REAL-TIME STATE OF CHARGE ESTIMATION IN ADSORPTION THERMAL ENERGY STORAGE SYSTEMS THROUGH DIELECTRIC SENSING

Summary

Adsorption thermal energy storage (ATES) systems store heat through reversible adsorption/desorption cycles between a porous solid and a working fluid. In these systems, the stored energy is directly related to the adsorption degree, making the State of Charge (SoC) dependent on sorbate uptake rather than temperature. Reliable real-time SoC monitoring remains a major limitation for advanced control and grid integration. This work proposes an in-reactor capacitive sensing approach that exploits the correlation between dielectric properties and adsorbed mass. Variations in permittivity are detected through an impedance Analyzer, enabling continuous SoC estimation. The method supports predictive control and improved operational management of adsorption storage systems.

Keywords: Adsorption thermal energy storage, State of Charge, Dielectric sensing, Sorption materials, Thermal storage control

Field of application for the findings: Solar thermal systems, renewable-based heating networks, seasonal thermal storage, smart thermal grids

Addressed audience: Researchers in solar thermal energy, TES developers, smart grid engineers.

1. Introduction

Adsorption Thermal Energy Storage (ATES) is a class of thermochemical storage technologies based on reversible adsorption/desorption cycles between a working fluid (typically water vapor) and a porous solid adsorbent such as zeolites, silica gels, or metal–organic frameworks (MOFs). These systems enable heat storage in the form of adsorption potential, offering high energy density and the possibility of long-term storage with negligible thermal losses (Vasta et al., 2018). The selection and optimization of adsorbent materials play a central role in determining storage capacity, operating temperature range, and cycling stability (Henninger et al., 2012).

In ATES systems, the stored energy is directly proportional to the amount of adsorbate retained within the porous matrix under specific thermodynamic conditions. Therefore, the State of Charge (SoC) is intrinsically linked to the adsorption degree, i.e., the ratio between the current adsorbed mass and the maximum achievable uptake under reference conditions. Unlike sensible or latent storage technologies, temperature alone does not provide a reliable indication of stored energy in adsorption systems, as it does not uniquely determine the adsorption state.

While extensive research has addressed reactor modelling and system-level performance prediction (Scapino et al., 2019), significantly less attention has been devoted to the real-time estimation and monitoring of SoC in adsorption storage. Recent studies on operational strategies for sorption thermal energy storage highlight the importance of accurately tracking the storage level during charging and discharging phases to enable optimized control and integration in building and district energy systems (Gado et al., 2025). These works emphasize that reliable SoC information is essential for predictive control, efficient dispatch of stored heat, and smart-grid interaction.

Despite its operational relevance, practical methodologies capable of directly monitoring the adsorption state within a reactor remain limited. Developing robust SoC estimation approaches tailored to adsorption processes is therefore a key step toward transforming ATES systems into controllable and grid-responsive thermal storage assets.

In this framework, the present work proposes and experimentally validates a dielectric-based in-reactor sensing methodology for real-time State of Charge estimation in adsorption thermal energy storage systems, directly correlating measurable electrical properties with the adsorption degree of sorbent material.

2. Dielectric-Based Methodology for Real-Time SoC Estimation

To overcome the limitations of indirect thermal measurements, this work proposes a dielectric-based methodology for real-time State of Charge estimation in ATES. The approach is founded on the correlation between the adsorption degree of the sorbent material and its effective dielectric properties. As water molecules are adsorbed within the porous structure, the permittivity of the material changes due to the high dielectric constant of water compared to the dry adsorbent matrix.

By integrating conductive electrodes inside the reactor, the adsorbent bed can be treated as the dielectric medium of a capacitor. The capacitance depends on the effective relative permittivity of the porous medium, which varies with sorbate uptake. Consequently, adsorption and desorption processes produce measurable capacitance variations.

To enable continuous monitoring, the capacitive element is integrated into a measurement system that relies on an impedance Analyzer. Variations in capacitance result in variations of capacitive impedance, which can be accurately detected and correlated with the adsorption state. While the measurements based on RLC frequency shifting provide only scalar single-parameter response and water adsorption lead to a reduction of the quality factor Q, the spectroscopy of the capacitive impedance enables the decoupling of the complex dielectric permittivity. Using these features, is possible have information on the capacitive contribution and the dielectric losses.

The sensing architecture is designed to be non-invasive and compatible with typical packed-bed reactor configurations. Stainless steel electrodes are selected to ensure chemical stability and durability under cyclic adsorption conditions. The methodology allows direct tracking of internal adsorption progression without relying solely on boundary temperature or pressure measurements.

By establishing a calibrated relationship between the capacitive impedance and adsorption degree, the proposed system provides a quantitative real-time estimation of SoC, enabling improved operational control and predictive energy management in ATES systems.

3. Prototype Development and Experimental Setup

A laboratory-scale prototype has been developed to experimentally validate the proposed dielectric-based State of Charge estimation methodology. The supporting structure of the sensing system has been realized through additive manufacturing using a 3D-printed polymeric frame, specifically designed to ensure mechanical stability, electrical insulation, and reproducible positioning of the electrodes.

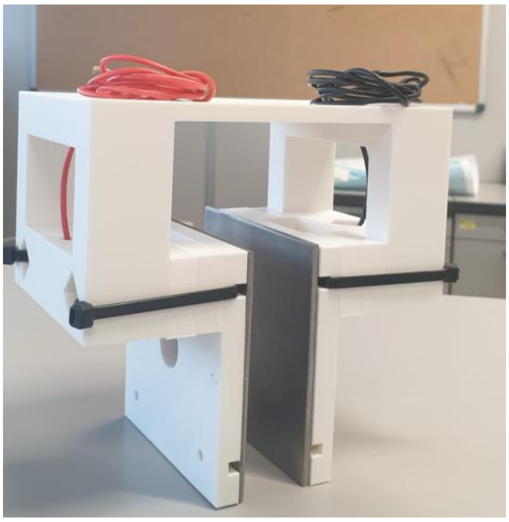
The sensing element consists of a parallel-plate capacitor with stainless steel electrodes of 100 × 100 mm surface area. The electrodes are arranged vertically and mechanically fixed within the 3D-printed structure to maintain a constant inter-plate distance and ensure geometric repeatability. Electrical connections are routed externally through cables to allow integration with the measurement system (Fig. 1a).

For the experimental campaign, the capacitor is fully immersed in approximately 3 kg of mesoporous silica gel, selected as a representative adsorption material due to its well-characterized water uptake behaviour and stability under cyclic adsorption conditions. The silica gel surrounds the sensing plates, so that variations in water adsorption directly affect the effective dielectric properties of the medium (Fig. 1b).

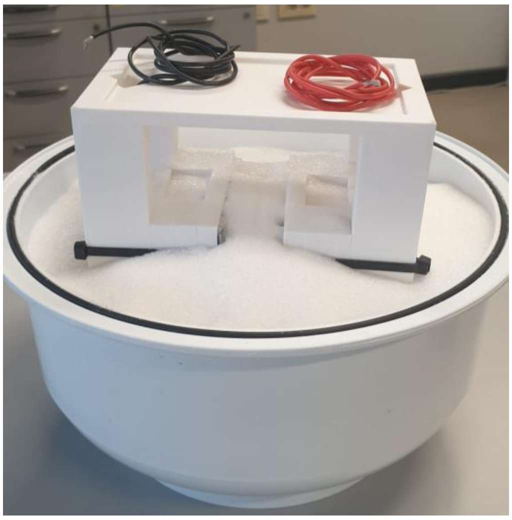
The experimental procedure is based on the simultaneous measurement of adsorbed mass and capacitive impedance variation. Exploit the sweep impedance analyzer feature will be investigates the frequency that linearizes as much as possible the correlation between the energy content and the impedance.

Initially, the silica gel is fully regenerated to reach an anhydrous condition. The dry material is then placed on a precision balance to continuously monitor mass variations. As the material progressively adsorbs moisture from ambient air, the increase in mass is recorded together with the corresponding change in capacitance.

By correlating gravimetric data with electrical measurements, a quantitative relationship between adsorption degree and capacitance can be established. This calibration curve will allow the translation of capacitance values into real-time SoC estimation. The experimental setup is currently under final assembly and instrumentation. The first measurement campaigns are scheduled within the next three months, aiming to validate sensitivity, repeatability, and stability of the proposed sensing approach under controlled adsorption conditions.



a)



b)

Fig. 1: a) 3D-printed prototype structure with integrated parallel-plate capacitor (100 × 100 mm stainless steel electrodes) used for dielectric-based State of Charge measurements in adsorption storage experiment. b) Experimental setup with the capacitive sensor fully immersed in approximately 3 kg of mesoporous silica gel during adsorption tests for capacitance–mass correlation measurements.

4. Conclusions

This work addresses the critical issue of real-time State of Charge estimation in adsorption thermal energy storage systems, where the stored energy is governed by sorbate uptake rather than temperature variations. A dielectric-based sensing methodology has been proposed, exploiting the dependence of the effective permittivity of the adsorbent bed on its hydration level.

A laboratory-scale prototype has been designed and assembled, consisting of a 3D-printed insulating structure integrating a 100 × 100 mm parallel-plate capacitor immersed in mesoporous silica gel. The experimental campaign is based on the simultaneous measurement of gravimetric mass variation and capacitance change during adsorption from ambient air, allowing the establishment of a quantitative correlation between adsorption degree and electrical response.

The proposed approach offers a non-invasive, scalable, and potentially low-cost solution for continuous SoC monitoring in ATES systems. The first experimental tests, scheduled within the next three months, will evaluate sensitivity, repeatability, and robustness of the sensing concept.

5. References

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