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Dynamic modelling and hybrid operation of CST, PV and molten salt TES at the PROTEAS facility

Summary

This work presents a dynamic, physic-based modelling framework for a hybrid photovoltaics-concentrating solar thermal with thermocline thermal energy storage, implemented and validated at the PROTEAS research facility in Cyprus. The model captures transient thermal-electrical coupling, storage stratification dynamics, and power-to-heat integration, enabling the assessment of coordinated hybrid control strategies under variable solar conditions. Experimental and simulation campaigns evaluate storage-driven operation and curtailment mitigation scenarios. The proposed framework supports the development of dispatchable concentrating solar power-photovoltaic hybrid systems for distributed and small grid applications.

Keywords: Hybrid systems, Thermal Energy Storage, Concentrating Solar Power, Photovoltaics, Power to Heat

Field of application for the findings: Dynamic modelling and control of hybrid renewable energy systems with thermal storage

Addressed audience: Research and industry in distributed energy systems, hybrid renewable integration, thermal storage and grid flexibility and stability

1. Introduction

The increasing penetration of variable renewable energy sources is reshaping the operational paradigm of modern power systems. High shares of photovoltaic (PV) and wind generation introduce variability, reduced inertia, and curtailment challenges, particularly in electrically isolated or weakly interconnected regions. Enhancing system flexibility through hybridization and storage integration has therefore become a central research priority.

Concentrating Solar Thermal (CST) technologies equipped with Thermal Energy Storage (TES) offer synchronous and dispatchable renewable generation. TES enables decoupling between solar collection and power production, allowing temporal shifting of energy and improved grid support capabilities. TES role becomes even more important in hybrid renewable configurations or Distributed Energy Systems (DES), where CST systems can act as stabilizing backbones that absorb variability from PV generation and increase overall renewable penetration without proportionally increasing curtailment. Hybrid PV-CST configurations are especially relevant in regions with high solar irradiation and constrained grid infrastructure.

The PROTEAS Facility (Sánchez-González et al., 2022) represents a unique large-scale experimental infrastructure designed to bridge fundamental research and industrial deployment of renewable energy systems. Its architecture, centred around molten salt TES, enables the analysis of thermally driven flexibility mechanisms under controlled conditions. The facility allows the dynamic interaction between PV, CST and centralized TES to be evaluated. This configuration is especially relevant for assessing power-to-heat coupling strategies, storage utilization efficiency, and transient system response. Consequently, PROTEAS offers an appropriate platform for validating modelling approaches aimed at enhancing flexibility and stability in hybrid renewable energy systems.

Within this context, the present work focuses on the deployment of a dynamic, physics-based modelling framework for the hybrid PV-CST-TES configuration at PROTEAS. The objective is to establish a unified simulation environment capable of capturing thermal-electrical coupling, storage dynamics, and coordinated hybrid control strategies under transient operating conditions. Emphasis is placed on power-to-heat operation as a flexibility mechanism, enabling the conversion of surplus PV generation into dispatchable thermal energy.

2. PROTEAS facility

The PROTEAS facility is in Cyprus; it is a large-scale renewable energy research infrastructure designed to investigate hybrid solar energy systems under real environmental conditions. The facility is organized around a central thermocline molten salt TES system that acts as an energy hub, enabling the integration of multiple renewable generation technologies within a common thermal and electrical framework. This architecture allows controlled experimentation on energy coupling, storage management and hybrid operation strategies.

The CST subsystem is based on heliostat field and central receiver configuration, enabling high-temperature heat production suitable for charging the molten salt storage. In parallel, a PV array provides direct electrical generation that can either be supplied to the grid, stored in batteries, or converted into thermal energy through power-to-heat strategies. The co-existence of thermal and electrical storage technologies within the same infrastructure enables the study of cross-sectoral flexibility mechanisms and coordinated control schemes. The overall configuration of the facility is shown in Fig. 1.

Fig. 1: Experimental hybrid PV-CST-TES PROTEAS facility used for dynamic modelling and hybrid operation analysis

3. Dynamic modelling framework

The modelling framework follows a physics-based time-dependent approach to reproduce the transient behaviour of hybrid CST-PV systems under variable irradiance conditions. The model is implemented in Python using an object-oriented programming structure. Each physical subsystem is represented as an independent class encapsulating its governing equations, thermophysical properties and control logic. The tower subsystem evaluates the incident thermal power on the receiver based on direct normal irradiance and aggregated optical efficiency factors. HEFESTO tool (Biencinto et al., 2025) is used to simulate the heliostat field, obtaining an efficiency matrix for the overall field in different sun positions. The absorbed thermal energy is coupled dynamically with the molten salt flow and receiver thermal inertia through a lumped energy balance formulation.

The molten salt TES system at PROTEAS is based on a single-tank thermocline configuration. The storage is modelled using a simplified approach based on an analytical function (Bayón and Rojas, 2014) that accounts for the longitudinal temperature stratification within the tank and the movement of the thermocline region during charging and discharging processes. Fig. 2 shows a simplified diagram of the facility, the specific energy subsystems implemented in the model and connections between them.

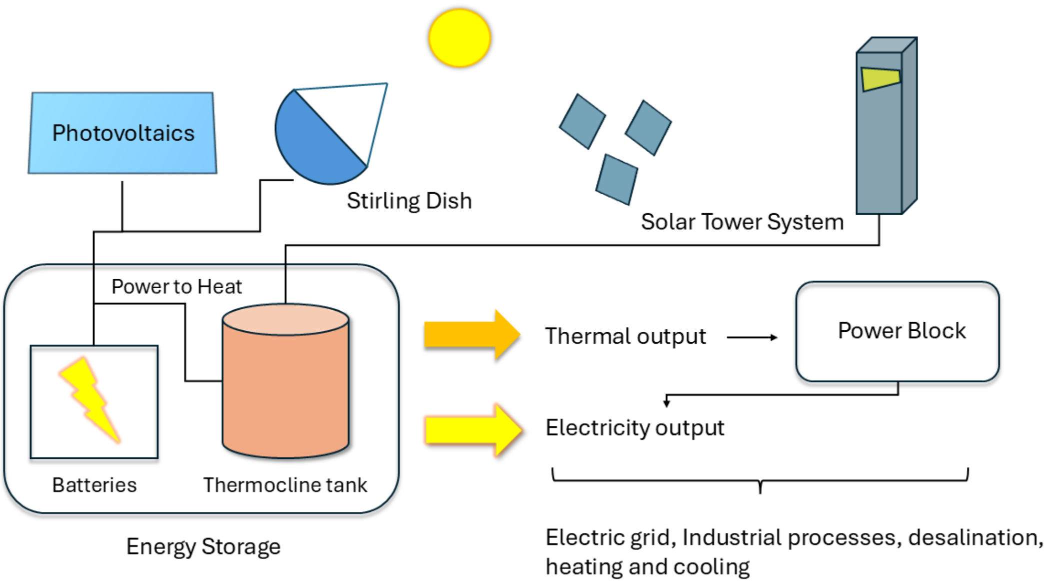

Fig. 2: Simplified diagram of the PROTEAS facility

A key feature of the framework is the integration of a power-to-heat pathway, enabling surplus PV electricity to be converted into thermal energy and injected into the TES system. Overall, this modelling approach enables the evaluation of different hybrid control strategies, and its modular architecture allows this without modifying the physical configuration model, making the framework suitable for experimental validation campaigns at PROTEAS.

4. Experimental campaign and outcomes

A dedicated experimental and simulation campaign validates the proposed hybrid modelling framework under real operating conditions at PROTEAS. The campaign is focused on coordinated PV-CST-TES operation under variable solar irradiance, with particular emphasis on storage-driven control and power-to-heat strategies. High-resolution measurements of direct normal irradiance, global horizontal irradiance, ambient temperature, molten salt temperatures, mass flow rates, and electrical output are used to calibrate and validate the dynamic response of the model. Different operational scenarios are tested, including hybrid charging sequences and controlled discharge strategies aimed at smoothing power fluctuations.

The outcome of this work is a validated, flexible hybrid simulation framework capable of supporting experimental campaign design and advanced control development. Beyond infrastructure-specific results, the study aims to provide methodological insights into the dynamic integration of PV and CSP technologies through TES, contributing to the development of flexible and dispatchable solar-based distributed energy systems.

5. References

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