Energy Storage Systems in Residential Applications for Optimised Economic Operation: Design and Experimental Validation

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***Abstract*—The integration of distributed battery energy storage systems has started to increase in power systems recently, as they can provide multiple services to the system operator, i.e. frequency regulation, system peak shaving, backup power etc. Additionally, batteries can be installed even in facilities where the installation of renewable energy sources are impossible, such as apartments within urban areas. Consequently, an aggregator could deploy distributed battery systems to households under his portfolio, utilising them to capitalize on Demand Response services while sharing benefits of electricity cost reduction with them. To enable that, this paper provides an integrated solution for monitoring, scheduling, and controlling a residential battery energy storage system. The proposed system has been realised in the context of inteGRIDy project to a pilot site that consist of 4 different dwellings that are located in Northern Greece. The analysis of the pilot results revealed that battery systems could exploit the variation in electricity price in order to succeed some profit alongside with the provided energy services.**

***Index Terms*—battery energy storage system, optimisation, demand side management, battery scheduling**

I. Introduction

Towards the transition from current power systems to Smart Grid, one of the aspects that has drawn the attention of both the industry and the scientific community is the integration of Renewable Energy Sources (RESs), with Photovoltaics and Wind Generators being the most prevalent among them [1]. One of the ways to achieve even greater penetration of RESs is the utilization of Demand-Side Management (DSM) strategies [2], and as part of the latter is the utilization of Battery Energy Storage Systems (BESS). The latter can perform and aid in the new era of Distribution Networks in a lot of different ways, such as Frequency Control [3], Voltage Control [4], and other ancillary services in general [5]. There is also a great variety of installation schemes available for BESS, such as either near or next to the Medium to Low Voltage (MV/LV) Substation [6] therefore choosing a more decentralized approach, or near the final end-user [7], choosing a more distributed approach.

Buildings have been identified as a source of enormous untapped efficiency potential, with 40% of global energy consumption and one third of Green-House-Gas emissions [8]. Thus, by optimally rearranging their energy consumption, especially from on-peak to off-peak load hours, this could prove rather beneficial to the end-user, the utility provider and the Distribution System Operator (DSO) [9]. BESS can aid towards that end [10]. In [11] a deterministic approach is proposed. However, a peaking interval is foretold empirically, and the BESS is charged to its full capacity prior to this interval. This could not necessarily lead to a global optimal result. Another approach could be, as proposed in [12], to monitor the energy consumption and discharge the BESS at its full rate when a peak occurs. However, this may lead to a premature depletion of the BESS due to the deep discharge of the BESS. Moreover, it can be considered not a sufficiently realistic approach, since it does not necessarily take into account the uncertainties of the energy consumption. The proposed work in [13], and [14], taken into consideration uncertainties in energy consumption. In [15] a stochastic optimization is proposed in order to incorporate the energy consumption uncertainties and therefore provide more realistic and accurate results improving the final outcome. The results have been retrieved by conducting simulations using real data.

In this paper however, an integrated BESS installation along with a Battery Management System (BMS) is examined. The integrated system is installed in either single or three phase residential facilities and its performance in real-life situations is presented. The system is auto-guided via an optimization engine aiming at minimizing operation cost, while considering the BESS' constraints, therefore overcoming any dangers of depleting the BESS, while providing optimized results.

The remaining of the paper is organised as follows: In Section II is analysed the system architecture. In Section III a detailed presentation of the experimental setup and the tested scenario are given, while Section IV presents the experimental results under real-life conditions. Finally Section V is devoted to conclusions and future work.

II. System Architecture

The design architecture for the installation, operation and monitoring of a residential DSM scheme based on small BESS is shown in Fig. 1. It constitutes of both software and hardware

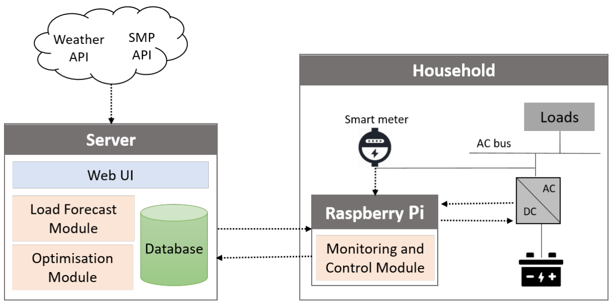


Fig. 1: System Architecture.

elements that enable the production of the necessary timeseries which are in turn applied to the distributed assets. First, the core components of the solution, namely the household consumption forecast and optimised BESS scheduling engines are installed on a server that interacts with web-based cloud services which provide the necessary input variables for both (i.e., the day-ahead pricing scheme and weather forecast). The server contains dedicated databases upon which all necessary variables are stored. At household level, a small computing device, coupled with the BESS and a smart meter, is responsible for the monitoring of the BESS operation and household consumption and whenever applicable, it controls directly the BESS in order to dispatch the optimised setpoints in regards to charging and discharging. In the following paragraphs, the system architecture components are described in detail.

A. *Optimal BESS Scheduling Engine*

An optimisation algorithm was developed based on an optimal microgrid energy management (shortly OptiMEMS) engine developed by the authors [16]. This component analyses and optimally schedules (in a day-ahead horizon) the dis-/charging of the BESS in order to modify dynamically the overall customer's energy consumption profile. This battery schedule is optimised towards operating cost minimization (including battery Levelized Cost Of Energy - LCOE) that eventually promotes the discharging of the BESS during high-price hours and charging during low-priced hours. Those periods coincide evidently with the peak and low load hours, promoting in this way a load shifting scheme, and providing the aggregator the ability to offer this as a service to the DSO, showcasing a scenario of potential participation in an intra-day market. It should be noted however that the latter is not yet possible for demonstration, since this market branch is not open for competition in Greece.

This optimisation tool is solving an adjusted version of the classic Unit Commitment Problem (a-UCP) in semi-real time, which is modelled as a Mixed-Integer Linear Programming (MILP) algorithm. The modelling of the problem takes into consideration dynamic constraints regarding the forecasted energy provided to the household loads, the last recorded State-of-Charge (SoC) of the BESS and the technical specifications of the battery module along with its interfacing inverter (i.e., nominal inverter power, maximum/ minimum SoC, Depth-of-Discharge (DoD), nominal charge and discharge C-rates). Furthermore, the OptiMEMS engine receives as input a day-ahead dynamic pricing scheme. Given the fact that currently there are no commercially available dynamic pricing schemes for aggregators (i.e., Real-Time Pricing - RTP) in Greece, the day-ahead System Marginal Price (SMP) from wholesale market is being used. An example of the input timeseries (load forecast and RTP) and output BESS setpoints are shown in Fig. 2. The most prominent dynamic constraints included in the mathematical model of the a-UCP are:

- Energy Consumption equal to grid import or battery discharge,
- Battery setpoints (translated both in power and energy terms) within the battery module's limitation (i.e., DoD, C-rate),
- Physical constraints of the inverter (i.e., binary operation of charge/discharge modes, power setpoint below the inverter's nominal power),
- Legal constraints based on national regulations (e.g. shared supply of loads by grid and battery prohibited).

Given the highly stochastic nature of residential load consumption, the probability of mismatches between the expected (forecasted) and measured consumption timeseries can be prohibitively high, especially in case there are not enough data to train the forecasting models properly -e.g., in the beginning of the system running in a household. As a result, the produced optimal BESS scheduling will not be able to be applied given that the system's economic operation will not be guaranteed. To tackle this issue, in case significant deviations between forecasted and measured consumption are detected, the system demands a re-calculation of the optimal BESS schedule starting from the upcoming timeslot for the remainder of the day. As input the updated short-term load forecast is used. This operation attempts to achieve profit even in case of deviations, making thus the overall system more robust. For detailed description and analysis of the OptiMEMS

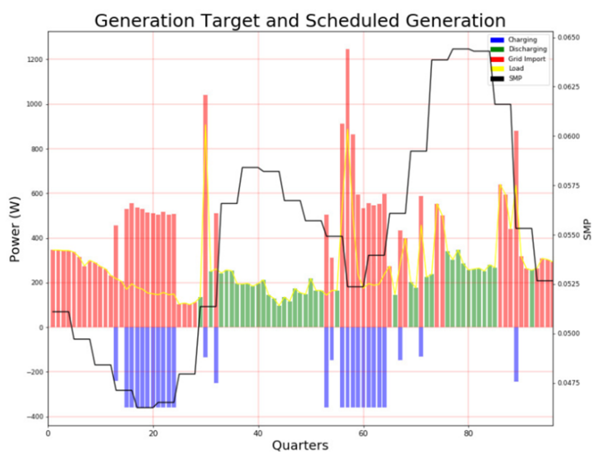


Fig. 2: Optimal Day-ahead BESS Scheduling result as a function of load forecast and day-ahead dynamic pricing.

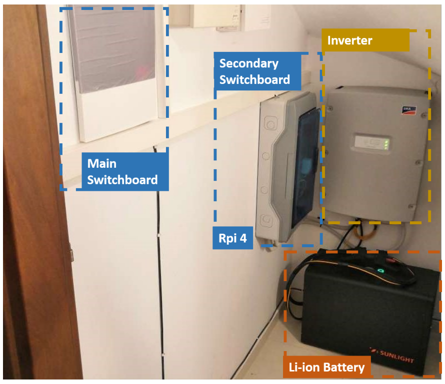


Fig. 3: BESS residential single-phase installation.

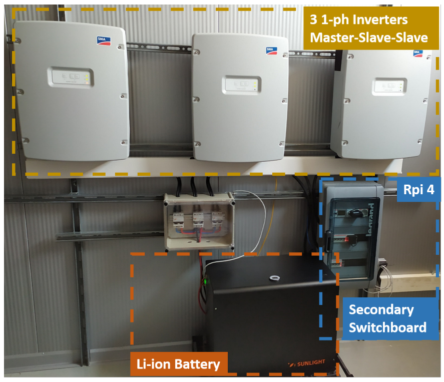


Fig. 4: BESS residential three-phase installation.

engine along with its experimental demonstration results from a real-life microgrid, the readers are kindly redirected to [16].

B. Load Forecasting

The Load forecasting tool was developed based on the requirements of the optimization engine. Thus, two different forecasts in terms of forecast horizons are utilized, namely a day-ahead and a complementary short-term load forecast. Both, are considered a multi-step time series forecasting problems, as multiple time horizons have to be forecasted [17] following either the recursive or the direct strategy, where in our case the direct strategy was adopted. In most cases, short-term is associated with the concept of forecasting one step ahead, but for the needs of the optimization engine it goes one step further by forecasting until the end of the day. Both forecasts use the same models with the only difference lies on the different inputs that they utilize. In particular, the day-ahead forecast is based on the historical load of the previous day, in contrast to the short-term, that is using the most recent load consumption values and it is calculated hourly. Additionally, external features that influence the outcome are integrated into the model, such as time and weather variables, regarding which third-party weather forecasting service is employed. The time features, the so-called cyclical features, are important in order to capture the seasonality included within load consumption time series (time, day of week, month, etc). As for the weather features, after a correlation analysis was conducted, the outdoor temperature was the most influential among all the other weather variables and was included in the model as well. Finally, regarding the training of the models several methods were deployed and experimented, ending up that Extreme Gradient Boosting (XGBoost) regressor [18], based on the gradient boosting framework, had the best performance in terms of accuracy and execution speed. Extended description about load forecasting algorithm is out of the scope of this paper and it will be presented in future publication.

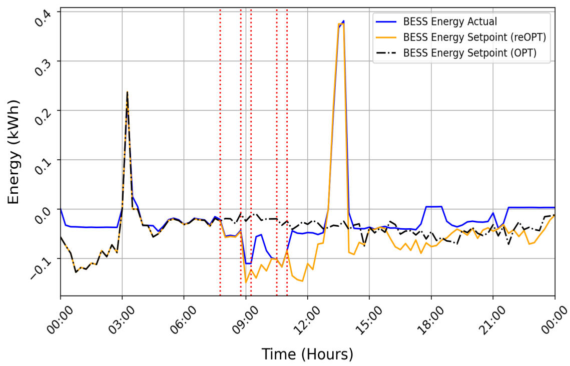
III. Experimental Setup and Scenario

The initial theoretical study of the system was based on the connection of the BESS in parallel with the distribution grid. This type of connection makes the BESS somewhat independent of the characteristics of each house, enabling the selection of an inverter-battery system with a size that is not related to the loads of the consumer. In addition, the system may be disabled for maintenance or other purposes without affecting the normal operation of the house as it will continue to be supplied by the electricity grid.

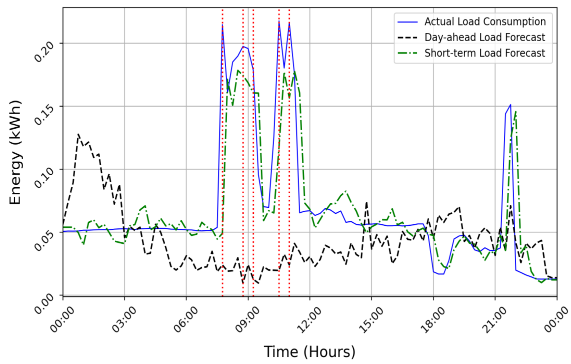
Nevertheless, as mentioned in a previous chapter, the proposed system should be installed in real dwellings in northern Greece. Unfortunately by the time this paper is written, the Greek legal framework does not permit the in-parallel connection of a BESS to the distribution grid, unless it is combined with a RES, i.e. PV, Wind Turbine etc. Therefore, BESS utilized within the inteGRIDy project pilot should be controlled in such manner to avoid injecting power to the grid, and supply only the load of the facility where they are installed. This condition could not be ensured by some kind of software implementation that would monitor the central energy meter of the installation and properly control the inverter. Therefore the in-series connection of the BESS with the distribution grid was selected for all facilities.

This pilot case involves a set of different types of residential buildings with various customer profiles. Therefore a proper BESS sizing and separation of the BESS powered loads had to be performed. All houses are equipped with a smart meter, allowing real-time monitoring of power flow. The presented single-phase house is equipped with an EM111 smart meter from Carlo Gavazzi company, a 5 kWh Li-ion battery from Sunlight company and a single phase Sunny Island 4.4M-12 inverter from SMA company or its equivalent three phase model as shown in Figures 3 and 4 respectively. The inverter supports Modbus TCP/IP protocol and has a number of registries to enable monitoring and perform fully control upon battery dis-/charge rate.

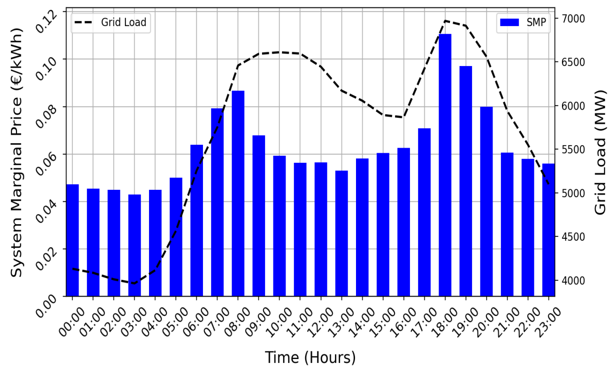
Regarding the proposed software package, it is separated in a central system and in many distributed ones. The central system is a Linux based server located in aggregator's premises and incorporates the optimization engine, the machine learning load forecasting tool and the databases. On the other hand the monitoring and control system of the distributed BESS is developed on Raspberry Pi 4, installed at each household.



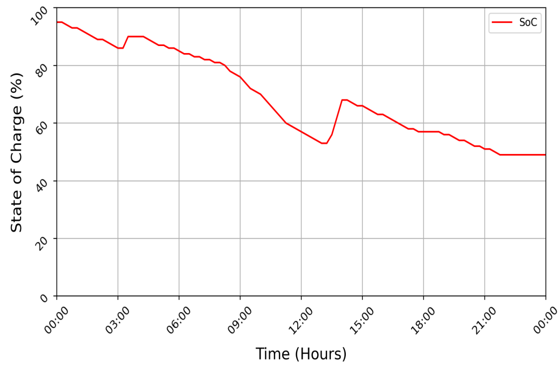
(a) BESS optimisation engine output and actual operation.



(b) Load forecasting output.



(c) Electricity Price and Grid Load



(d) BESS SoC variation.

Fig. 5: Optimal BESS operation on 08/03/2021

IV. Experimental Results

.In order to demonstrate the efficient operation of the proposed integrated system Fig. 5a, 5b, 5c and 5d present the scheduling and the actual operation of the BESS for the day 08/03/2021. The data are extracted from a house that has quite low daily load consumption. Its average daily consumption ranges between 5kWh and 10kWh, while this specific day is 6kWh. As mentioned again in the corresponding section, the scheduling of the battery's operation depends on the day-ahead load consumption forecast and the electricity prices.Fig, 5a shows in black dashed line the schedule that was calculated at the beginning of the day (at midnight). It is obvious that after the first vertical red line the black dashed line is separated from the orange one that is related to the rescheduling of the BESS. From this point on the control system sends set-points to the battery inverter according to the updated schedule. Observing this graph as a whole, it is evident that the actual operation of the battery follows very closely the scheduling that the optimisation algorithm has proposed. At this point it should be noted that the distinctive ability of this inverter in terms of the set-points it receives is of the order of 100 W. Therefore in cases where the algorithm proposes discharging for the battery but the load consumption of the house is less than 100 W, then no command for discharge is sent to the inverter.

Fig. 5b depicts the load forecast as it is calculated at the beginning of the day (black dashed line) and as it is recalculated every one hour (green line). The load consumption in residential facilities shows high variance as it depends a lot on consumer's behaviour. Consequently the prediction in many steps ahead could lead in high deviations. In order to alleviate these errors the short term forecast is calculated every one hour. It is evident that the actual consumption (blue line) is close enough with the short term forecast. Each time the monitoring system detects a high deviations it triggers (red vertical lines) the optimisation module to calculate an updated schedule based on the updated short term load forecast.

The examined day based on the SMP and without using the BESS the aggregator would have paid 0.42€ for purchasing the electricity energy for this customer in the exchange market. Nonetheless, due to the optimal scheduling and operation of the BESS they save 0.13€ that corresponds to approximately 31% reduction. Based only on the results of this day the final conclusion would be misleading, as observing Fig. 5d the battery started fully charged and at the end of the day reached at 60% SoC. A more representative graph is in Fig. 6 that depicts the results of 72 hours of system operation, during which the battery discharges up to 60% and recharges again up to 100%. The economic result of these days is

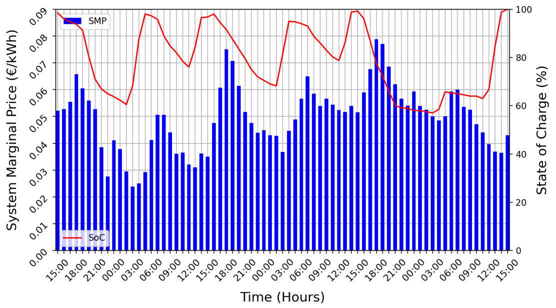


Fig. 6: BESS operation for 72 hours.

only 0.01€ profit compared to 0.90 € cost. This is caused as the operation of the system is inextricably linked to the household's consumption. Therefore the system can not fully discharge at the lowest price but it is also discharged at times when the price is higher leading to lower daily profits or even negative in cases where the battery charges but there isn't enough load consumption to discharge again. In addition, on days that the load is quite low, the self-consumption of the system i.e. the energy needed for the 24-hour operation of the inverter, BMS and control devices, becomes comparable to the total consumption.

V. Conclusion & Future Work

This paper presents the design and the implementation of an integrated system that monitors, schedules and controls a BESS for residential building purposes. The proposed system exploits the variable electricity price in the markets to provide additional income to an aggregator and consequently to their customers. The results showed that the benefits of the proposed installation cannot yet be yield. Therefore, the proposed solution cannot be considered yet financially viable in its current configuration and the considered circumstances, current variations of electricity prices of the particular electricity market considered, current procurement and installation costs of BESS etc. Perhaps a more volatile variation of the electricity price could provide the necessary revenue for such a solution to be considered as sustainable, especially in case that it could reach negative values as well. Thus, it could be argued that another market, e.g Germany, or in future markets, this solution could be made viable. Furthermore, it should be stated that apart from participating in the day-ahead market, no other revenue has been taken into account. If this were to be changed and the participation in other markets was available, perhaps by providing ancillary services during the intra-day market, this could also provide some additional income.

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References

[1] H. Azaioud, R. Claeys, J. Knockaert, L. Vandevelde, and J. Desmet, "A low-voltage dc backbone with aggregated res and bess: Benefits compared to a traditional low-voltage ac system," *Energies*, vol. 14, no. 5, 2021. [Online]. Available: https://www.mdpi.com/1996-1073/14/5/1420

[2] S. P. Anjana and T. S. Angel, "Intelligent demand side management for residential users in a smart micro-grid," in *2017 International Conference on Technological Advancements in Power and Energy (TAP Energy)*, 2017, pp. 1–5.

[3] Z. Wu, D. W. Gao, H. Zhang, S. Yan, and X. Wang, "Coordinated control strategy of battery energy storage system and pmsg-wtg to enhance system frequency regulation capability," *IEEE Transactions on Sustainable Energy*, vol. 8, no. 3, pp. 1330–1343, 2017.

[4] T. Tewari, A. Mohapatra, and S. Anand, "Coordinated control of oltc and energy storage for voltage regulation in distribution network with high pv penetration," *IEEE Transactions on Sustainable Energy*, vol. 12, no. 1, pp. 262–272, 2021.

[5] M. Brenna, F. Foiadelli, M. Longo, and D. Zaninelli, "Ancillary services provided by bess in a scenario characterized by an increasing penetration of unpredictable renewables," in *2017 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*, 2017, pp. 1–6.

[6] H. Mehrjerdi, E. Rakhshani, and A. Iqbal, "Substation expansion deferral by multi-objective battery storage scheduling ensuring minimum cost," *Journal of Energy Storage*, vol. 27, p. 101119, 2020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2352152X19312034

[7] P. Singh, S. Dhundhara, Y. P. Verma, and N. Tayal, "Optimal battery utilization for energy management and load scheduling in smart residence under demand response scheme," *Sustainable Energy, Grids and Networks*, vol. 26, p. 100432, 2021. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2352467721000035

[8] https://www.iea.org/reports/tracking-buildings 2020, "Tracking buildings," 2020.

[9] N. Lior, "Sustainable energy development: The present (2011) situation and possible paths to the future," *Energy*, vol. 43, no. 1, pp. 174–191, 2012, 2nd International Meeting on Cleaner Combustion (CM0901-Detailed Chemical Models for Cleaner Combustion). [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360544211007699

[10] L. Cheun Hau and Y. Seng Lim, "Financial benefits of pv only, bess only and pv with bess under the trading arrangements of nem and etou in malaysia," in *2020 International Conference on Smart Grid and Clean Energy Technologies (ICSGCE)*, 2020, pp. 59–64.

[11] A. Akhil, G. Huff, A. B. Currier, J. Hernández, D. Bender, B. C. Kaun, D. Rastler, S. Chen, A. L. Cotter, D. Bradshaw, W. D. Gauntlett, J. M. Eyer, T. Olinsky-Paul, M. Ellison, and S. Schoenung, "Doe/epri electricity storage handbook in collaboration with nreca," 2016.

[12] G. Aneiros, J. Vilar, and P. Raña, "Short-term forecast of daily curves of electricity demand and price," *International Journal of Electrical Power & Energy Systems*, vol. 80, pp. 96–108, 2016. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0142061516000466

[13] Y. Wang, B. Wang, T. Zhang, H. Nazaripouya, C.-C. Chu, and R. Gadh, "Optimal energy management for microgrid with stationary and mobile storages," in *2016 IEEE/PES Transmission and Distribution Conference and Exposition (T D)*, 2016, pp. 1–5.

[14] Y. Ma, J. Matuško, and F. Borrelli, "Stochastic model predictive control for building hvac systems: Complexity and conservatism," *IEEE Transactions on Control Systems Technology*, vol. 23, no. 1, pp. 101–116, 2015.

[15] M. Amoasi Acquah, D. Kodaira, and S. Han, "Real-time demand side management algorithm using stochastic optimization," *Energies*, vol. 11, no. 5, 2018. [Online]. Available: https://www.mdpi.com/1996-1073/11/5/1166

[16] A. Bintoudi, L. Zyglakis, A. Tsolakis, P. Gkaidatzis, A. Tryferidis, D. Ioannidis, and D. Tzovaras, "Optimal day-ahead microgrid scheduling via milp: Modelling and real-life application," *Energies*, 2021.

[17] S. Masum, Y. Liu, and J. Chiverton, "Multi-step time series forecasting of electric load using machine learning models," in *International conference on artificial intelligence and soft computing*. Springer, 2018, pp. 148–159.

[18] T. Chen and C. Guestrin, "Xgboost: A scalable tree boosting system," in *Proceedings of the 22nd acm sigkdd international conference on knowledge discovery and data mining*, 2016, pp. 785–794.