing net energy consumption by auxiliary systems when gross generation is insufficient to meet internal loads.

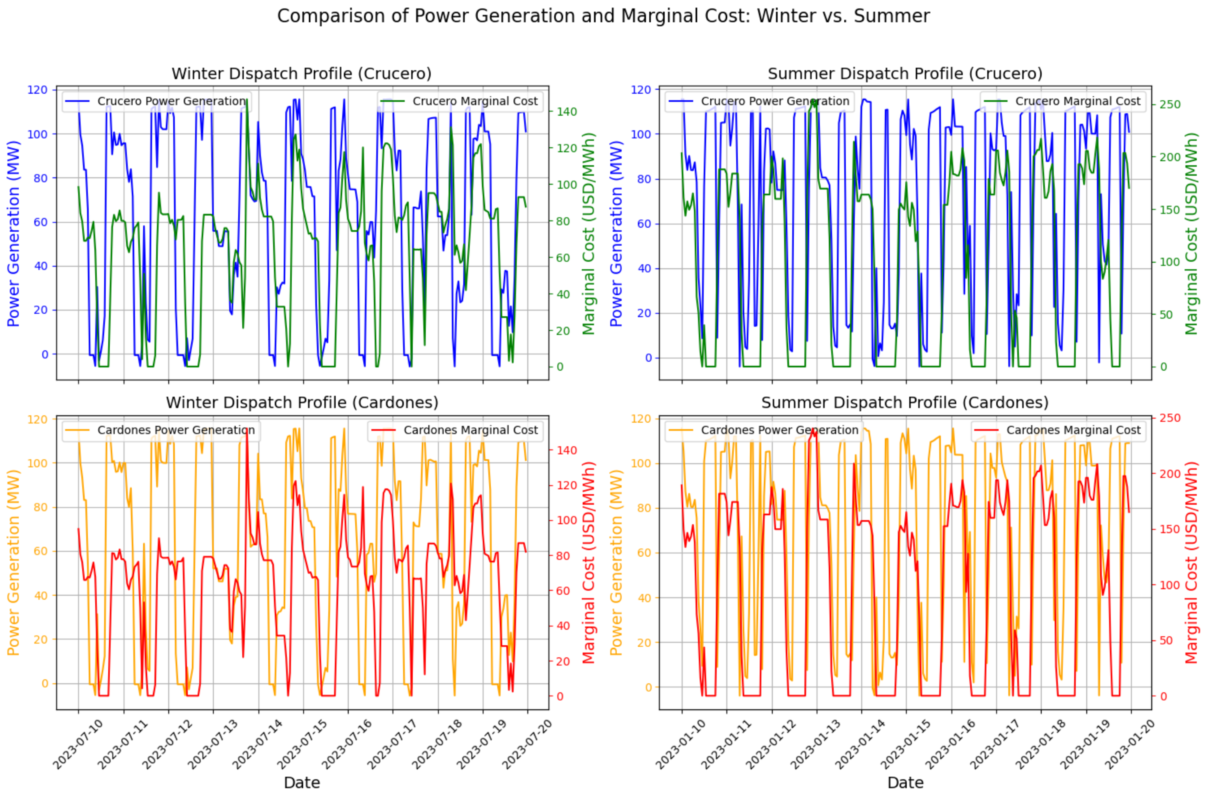

Figure 1. *Seasonal Comparison of Power Generation and Marginal Cost Profiles for Crucero and Cardones Substations*

Table 1 shows that Scenario 1 (Marginal Cost-Responsive Dispatch) results in the highest annual energy production for both Crucero (600.68 GWh) and Cardones (601.66 GWh), along with the most operational hours (6007 and 6017 hours, respectively). Scenario 3 (Continuous Base Load Dispatch) also produces significant energy but with slightly fewer operational hours. Scenario 2 (Daytime Mandated Dispatch) generates the least energy, with Crucero at 471.68 GWh and Cardones at 461.78 GWh, reflecting the limitations of operating only during daylight hours.

Table 1. *Technical Performance Metrics for Crucero and Cardones Substations*

Metric	Substation	Scenario 1	Scenario 2	Scenario 3
Annual Energy Production (GWh)	Crucero	600.68	471.68	638.76
	Cardones	601.66	461.78	601.66
Load Factor (%)	Crucero	68.57	53.84	72.92
	Cardones	68.68	52.71	68.25
Annual Operating Hours	Crucero	6007	4717	6388
	Cardones	6017	4618	5979

3.2 Economic Performance

The economic performance of CSP plants operating at the Crucero and Cardones substations was evaluated across three distinct operational scenarios: Scenario 1 (Marginal Cost-Responsive Dispatch), Scenario 2 (Daytime Mandated Dispatch), and Scenario 3 (Continuous Base Load Dispatch). The results provide critical insights into the financial viability of each dispatch strategy, considering revenue generation, marginal costs, and the alignment with capital expenditures.

Table 2. *Economic Performance Metrics for Crucero and Cardones Substations*

Metric	Substation	Scenario 1	Scenario 2	Scenario 3
Annual Revenue (MMUSD/year)	Crucero	52.98	15.63	39.91
	Cardones	50.70	14.78	36.52
Average Marginal Cost (USD/MWh)	Crucero	77.02	77.02	77.02
	Cardones	73.96	73.96	73.96
Annual Hours with Zero Marginal Cost	Crucero	2911	2911	2911
	Cardones	2892	2892	2892

As indicated in Table 2, Scenario 1 (Marginal Cost-Responsive Dispatch) generates the highest annual revenues, with 52.98 MMUSD/year at Crucero and 50.70 MMUSD/year at Cardones. This is due to its effective alignment with periods of higher market prices, enabling the CSP plants to maximize revenue by dispatching energy during the most favorable market conditions.

Conversely, Scenarios 2 and 3, characterized by forced or continuous energy injection, exhibit substantially lower financial returns. Specifically, Scenario 2 (Daytime Mandated Dispatch) yields the lowest revenues—15.63 MMUSD/year at Crucero and 14.78 MMUSD/year at Cardones. A key factor behind these reduced revenues is the extended periods of zero marginal cost, which occur when spot market prices drop to zero due to excess renewable generation. In such cases, the marginal cost—the cost of supplying an additional unit of electricity—

effectively becomes zero, preventing any revenue generation. As shown in Figure 2, the heatmaps qualitatively depict the extended periods of zero marginal cost, indicated by the extensive blue areas. In 2023, Crucero experienced 2911 hours of zero marginal cost, while Cardones recorded 2892 such hours. During these intervals, the absence of a market price significantly constrained revenue generation, making it insufficient to cover the annualized capital expenditure requirements.

This forced injection during zero-cost periods directly undermines the plant's revenue potential, as it compels the CSP plants to generate electricity when it is least profitable. The lower revenues observed in Scenario 2, and to a lesser extent in Scenario 3, underscore the economic disadvantage of inflexible dispatch strategies that do not consider real-time market pricing signals. These findings, as highlighted in Table 3, emphasize the importance of aligning CSP operations with market dynamics to avoid financial underperformance.

Table 3. *Specific Capital Costs and Annualized CAPEX for CSP Plants*

Specific CAPEX	**3250 USD/kW**	**5078 USD/kW**	**7254 USD/kW**
Annualized CAPEX (MMUSD/year)	26.19	40.92	58.46

When comparing the revenue with the annualized CAPEX calculated at three specific capital cost levels—3250 USD/kW, 5078 USD/kW, and 7254 USD/kW—the results indicate that Scenario 1 is the only strategy where the revenues consistently exceed the CAPEX, particularly at the lower CAPEX levels. For instance, with a specific CAPEX of 3250 USD/kW, the annualized CAPEX is 26.19 MMUSD/year, while the revenues in Scenario 1 (52.98 MMUSD/year at Crucero and 50.70 MMUSD/year at Cardones) comfortably cover this expenditure, ensuring a positive economic return.

However, as the specific CAPEX increases to 5078 USD/kW and 7254 USD/kW, with corresponding annualized CAPEX of 40.92 MMUSD/year and 58.46 MMUSD/year, the financial margin narrows significantly. In Scenario 2, the revenue falls drastically short of covering even the lowest CAPEX level, highlighting the financial unsustainability of this approach. Scenario 3, while better than Scenario 2, still struggles to justify the higher CAPEX levels, particularly when forced to inject power during zero-cost periods.

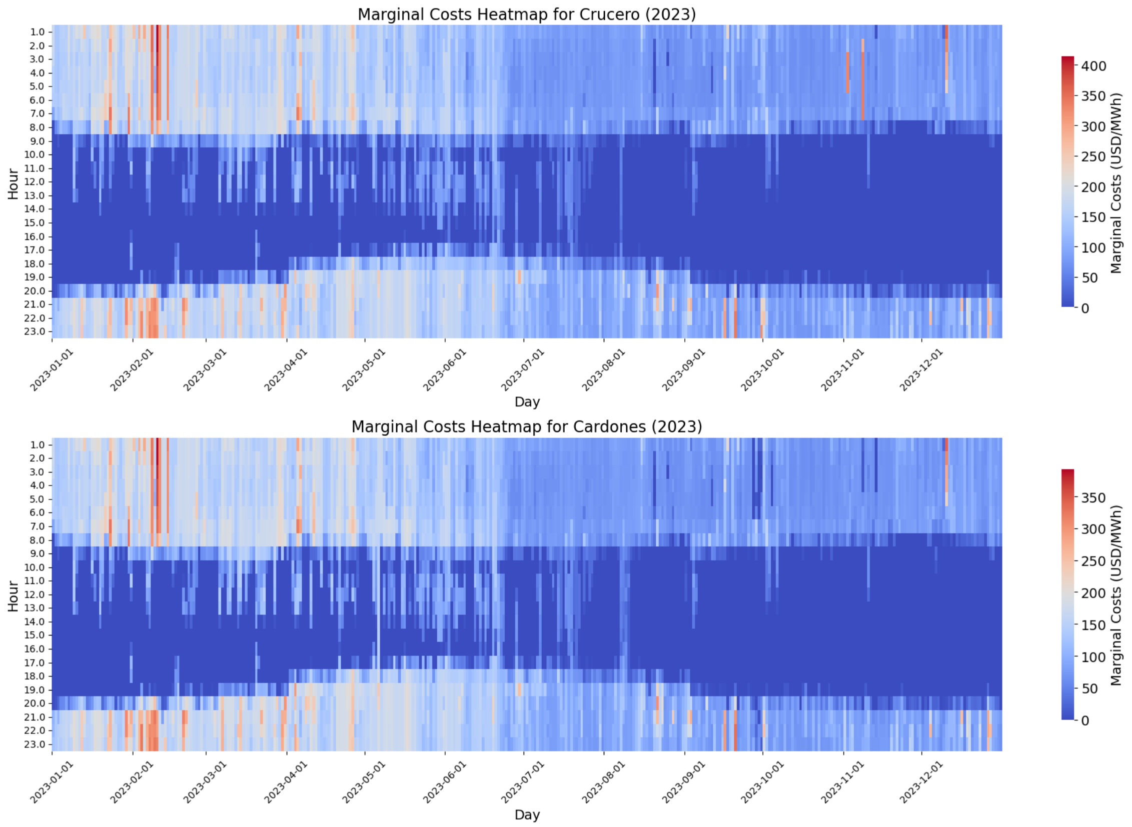

Figure 2. *Annual Heatmap of Hourly Marginal Costs for Crucero and Cardones Substations (2023)*

4. Conclusions

The findings of this study highlight the critical importance of dispatch flexibility for optimizing CSP plant performance in Chile's spot electricity market. The analysis demonstrates that the Marginal Cost-Responsive Dispatch strategy is the most effective, as it allows CSP plants to synchronize energy production with periods of elevated market prices. This alignment not only maximizes revenue but also ensures that it surpasses annualized capital expenditures, securing the financial sustainability of CSP plants. Consequently, this strategy proves to be a viable approach for long-term investment and integration into the energy market. In contrast, more rigid dispatch strategies, such as Daytime Mandated Dispatch and Continuous Base Load Dispatch, result in significantly lower revenues due to the high incidence of zero-marginal-cost hours. These periods undermine the financial viability of CSP plants under inflexible dispatch regimes, highlighting the limitations of such approaches.

The implications for energy market regulations are substantial. To enhance the economic viability of CSP technology, regulatory frameworks must incentivize flexible dispatch strategies that enable CSP plants to respond dynamically to real-time market signals. This would facilitate better alignment of energy generation with high market demand, promoting broader integration of renewable energy sources and contributing to Chile's decarbonization goals.

Data availability statement

The data that support the findings of this study are available from the corresponding author, Francisco Moraga, upon reasonable request.

Author contributions

Francisco Moraga: Conceptualization, Data curation, Methodology, Validation, Writing – original draft. **Carlos Felbol**: Conceptualization, Writing – review & editing. **Maria Cerda:** Writing – review & editing. **Frank Dinter:** Supervision, Writing – review & editing.

Competing interests

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

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