Supercapacitors as a system-level solution for enhanced self-consumption strategies

Abstract

In the recent past, new frontiers have opened up in the field of district-level energy generation and utilization, due to the promulgation of the European Renewable Energy Directive. In this work, carried out under the MASE - ENEA program agreement on Electrical System Research, we introduce the new expanded composition and operation logics of the experimental test facility S.A.P.I.EN.T.E. installed at the ENEA Casaccia Research Centre (north of Rome), in a state of continuous plant evolution. Then, we demonstrate, through initial experimental activities, and a sequent extensive experimental campaign, the advantages in terms of energy self-consumption and self-sufficiency that the use of supercapacitors can bring in the context of Thermal Energy Communities (TECs) and Jointly Acting Renewable Self-Consumers (JARSCs).

Introduction

The energy transition is progressively shifting electricity production from centralized plants to distributed renewable systems embedded within urban and peri-urban environments. European legislation now explicitly recognizes collective self-consumption schemes such as TECs and JARSCs, encouraging local generation, shared use of renewable electricity, and active participation of consumers in energy management. Although this decentralized model increases local resilience and supports decarbonization targets, it also introduces operational complexity. Photovoltaic generation is inherently intermittent and largely determined by meteorological conditions. Demand, on the other hand, follows behavioral and climatic patterns that do not necessarily coincide with solar availability. As a result, even in well-sized systems, instantaneous imbalances between generation and load occur frequently. Improving SC and SS requires coordinated strategies that operate at different temporal scales. Medium-term mismatches can be mitigated through thermal storage coupled with heat pumps, allowing surplus electricity to be converted into stored heat or cooling. This approach exploits the high coefficient of performance (COP) of heat pumps to shift energy use in time. However, short-duration imbalances, often lasting seconds or minutes, cannot be effectively addressed by thermal inertia alone. Heat pump compressor start-up, PID overshoot, and sudden activation of auxiliary loads can cause transient power peaks that exceed available PV generation. Even if average daily production covers demand, these short peaks trigger grid imports and reduce SS. Addressing this dynamic component requires storage technologies with high power density and rapid response capability. Supercapacitors, though characterized by lower energy density compared to lithium-ion batteries, are capable of delivering high power in very short timeframes and sustaining a large number of charge–discharge cycles without significant degradation. Their integration within a hybrid system may therefore provide a buffering function specifically targeting transient imbalances. This study evaluates their performance experimentally under controlled but realistic operating scenarios.

The S.A.P.I.EN.T.E. System

System Description

S.A.P.I.EN.T.E. (Integrated Accumulation and Production System of Thermal and Electrical Energy) is an experimental platform developed at the ENEA Casaccia Research Centre within the MASE–ENEA Program Agreement on Electric System Research. The system integrates electrical generation, thermal production, storage, and controllable loads within a flexible architecture. Electrical generation is provided by an 11.6 kW photovoltaic plant and a 6.4 kW thermo-photovoltaic system. Thermal production relies on a 30.4 kW air-to-water heat pump supported by 4.5 kW electrical boost resistors. Thermal storage consists of two 1,500 L hot/cold storage tanks and one 1,000 L domestic hot water (DHW) tank. Electrical storage is composed of four supercapacitor modules connected to a hybrid inverter, for a total nominal capacity of 14 kWh. The facility includes regenerative electronic loads (15 kVA each) and dry coolers (70 kW) to emulate electrical and thermal demand profiles. Additionally, nine fan-coils in a nearby office building provide real thermal load conditions. This configuration allows reproducible experimentation across seasonal and usage scenarios.

System Control Strategies

Energy flows are managed by a programmable logic controller implementing a power-to-heat (P2H) strategy based on proportional–integral–derivative (PID) control. The controller continuously measures PV production and modulates heat pump compressor speed to match instantaneous renewable generation. Thermal storage operates within defined Low Temperature Setpoints (LTS) and High Temperature Setpoints (HTS). When storage temperature reaches HTS, the heat pump is stopped and surplus PV electricity can be diverted to boost resistors or stored electrically. This approach prioritizes direct renewable utilization while maintaining thermal comfort constraints. The addition of supercapacitors extends the control framework by introducing a fast-response electrical buffer capable of compensating transient mismatches between generation and load.

On the Employment of SpCs

Supercapacitors differ fundamentally from lithium-ion batteries in their energy–power characteristics. While their energy density is lower, their power density is significantly higher, enabling rapid charge and discharge cycles with minimal efficiency loss. They also exhibit extended cycle life, often exceeding hundreds of thousands of cycles, and reduced fire risk compared to battery systems. In the present configuration, supercapacitors are not intended to store large amounts of energy over extended periods. Instead, they serve as a dynamic buffer operating on short timescales, absorbing or delivering power when instantaneous imbalances occur. This functional distinction complements thermal storage, which operates over longer time horizons. The chosen commercial modules exhibit approximately 2% monthly self-discharge in sleep mode, making them suitable for repeated daily cycling. Their integration within S.A.P.I.EN.T.E. allows evaluation of hybrid storage strategies combining thermal inertia and high-power electrical buffering.

Experimental

Practical Experiments on P2H Strategy

Winter experiments confirmed the effectiveness of P2H control in increasing self-consumption. With storage temperature set between 35°C (LTS) and 50°C (HTS), the heat pump operated in PV tracking mode for extended periods, achieving SC of 76% and SS of 95%. When thermal boost resistors were activated to absorb additional surplus energy, SC increased from 26% (without resistors) to 83%, and SS reached 97%. These results demonstrate the impact of controlled thermal accumulation on renewable utilization. However, analysis of power curves revealed short-duration overshoots of heat pump absorption over PV production, especially during compressor transitions.

Qualification Experiment Using SpCs to Compensate Fast Load Changes

A spring scenario was designed to isolate the impact of supercapacitors. With DHW setpoints at 45–50°C and HCS at 11–20°C, transient overshoots were observed during PID tracking. When supercapacitors were enabled, they immediately compensated power deficits, reducing grid imports. Under equivalent conditions, SC increased from 57% to 65%, and SS rose from 76% to 92%. This qualification test confirmed the ability of SpCs to address rapid load variations.

Use of SpCs to Compensate Fast Power Demand in an Office Building Context

An all-day experiment reproduced an office-building thermal load profile. Because thermal demand overlapped with PV production, SC without SpCs was already high (90%). The integration of supercapacitors produced a modest SC increase (to 92%) but substantially improved SS, from 74% to 97%, by compensating compressor overshoot and resistor activation peaks.

Use of SpCs to Maximize SC and SS in a Residential Context

A winter residential scenario was implemented with morning and evening demand peaks. Without supercapacitors, SC was 21% and SS 47%. With SpCs enabled, SC increased to 31% and SS to 71%. Although generation–demand misalignment limited overall SC, supercapacitors reduced short-duration grid imports during peak demand.

Conclusions

The experimental campaign demonstrates that supercapacitors enhance hybrid renewable systems by addressing short-term power dynamics that thermal storage alone cannot manage. Power-to-heat control remains the primary mechanism for increasing self-consumption. Supercapacitors operate on a complementary timescale, mitigating transient mismatches and increasing self-sufficiency. Their integration within distributed renewable architectures serving TECs and JARSCs provides measurable improvements in energy performance indicators without altering generation capacity. Hybrid storage configurations combining thermal inertia and high-power electrical buffering represent a promising direction for decentralized energy systems. Future work will focus on techno-economic assessment and multi-node community integration.