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A SMART OPERATIONAL ASSISTANCE SYSTEM FOR THERMAL ENERGY STORAGE WITH INTEGRATED FORECASTING AND MODEL-BASED OPTIMIZATION

Summary

The increasing share of renewable energy sources leads to stronger volatility in electricity markets and increases the value of operational flexibility on the demand side. Thermal energy storage systems (TESS) can provide such flexibility, but their efficient operation requires intelligent decision support that considers forecasts of solar energy generation, thermal energy demand, and electricity prices. This work introduces smartTESS, a smart operational assistance system for thermal energy storage that integrates forecasting, optimization, and simulation modules within a unified architecture. The system incorporates forecasts of weather conditions, solar energy generation, electricity demand, and electricity prices to support economically optimized system operation. Particular attention is given to the integration of data-driven forecasting methods and physics-based system models within the operational decision framework.

Keywords: smart thermal energy storage, operational assistance system, electricity price forecasting, day-ahead market, machine learning, energy system optimization

Field of application for the findings: Sustainable Energy Infrastructure and Electrification

Addressed audience: Researchers and engineers working on TESS and energy system optimization

1. Introduction

The growing integration of renewable energy sources is transforming the operation of modern energy systems. Fluctuating generation from wind and solar increases market volatility and highlights the need for flexible demand-side resources [Kyritsis et al., 2017]. Thermal energy storage systems can provide such flexibility by shifting energy consumption in time and supporting the integration of renewable energy sources [Arteconi et al., 2012]. The increasing availability of short-term electricity markets enables flexible energy consumers to adjust their electricity consumption according to dynamic price signals. However, exploiting this potential requires intelligent decision support that combines reliable forecasts with optimized operational strategies. In particular, the recent transition of European day-ahead electricity markets from hourly to 15-minute trading intervals increases both the complexity of electricity price prediction and the value of accurate forecasts for flexible energy systems [ENTSO-E, 2025]. To address these challenges, this work introduces the smartTESS framework, a smart operational assistance system for thermal energy storage systems. The proposed architecture integrates forecasting modules for weather conditions, solar energy generation, electricity demand, and electricity prices with a hierarchical optimization framework supporting day-ahead planning and short-term operational adjustments. This study focuses on the system architecture of smartTESS and presents initial results on electricity price forecasting and dynamic modeling of concentrating solar systems as a heat source. The development of additional components is part of ongoing work.

2. Concept and Architecture of the smartTESS Framework

The smartTESS framework is designed as a modular operational assistance system supporting the economically optimized operation of TESS in renewable energy systems. The framework combines forecasting, optimization, and simulation components in order to support decision making for the operation of thermal energy storage under dynamic electricity market conditions, load requirements, and solar energy generation. The considered energy system is illustrated in Figure 1. The system consists of a TESS that can be charged using electricity from the grid or from solar energy generation. The stored thermal energy can subsequently be discharged to meet industrial heat demand. Electricity or heat from solar generation can either be used directly to supply the load or to charge the thermal energy storage system. Similarly, electricity from the grid can be used to charge the storage depending on electricity price signals. By shifting energy consumption in time through thermal energy storage, the system enables flexible operation and allows the exploitation of dynamic electricity market conditions.

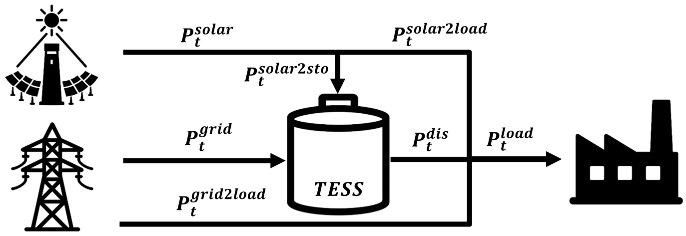

Fig. 1: Simplified representation of the energy system operated by smartTESS

The operational control of the system is supported by the smartTESS framework shown in Figure 2. The framework integrates forecasting modules, optimization algorithms, and simulation components in a modular architecture. Forecasting modules provide predictions of weather conditions, solar energy generation, electricity, heat demand, and electricity prices. These forecasts serve as inputs to a hierarchical optimization framework consisting of long-term, day-ahead, and short-term optimization modules. The day-ahead optimization determines the operating schedule while considering long-term characteristics of demand, supply, and electricity prices, whereas short-term optimization continuously refines the schedule using a rolling horizon approach. The optimization framework applies model predictive optimization, using a dynamic model of the TESS to predict system behaviour over the optimization horizon and determine optimal operating strategies. The architecture further includes interfaces to external data sources as well as a data layer that stores simulation results, optimization outputs, and forecast data. Through a user interface, the system provides decision support by recommending operational strategies and visualizing system performance.

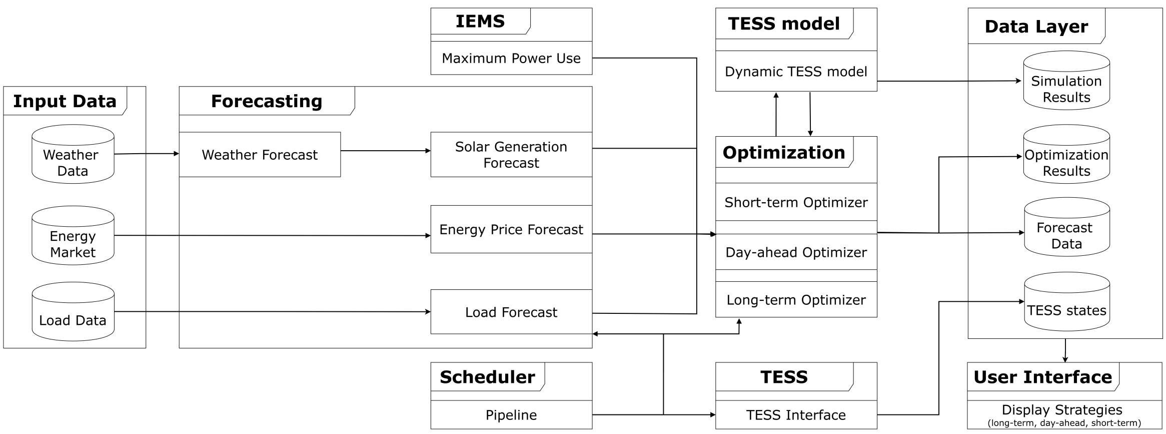

Fig. 2: Simplified architecture of the smartTESS framework showing data inputs, forecasting modules, optimization, and system interfaces

3. Results

3.1 Electricity Price Forecasting

EPF is used within the smartTESS framework to support day-ahead operational planning. Historical electricity prices for the German Luxembourg bidding zone were obtained and processed with a temporal resolution of 15 minutes, which reflects the recent transition of the European day-ahead market to quarter-hourly trading intervals. Data-driven forecasting approaches based on gradient boosting (XGBoost) and recurrent neural networks (LSTM) were implemented to predict short-term electricity price dynamics. Figure 3 shows example prediction results for two representative test periods. The models were evaluated on 30 unseen test days, where

XGBoost achieved a mean absolute error (MAE) of 11.4 EUR/MWh and rootmean squared error (RMSE) of 16.9 EUR/MWh (R^2 = 0.74), slightly outperforming the LSTM model with MAE of 12.4 EUR/MWh and RMSE of 18.6 EUR/MWh (R^2 = 0.69). Despite the described deviations of both models, qualitatively the models are already qualitatively capable of accurately predicting high- and low-price periods, which indicates that machine learning based forecasts can provide suitable price signals for forecast-driven operation.

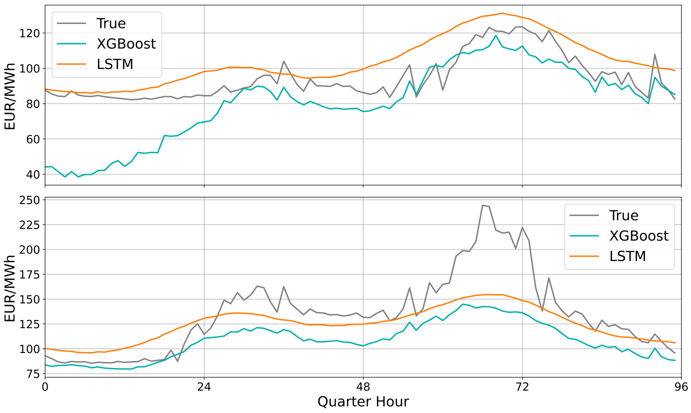

Fig. 3: Comparison of day-ahead EPF from XGBoost and LSTM with observed market prices for two example days

3.2 Dynamic Simulation of a Parabolic Trough Collector System with Oil-Air Heat Exchanger

A dynamic model of a PTC system with an integrated oil to air heat exchanger has been developed. In Fig. 4, first simulation results show controlled oil outlet temperatures of up to 390 °C at peak direct normal irradiance (DNI), while the heat exchanger provides controlled air outlet temperatures of approximately 340 °C, enabling preheating, charging of the thermal energy storage system, or direct load supply. The oil and air temperatures are controlled via the respective mass flow rates.

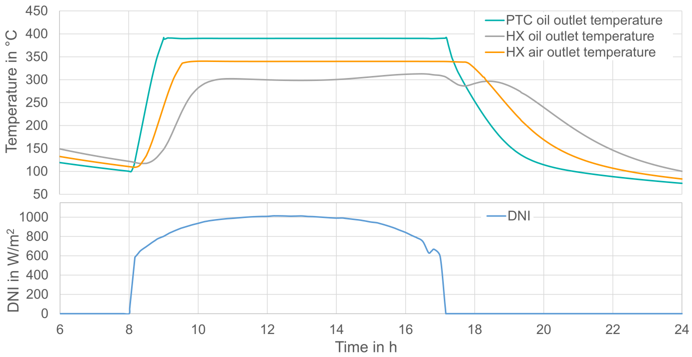

Fig. 4: Simulation results of PTC and heat exchanger temperatures under varying DNI

References

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