



Research Papers

Stackelberg game-driven digital decision intelligence for carbon-neutral hydrogen sustainable energy consortia with electric scooter fleet-based transportable storage

SyedJalal SeyedShenava ^{a,*} , Peyman Zare ^a , Amir Mohammadian ^a 

^a Department of Electrical Engineering, Faculty of Technology and Engineering, University of Mohaghegh Ardabili, P.O. Box 179, Ardabil, Iran

ARTICLE INFO

Keywords:

Stackelberg game
Sustainable Energy Consortium
Transportable storage
Energy–mobility integration

ABSTRACT

Achieving deep decarbonization in urban energy systems depends on decision-intelligent coordination of advanced storage technologies embedded within multi-vector energy infrastructures. This study introduces a Stackelberg game-driven digital energy decision intelligence framework for carbon-neutral hydrogen sustainable energy consortia, highlighting the combined contribution of stationary storage assets and transportable storage provided by shared electric scooter fleets (ESFs). The framework enables coordinated scheduling of electricity, heat, cooling, and hydrogen subsystems while integrating electrolysis, methanation, fuel-cell conversion, and carbon capture to support carbon-neutral operation. ESFs are modeled as mobile distributed storage units engaged in grid-to-vehicle and vehicle-to-grid interactions, supplying controllable charging and discharging flexibility that strengthens renewable integration, load balancing, and peak reduction. The digital decision structure employs a hierarchical leader–follower interaction in which the regulator specifies the carbon emission cap and incentive parameters, and the consortium operator performs cost-optimal dispatch of generation, storage, hydrogen processes, and flexibility resources under renewable and market variability. Case studies demonstrate that coordinated utilization of stationary storage, transportable storage, and hydrogen conversion pathways lowers total operational costs by more than 25%, reduces net greenhouse gas emissions by more than 90% following carbon capture, and increases renewable utilization through significant curtailment reduction. Results indicate that transportable storage fleets increase system flexibility, improve carbon-market compliance, and enhance the robustness of hydrogen-based energy systems, highlighting their role in storage-intensive carbon-neutral urban infrastructures.

Nomenclature

Abbreviation	Description
A-CAES	Adiabatic Compressed Air Energy Storage
CAES	Compressed Air Energy Storage
CH	Cooling hub
CHP	Combined heat and power
DRP	Demand response problem
EL	Electrolyzer
FC	Fuel cell
GT	Gas turbine
HST	Hydrogen storage tank
IGDT	Information gap decision theory
P2G	Power to gas
PV	Photovoltaic
SEC	Sustainable Energy Consortium

(continued on next column)

(continued)

TH	Thermal hub
WT	Wind Turbine
AC	Absorption chiller
CCUS	Carbon Capture, Utilization, and Storage
CH ₄	Methane
CO ₂	Carbon dioxide
EHP	Electric heat pump
ESS	Energy storage system
GB	Gas boiler
HEH	Hydrogen energy hub
HTS	Hydrogen Tank System
MR	Methanation reactor
P2X	Power to X
RES	Renewable Energy Sources
SSW	Social Stakeholders Welfare

(continued on next page)

* Corresponding author.

E-mail addresses: seyedshenava@uma.ac.ir (S. SeyedShenava), peymanzare@uma.ac.ir (P. Zare), a.mohammadian@uma.ac.ir (A. Mohammadian).

<https://doi.org/10.1016/j.est.2026.123042>

Received 28 November 2025; Received in revised form 9 May 2026; Accepted 4 June 2026

Available online 12 June 2026

2352-152X/© 2026 Elsevier Ltd. All rights are reserved, including those for text and data mining, AI training, and similar technologies.