



Title	A Study on Integrated Forecasting and Optimization Framework for Behind-the-Meter Energy Management
Author(s)	岩渕, 厚樹
Citation	大阪大学, 2026, 博士論文
Version Type	VoR
URL	https://doi.org/10.18910/105499
rights	
Note	

The University of Osaka Institutional Knowledge Archive : OUKA

<https://ir.library.osaka-u.ac.jp/>

The University of Osaka

論文内容の要旨

氏 名 （ 岩渕 厚樹 ）	
論文題名	A Study on Integrated Forecasting and Optimization Framework for Behind-the-Meter Energy Management (需要家側エネルギーマネジメントのための予測と最適化を統合したフレームワークに関する研究)
論文内容の要旨 The accelerating deployment of photovoltaic (PV) generation plays a critical role in the global transition toward environmentally sustainable power systems. PV systems offer carbon-neutral energy production with low operating cost, which makes them highly attractive for both residential and commercial adoption. Their installation continues to expand rapidly due to decreasing manufacturing costs, policy support, and improved power conversion technologies. However, PV generation is strongly affected by weather conditions, solar irradiance variability, and rapid cloud movements, leading to unstable and unpredictable power output. Such variability causes significant fluctuations in PV power generation, including steep ramp rates that pose severe challenges for maintaining stable grid operation. In conventional grid architectures, these fluctuations are typically mitigated by large-scale storage or dispatchable power plants. In practice, grid operators rely heavily on quickly dispatchable backup units, especially diesel engines and, more recently, gas turbines, to compensate for rapid PV variability and maintain system stability. Yet, these solutions remain costly, resource-intensive, and environmentally burdensome. Behind-the-meter (BTM) systems present an alternative approach by enabling localized energy management performed directly by end users equipped with distributed energy resources. BTM systems allow users to monitor, forecast, and regulate their own energy generation and consumption. This transforms traditional consumers into “prosumers” capable of both producing and controlling local power in coordination with the wider grid. The emergence of BTM energy management systems (EMS) creates new opportunities for efficient PV utilization. An EMS can schedule battery operation, manage flexible loads, and regulate PV output while reflecting user objectives and system constraints. A central motivation for BTM energy management is to minimize the amount of renewable energy that would otherwise be curtailed or wasted during periods when PV generation exceeds instantaneous local demand. By coordinating storage, controllable loads, and conversion efficiency, the EMS enables surplus energy to be absorbed, shifted, or delivered more effectively. Nevertheless, BTM energy management remains challenging due to several key factors. These include the non-stationarity of energy-related time series, limitations of forecasting accuracy, steep ramp rates in PV output, and operational constraints associated with batteries and power electronics. These issues highlight the need for EMS approaches that couple accurate forecasting with proactive control strategies, ensuring that renewable resources are utilized as efficiently as possible while maintaining stable operation. This dissertation addresses these challenges by presenting an integrated forecasting and optimization framework for BTM PV systems. The research is structured around three key questions concerning forecasting, ramp rate control, and forecast-informed system integration. The first question focuses on how accurate forecasting of critical time series can be achieved for EMS decision-making. The second question examines how PV ramp rates can be mitigated without requiring large battery capacity. The third question investigates how forecasting and optimization can be integrated to enable proactive BTM operation. To address the first question, this dissertation develops a wavelet transform-long short-term memory forecasting framework tailored to non-stationary time series in BTM environments. Conventional statistical approaches rely on linear assumptions that fail to capture nonlinear and complex variations in solar irradiance, electricity demand, and electricity prices. Existing wavelet-machine learning approaches improve accuracy, but they often depend on fixed decomposition, ad hoc feature selection, and limited use of explanatory variables. To overcome these limitations, the proposed method introduces a	

systematic feature screening process and an adaptive mother wavelet selection technique. These innovations jointly improve decomposition quality and predictive performance across multiple forecasting tasks. As a result, the proposed method provides a reliable forecasting foundation for EMS planning and real-time control.

Building upon forecasting capabilities, this dissertation addresses the second research question by introducing a novel control knob that directly influences the amount of PV energy supplied to the local grid, implemented through a cooling-based PV ramp rate control strategy. Unlike battery-only solutions, the method regulates PV output by adjusting panel temperature to modulate conversion efficiency. This approach leverages the thermal properties of PV cells to suppress steep power fluctuations. By selectively activating cooling during rapid irradiance transitions, the method reduces ramp rate violations without excessive storage use. Simulation studies based on real-world irradiance measurements demonstrate reductions of 43.5% in mean ramp rates and 76.2% in maximum ramp rates. Moreover, these improvements are achieved using a cooling device with a coefficient of performance below 10 and only 20 kWh of storage capacity. These results reveal a cost-effective method that minimizes dependence on large batteries while increasing PV usability.

To address the third research question, the forecasting and cooling-based control strategies are integrated into an iterative hierarchically organized forecast-informed EMS framework. The framework anticipates power fluctuations using short-term predictions and preemptively optimizes output prior to ramp rate violations. Forecasts with a horizon of 30-60 seconds reduce ramp rate violations by up to 20% relative to a no-control baseline. Overall, this dissertation provides a unified perspective on forecasting and control for BTM PV systems. It demonstrates that accurate forecasting, thermal regulation, and sequential optimization enable stable, cost-effective, and lightweight BTM system design. The results show that proactive control strategies can reduce ramp rate violations, minimize unnecessary battery cycling without costly infrastructure expansion. Future research will explore uncertainty-aware forecasting, online learning for adaptive model updates, improved cooling system modeling, and hardware-in-the-loop validation for field deployment. Together, these directions aim to further increase the practicality and robustness of forecast-informed PV control in BTM environments.

論文審査の結果の要旨及び担当者

氏 名 (岩 淵 厚 樹)			
	(職)	氏 名	
論文審査担当者	主 査	准教授	谷口 一徹
	副 査	教授	尾上 孝雄
	副 査	教授	櫻井 保志
	副 査	Associated Guest Professor	Francky Catthoor (National Technical University of Athens)

論文審査の結果の要旨

本論文は、Behind-the-Meter (BTM) 環境における太陽光 (PV) 発電システムを対象として、予測と最適化を統合したエネルギーマネジメントの高度化に関する研究成果をまとめたものであり、以下の主要な成果を得ている。

1. WT-LSTMを用いたBTM向け時系列予測手法に関する研究
BTMエネルギーマネジメントシステムでは、電力価格、電力需要、日射量といった時系列情報を高精度に予測することが、経済性および運用安定性の観点から重要である。しかし、これらの時系列は非定常性や短時間スケールでの急激な変動を有するため、従来の統計的手法や単純な機械学習モデルでは十分な予測精度を得ることが困難であった。本論文では、ウェーブレット変換 (WT) とLong Short-Term Memory (LSTM) を組み合わせたWT-LSTM予測フレームワークを提案し、補助特徴量、体系的な特徴量選択、マザーウェーブレットの動的選択を導入することで予測性能を向上させた。評価実験の結果、提案手法は電力価格、電力需要、日射量の各予測タスクにおいて従来手法を上回る精度を達成し、特に電力価格予測では平均絶対誤差を約41%削減できることを示した。
2. PVモジュール冷却によるランプレート抑制手法に関する研究
PVモジュールの発電量は日射に大きく依存し、短時間で急激な出力変動が発生する。そのためPV発電における出力変化速度 (ランプレート) の抑制は系統への影響緩和の観点から重要な課題である。従来は大容量蓄電池による変動緩和が一般的であったが、コスト面での課題が知られている。本論文では、PVモジュールの温度依存性に着目し、冷却を調整することで発電効率を間接的に最適化する新たなランプレート抑制手法を提案した。提案手法は、大容量蓄電池を用いずに、急激な日射変動時に冷却を能動的に用いることでランプレートの抑制を実現する。実データに基づく評価実験より、平均ランプレートを最大43.5%、最大ランプレートを最大76.2%低減できることを示した。
3. 予測情報に基づくランプレート最適化フレームワークの実装と評価
PVモジュールの出力変動への対処をより効果的に行うためには、リアルタイムの最適化に加えて、将来の変動を見越した予測に基づく最適化が不可欠である。本論文では、短時間日射量予測と冷却ベースのランプレート最適化を統合した、予測指向型エネルギーマネジメントフレームワークを提案した。本フレームワークでは、予測結果を活用し、所定のランプレート違反が発生する前に冷却操作を最適化することで、PV出力の平滑化を図る。評価実験より、予測を用いない場合と比較してランプレート制約違反回数を最大20%削減できることを示し、予測と最適化を連携させたBTM環境におけるエネルギーマネジメントの有効性を示した。

以上のように、本論文は、BTM環境における予測・最適化統合型エネルギーマネジメントの実現に向けて有用な知見を提供するものであり、再生可能エネルギーの効率的利用と電力系統への影響緩和に貢献することが期待される。加えて、新興のマイクログリッド市場は新たなビジネスの可能性を提供し得る領域であり、本論文の成果は学術的観点のみならず、産業応用の観点からも意義を有するものと期待される。よって、博士 (情報科学) の学位論文として価値のあるものと認める。