After the RISEnergy Transnational Access, Users are required to submit a User Report. This should be done within 4 weeks after the Access is completed unless otherwise agreed. The User Report will be given to the User(s) by the WP2 leader. The report contains sections related to the work performed, the main results and observations that were achieved.

This document should be completed, signed, and sent by e-mail to risenergy@for.kit.edu.

Summary questionnaire for Users who have been granted Transnational Access (TA) under the RISEnergy project Horizon Europe TA scheme. More information on RISEnergy TA can be found in "General Rules" and in "Access Policy" which can be found on the RISEnergy webpage.

Please complete, sign, and send this form, together with the Cost claim by e-mail to risenergy@for.kit.edu with title: RISEnergy APPXXX - reports.

General information about the project	
Project title (as used in Application)	Optimal sizing of a hybrid storage standalone microgrid based on stochastic photovoltaic modelling
Project number (APPXXX) and acronym (max 15 characters)	APP148 - OSHSPV
RISEnergy RI(s) accessed	TA52 – UniCyprus-DGSF
Keywords (up to five, free text)	Optimal sizing, Hybrid storage, Multiple demands, Integrated grids
Arrival date (in town where RI is located)	12.05.2025
Departure date (from town where RI is located)	04.06.2025
Starting date of Access (first day at RI)	14.05.2025
Finishing date of Access (last day at RI)	03.06.2025
Number of days not using the RI (during the above period)	6
Reason for not using RI those days (describe)	Weekends
Number of days using the RI	15
Number of Users granted Access (group size)	1
Comments	
User	

User group leader or sole applicant (user group member 1)	
First name	
Last name	
Affiliation / Employer	
Country of Employer	
E-mail	
User travelling to RI?	
Comments	
User group member 2	
First name	-
Last name	-
Affiliation / Employer	-
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E-mail	-
User travelling to RI?	-
Comments	-
Please insert more fields if your groups had more than four members.	

Access Summary Report - work performed and initial results

Brief description of the objectives of your project (up to 200 words)

The primary objective of this project is to design and optimize a standalone microgrid system incorporating a battery-thermal-hydrogen hybrid energy storage system. Figure 1 illustrates the main concept of the studied system.

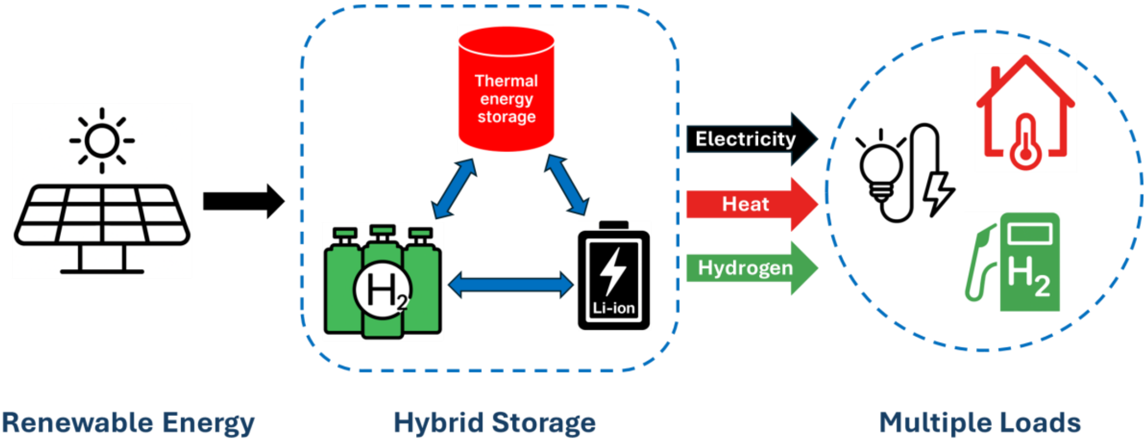

Figure 1. Graphical overview of the hybrid energy storage microgrid.

The microgrid aims to fulfil electrical, heat, and hydrogen demands while minimizing the annual energy cost. Key objectives include:

- Development of an optimization framework for hybrid energy storage in standalone microgrids, utilizing hourly solar radiation data and load profiles for electricity, heat, and hydrogen.

- Finding the optimal sizing of different components that meets the several electric, heat, and hydrogen demands while minimizing the Levelized Cost of Energy (LCOE).

- Evaluation of system performance under realistic conditions, incorporating uncertainties in solar radiation and demand variations.

Given that the transnational access was conducted at the University of Cyprus (UCY), a generic optimization model was developed and then applied to a UCY-based case study. Ultimately, on-site renewable energy production self-consumption increase, and reliance on grid electricity and fuel-based heating reduction is expected.

Activities performed (up to 600 words)

Steps Undertaken

Phase 1 - Data Collection and Initial Planning:

- Engaged with the host institution to define the approach and identify the components to be included in the microgrid system.
- Collected detailed energy consumption data from the University of Cyprus (UCY) to characterize electrical, thermal, and hydrogen demands.
- Obtained five years of on-site solar radiation measurements from UCY to develop a stochastic solar input model.
- Compiled realistic technical and economic parameters for all system components using supplier quotations provided by the host and validated them against literature sources.

Phase 2 - Data Preparation and Model Development:

- Processed the solar radiation data by grouping it temporally, fitting it to an appropriate statistical distribution, and applying Monte Carlo simulations to generate synthetic hourly profiles.
- Estimated hydrogen demand based on the projected share of hydrogen vehicles by 2030, scaled according to UCY's population share relative to Cyprus.
- Developed the optimization model, including the definition of parameters, decision variables, objective function, and system constraints.
- Validated the model outputs against reference studies and internal analyses conducted by the host institution.

Phase 3 - Optimization and Analysis:

- Executed the optimization using the prepared datasets and model framework.
- Evaluated system results to interpret energy flow and storage dynamics.
- Visualized the results through appropriate plotting and graphical representation.
- Compiled and documented the findings for analysis and reporting purposes.

Summary of the studied system

Solar photovoltaic (PV) panels convert sunlight into direct current (DC) electricity, which is then transformed into alternating current (AC) via an inverter to meet the electrical demand of the University of Cyprus (UCY). Excess electricity can be stored in batteries, used to charge a thermal energy storage (TES) system via an electric heater, or converted into hydrogen through an electrolyzer and stored in a hydrogen tank. The stored thermal energy can later be utilized to supply the heat demand or/and to generate electricity using a Stirling engine (SE), while the hydrogen can be reconverted into electricity through a fuel cell. Heat demand at UCY is met either by the electric heater, TES, or by capturing the waste heat rejected from the SE. Importantly, the different energy storage systems are interconnected and can interact with one another, allowing for greater flexibility, improved energy management, and enhanced overall system performance. Figure 2 represents the studied system in detail.

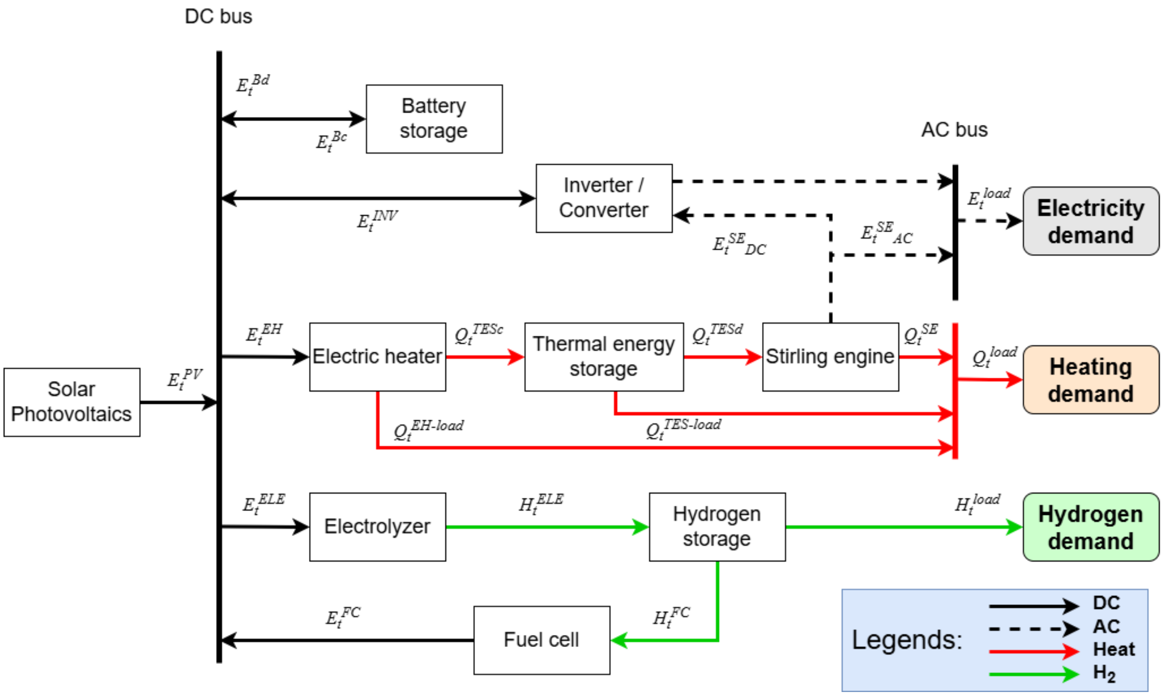

Figure 2. Detailed schematic diagram of the considered system.

Since this work involves extensive use of mathematical notations, this subsection provides definitions and explanations for these notations and how they are interpreted:

- $\mathrm{E}_\mathrm{t}^\mathrm{x}$ is the amount of electricity produced/consumed/passes through by component x at time t
- $\mathrm{Q}_\mathrm{t}^\mathrm{x}$ is the amount heat produced/consumed/passes through by component x at time t
- $\mathrm{H}_\mathrm{t}^\mathrm{x}$ is the amount hydrogen produced/consumed/passes through by component x at time t

Data sources consulted

The technical and economic parameters were sourced from real quotations and technical sheets as well as from the available literature from sources [1-8]. The table below summarizes these parameters.

Table 1. Summary of the technical and economic parameters [1-8].

Component	Unit capital cost (USD/kW)	Unit O&M cost (USD/kW/year)	Efficiency (%)	Lifetime (year)	Others
Photovoltaic	500	54	21.2	20	-
Inverter	528	5	95	10	-
Battery storage	350	4.76	94	9	Hourly self-discharging rate: 0.02%
Thermal energy storage	55	5	95	20	Hourly self-discharging rate: 0.3%

Hydrogen storage	600	12	100	20	Hydrogen energy content: 33.3 kWh/kg
Stirling engine	1000	40	Electrical: 25% Heat: 55%	20	-
Electrolyzer	1920	38.4	65	8	-
Fuel cell	3240	226.8	55	8	-

Techniques employed

Hourly solar irradiance data measured at UCY over four consecutive years (2021–2024) were used in the analysis. The data were organized into 288 datasets, each representing one hour within 12 representative days (one per month). Each dataset was fitted to a Beta distribution using EasyFit software, and the corresponding distribution parameters were recorded. Based on these fits, Monte Carlo simulation was performed using a Python script to generate solar irradiance scenarios. These scenarios were then incorporated into the PV production calculations to enhance the robustness of the optimization approach. The optimization problem was solved using the simplex method, a linear programming technique, implemented using the Gurobi solver. The formulation incorporated various constraint types, including energy balance constraints, storage dynamics constraints, component performance constraints, and design (sizing) constraints. The objective is to minimize the system's annual cost—including capital, operation and maintenance, and replacement expenses—while satisfying the electrical, thermal, and hydrogen demands.

Objective function (minimize the annual cost):

$$\min C^{\mathrm{annual}} = \mathrm{CRF}\left(\sum x^{\mathrm{CAP}} x^{\mathrm{CAPEX}}\right) + \sum x^{\mathrm{CAP}} x^{\mathrm{OPEX}} + \sum x^{\mathrm{CAP}} x^{\mathrm{CAPEX}} \frac{j}{(j+1)^{Y^{x}} - 1}$$

In the right-hand side of the above equation, the first term denotes the annual capital cost, the second term accounts for the annual O&M cost, and the third term reflects the annualized replacement cost for components with lifespans shorter than that of the microgrid. The capital recovery factor (CRF):

$$\mathrm{CRF} = \frac{j(j+1)^{Y^{\mathrm{SL}}}}{(j+1)^{Y^{\mathrm{SL}}} - 1}$$

The levelized cost of energy (LCOE):

$$\mathrm{LCOE} = \frac{C^{\mathrm{annual}}}{\frac{365}{12} \Sigma_t \left(E_t^{\mathrm{load}} + H_t^{\mathrm{load}} \mathrm{HHV} + Q_t^{\mathrm{load}}\right)}$$

Where x represents the various microgrid components, and j denotes the interest rate. The variable y indicates the lifetime, either of a specific component (x) or the entire system (denoted as SL). CAP refers to the capacity of a component, while CAPEX and OPEX correspond to capital expenditure and operational expenditure, respectively. The figure below provides a general overview of the approach used.

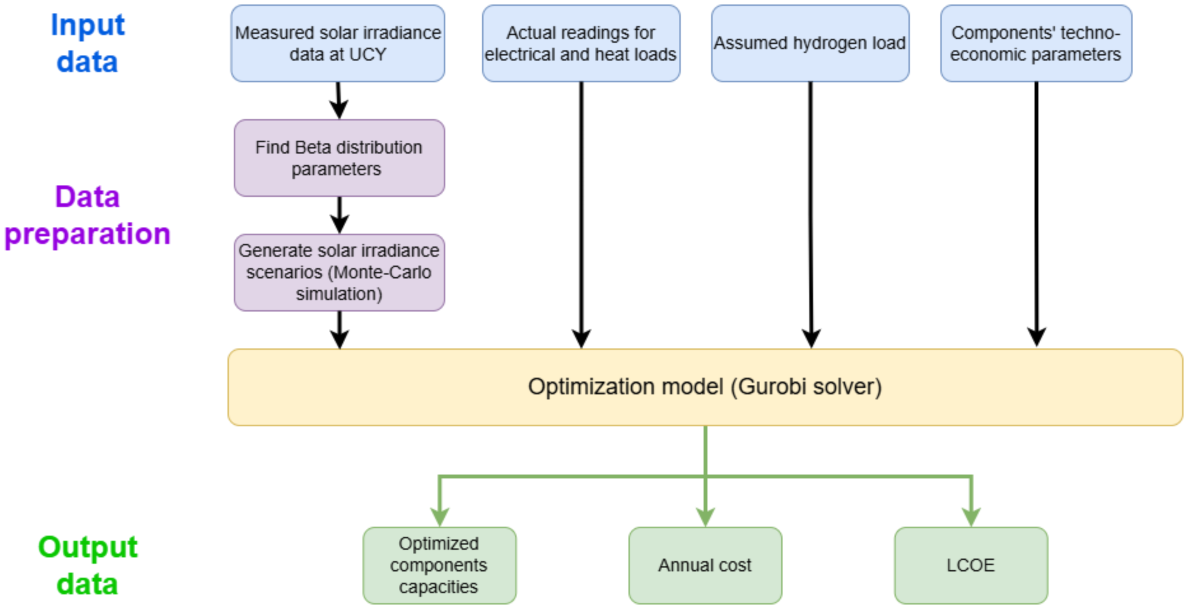

Figure 3 Optimization approach showing inputs and outputs.

References:

1. Maleki A. Design and optimization of autonomous solar-wind-reverse osmosis desalination systems coupling battery and hydrogen energy storage by an improved bee algorithm. Desalination [Internet]. 2018;435(May 2017):221–34. Available from: https://doi.org/10.1016/j.desal.2017.05.034
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Scientific results (up to 800 words)

This section presents the results of the hybrid energy system optimization for the case of University of Cyprus (UCY), beginning with an analysis of the energy demand profiles that shape the system design, followed by detailed insights into component sizing, energy flow, and storage dynamics.

Figure 4 exhibits the hourly energy demand across twelve representative days—one per month—covering electricity, heating, and hydrogen. Electricity shows two peak patterns: daily peaks during working hours and seasonal peaks due to cooling in summer. Heating demand is strongly seasonal, peaking in winter and dropping significantly during warmer months. Hydrogen demand remains low and stable year-round, reflecting a modest and consistent mobility-related load. These patterns are essential for designing and sizing hybrid energy storage systems that can efficiently meet varying demand profiles.

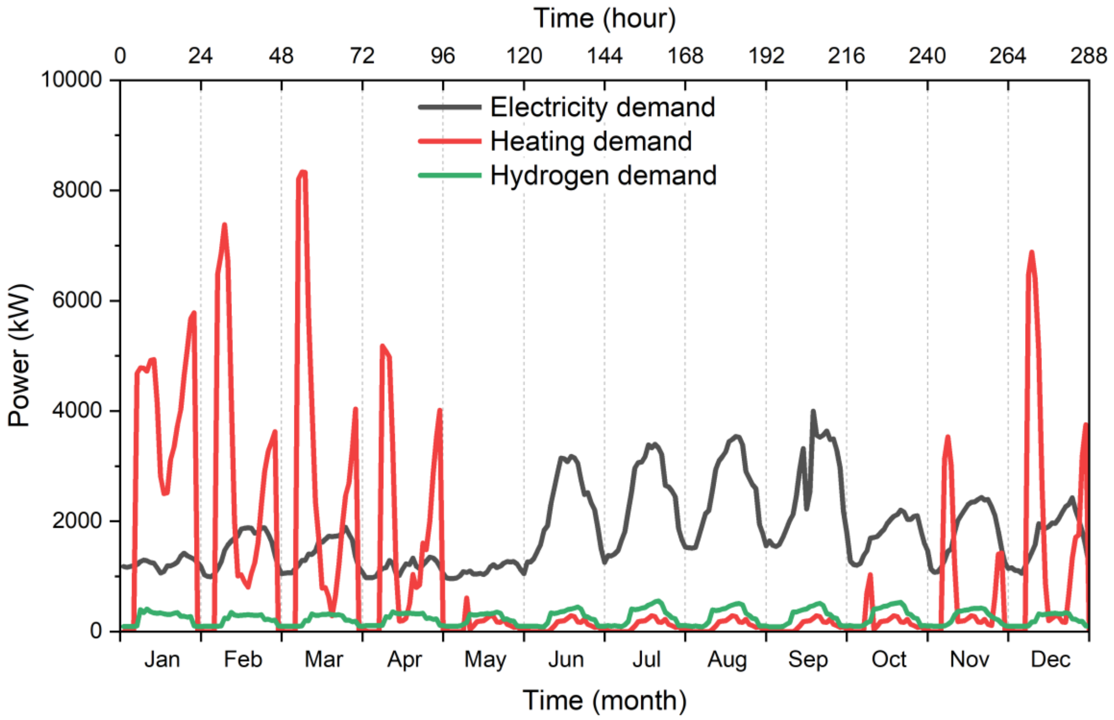

Figure 4. Hourly energy demand at the University of Cyprus on 12 representative days

The optimization results shown in Table 2, solar photovoltaics is sized at 14,479 kWp as it is the primary energy source, supported by a diversified mix of storage technologies. The system's optimized capacities for its energy storage components are: 27,008 kWh for battery storage, 250,925 kWh for thermal energy storage, and 727 kWh for hydrogen storage. The battery storage is incorporated for short-term energy balancing. Thermal energy storage, at a substantially larger capacity, effectively facilitates medium-term energy management. Finally, despite its comparatively smaller size, which is consistent with the scale of hydrogen demand, hydrogen storage provides a suitable option for long-term energy reserves, benefiting from minimal idle-mode losses over time. This hybrid storage approach ensures system flexibility across daily and seasonal variations. The total annualized system cost is approximately 5.94 million USD, with a resulting levelized cost of energy (LCOE) of 0.218 USD/kWh, indicating a cost-effective configuration for meeting the electrical, thermal, and hydrogen demands.

Table 2. Microgrid components' capacities optimization results.

Component	Optimized capacity
Photovoltaic (kWp)	14,479
Inverter (kW)	4,213
Battery storage (kWh)	27,008
Hydrogen storage (kg)	727
Thermal energy storage (kWh)	250,925
Stirling engine (kW)	982
Electrolyzer (kW)	663
Fuel cell (kW)	130
Annual cost (USD/year)	5,939,858
LCOE (USD/kWh)	0.218

Figure 5 shows the hourly photovoltaic (PV) energy generation and its distribution into three storage systems—thermal, battery, and hydrogen. PV generation follows a clear seasonal trend, with higher output observed from April to September, coinciding with longer daylight hours and higher solar irradiance. During these months, a significant portion of the generated energy is directed to thermal energy storage, indicating its dominant role in storing excess energy. Battery storage consistently absorbs energy across all months, reflecting its use for daily load balancing. Hydrogen storage shows more pronounced energy input during the spring and summer months, when PV surplus is high, supporting its role as a long-term seasonal storage medium. It is observed that hydrogen storage is occasionally charged during non-PV production hours, indicating effective interaction and energy exchange between the different storage systems. In the winter months (January, February, November, and December), overall PV generation is lower, and storage charging is visibly reduced.

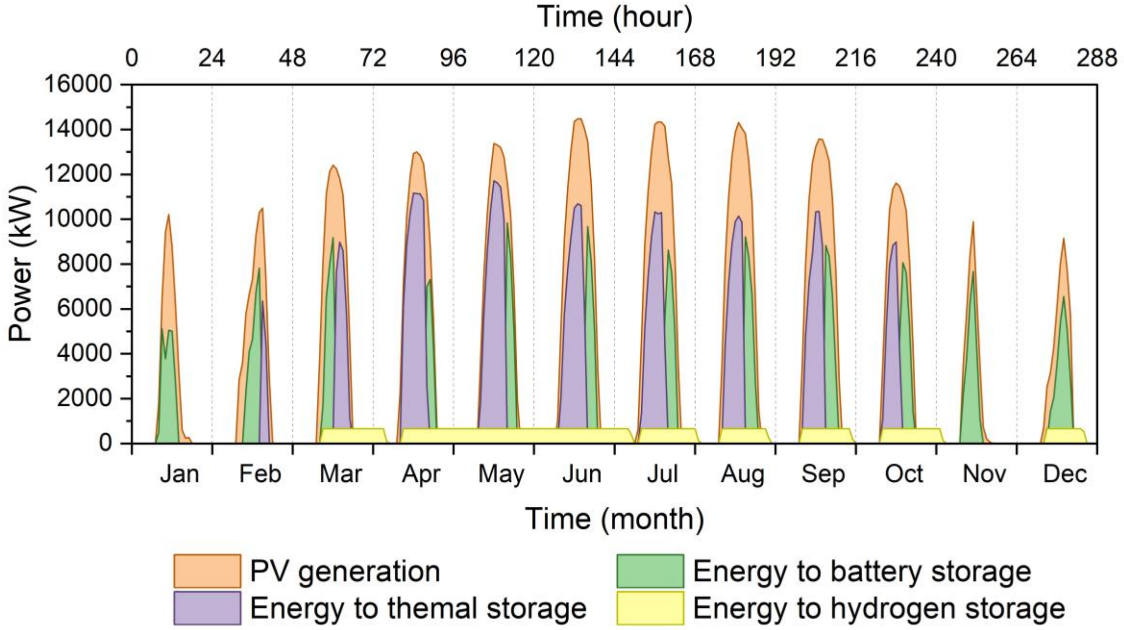

Figure 5 Generated energy flow into the different storage types

A clearer understanding is provided by the state of charge (SOC) dynamics of the different energy storage systems, as shown in Figure 6. The battery storage exhibits sharp daily charge and discharge cycles, with its SOC frequently rising to near full capacity and then quickly dropping, reflecting its role as a short-term or intraday buffer that responds to daily fluctuations in solar production and demand. In contrast, the hydrogen storage demonstrates a slow, cumulative charging pattern from January through August, followed by a gradual discharge towards the end of the year. This behavior confirms hydrogen's suitability as a seasonal storage medium, effectively capturing excess energy over long periods and discharging when renewable input or other resources are insufficient. The thermal energy storage shows a hybrid pattern: it experiences both shorter-term fluctuations and a noticeable seasonal cycle. The SOC decreases steadily through the colder months—indicating frequent use for heating—and accumulates over spring and summer, when heating demand is low, peaking around September. This pattern suggests TES serves both as a short-term buffer and a seasonal storage component, balancing heating needs across timescales. Overall, the SOC trends highlight the complementary roles of each storage type—battery for daily balancing, hydrogen for long-term seasonal storage, and TES for both intraday and seasonal heat demand management—underscoring the strength of a hybrid storage approach in optimizing energy resilience and flexibility.

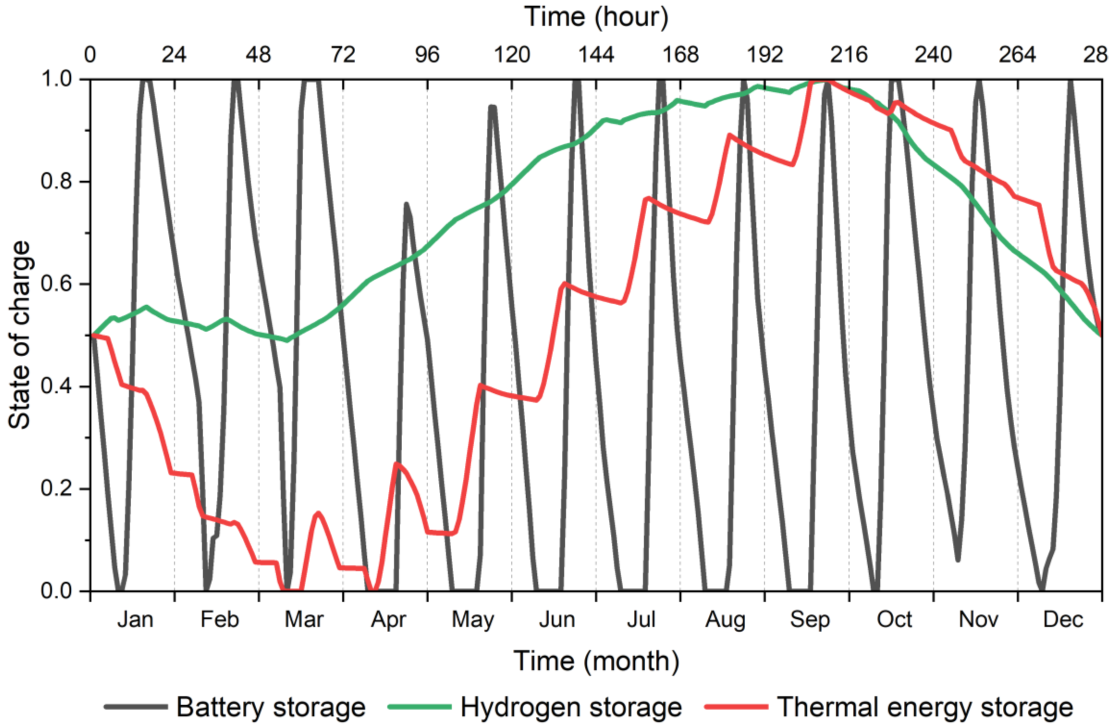

Figure 6. State of charge profiles of the different energy storage systems.

Interpretation of the results (up to 400 words)

Conclusions

This work provides a detailed evaluation of the performance of a hybrid energy storage system designed to meet complex energy needs (electricity, heating, and hydrogen) for standalone microgrids. A generic optimization framework was developed and applied to the University of Cyprus as a case study. By optimizing system design and component sizing, the results demonstrate how multiple storage technologies can be integrated effectively to enhance operational flexibility, accommodate renewable variability, and achieve cost-effectiveness. Based on the results obtained, the following key conclusions can be made:

- Solar PV (14,479 kWp) served as the system's primary energy source, covering most of the energy supply.
- Battery storage (27,008 kWh) provided short-term balancing and daily load-shifting capacity.
- Thermal energy storage (250,925 kWh) addressed both daily heating needs and seasonal thermal energy requirements.
- Hydrogen storage (727 kWh) enabled long-term energy shifting and maintained low standby losses.
- Interaction between storage systems was observed, such as hydrogen charging during non-PV production hours, enhancing flexibility.
- The system achieved an annualized cost of 5.94 million USD with an LCOE of 0.218 USD/kWh, indicating economic viability.

The study highlights the technical and economic advantages of combining battery, thermal, and hydrogen storage in a hybrid system. Tailoring each storage type to specific temporal demands ensures efficient resource utilization and energy security. These findings support the broader implementation of hybrid energy storage systems in standalone microgrids aiming for sector-wide energy independence.

Limitations

Despite the comprehensive nature of this work, several limitations should be acknowledged:

- Hydrogen demand was estimated based on projections rather than measured data.
- Only weekday data were used in simulations, excluding weekends and holidays, which may lead to oversized capacities.
- Initial and final SOC values for all storage systems were fixed at 50%.
- Component degradation was not modeled; a simplified replacement approach was adopted.
- Although the developed optimization framework is generic, the analysis was conducted using a university-specific demand profile; thus, outcomes may vary for residential, commercial, or industrial applications.

Main achievements during the TA related work (up to 250 words)

During the research stay at University of Cyprus, a comprehensive optimization framework for hybrid energy storage in standalone microgrids was successfully developed and applied to the University as a case study. The framework integrates solar photovoltaics with battery, thermal, and hydrogen storage to meet multi-energy demands while minimizing system costs.

Key achievements

- Development and implementation of a generic energy optimization model for multi-storage microgrids.
- Integration of real solar and demand data to reflect realistic operating conditions.
- Optimal sizing and operation of diverse storage technologies tailored to temporal energy needs.
- Demonstration of the benefits of a hybrid storage approach in enhancing flexibility, reliability, and energy autonomy.

Publications

Following discussions with the host institution, it was agreed that the outcomes of this TA may be used for future scientific publications—either journal articles or conference papers, to be decided at a later stage.

Future collaboration

This TA opportunity has also laid the groundwork for a stronger potential collaboration between the University of Cyprus and Khalifa University, with plans underway to organize a joint meeting to explore further opportunities for research collaboration.

Potential impact

As the University of Cyprus already meets a significant share of its energy needs through photovoltaics, the outcomes of this TA will support future decision-making aimed at achieving full reliance on renewable energy sources.

Data Management

All data generated and used in the project will be backed up on both cloud storage and an external hard drive. Asem Alemam, the user member, is responsible for managing and maintaining the data.

Data includes:
- Codes (optimization and solar scenarios generation)
- Results (optimized capacities, energy flows, cost results, graphical plots)
- Input datasets (solar irradiance, demand profiles)
  Model parameters (technical and economic specifications)

Difficulties during the TA related work (up to 250 words)

No technical challenges were encountered. The only difficulty was the tight timeline of the proposed tasks, which was ultimately the user's responsibility.

Intended publications

The outcomes of the project are expected to be published in peer-reviewed journals or presented at relevant scientific conferences. A discussion with the host institute confirmed that the results may be jointly used for future publications. No outputs have been published yet.

If the contributors decide to submit the project outcomes to a journal or conference, RISEnergy will be notified in advance.

Expected impact

The results of this project are expected to contribute significantly to advancing hybrid energy storage solutions for standalone microgrids, promoting energy independence and sustainable growth. The developed optimization framework can support future research and practical applications targeting sector-wide decarbonization. The collaboration between Khalifa University and the University of Cyprus lays the foundation for further joint proposals and research initiatives. Outcomes may inform institutional decisions, enhance competitiveness in renewable integration, and align with broader European sustainability and cohesion goals.

Conclusions / additional comments

No further comments. The user extends sincere thanks to the host for their support and warm hospitality.

Did you complete the European Commission User questionnaire https://ec.europa.eu/eusurvey/runner/RIsurveyUSERS?

☒ Yes ☐ No

Feedback – HSE, Ethics and Satisfaction

Please rate on a scale from 1 (excellent) to 5 (poor). Feel free to provide additional comments

Practical information on how to apply for Transnational Access and the overall application process	1 (excellent)	2	3 (neutral)	4	5 (poor)

	☐ ☒ ☐ ☐ ☐
Comment	
Information provided, once your project was accepted, on how to proceed	1 (excellent) ☒ 2 ☐ 3 (neutral) ☐ 4 ☐ 5 (poor) ☐
Comment	
Support received at the site(s) regarding technical/scientific matters and logistics	Have you got sufficient support from the RI staff during the project? If not, please, specify the problems. ☒ Yes ☐ No
Please specify any problems	
RI extension / upgrades required	In your opinion, is the RI needed to be upgraded? If yes, please give an explanation. ☐ Yes ☒ No
Please specify	
Problems with local regulations	Have you had any problems with regulations of the visited RI owner (HSE, lab working hours, etc.)? If yes, please, specify ☐ Yes ☒ No
Please specify	
Health and safety issues	Did you encounter any health or safety issue during your research? Please provide details. ☐ Yes ☒ No
Please provide details	
Environment & Ethics	Did your research involve the use of elements that may cause harm to the environment, to animals or plants? Please provide details. ☐ Yes ☒ No
Please provide details	
Environment & Ethics	Did your research deal with endangered fauna and/or flora and/or protected areas? Please provide details. ☐ Yes ☒ No
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☐ Yes ☒ No</td></tr>
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<tr><td>Environment & Ethics – Dual use</td><td>Does your research have the potential for military applications? Please provide details.
☐ Yes ☒ No</td></tr>
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<tr><td>Environment & Ethics – Misuse</td><td>Does your research have the potential for malevolent /criminal/terrorist abuse? Please provide details.
☐ Yes ☒ No</td></tr>
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<tr><td>Environmental issues</td><td>Were any potentially dangerous substances (materials / gases etc.) released into the environment (atmosphere, water, or land)? Please provide details.
☐ Yes ☒ No</td></tr>
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<tr><td colspan="2">Suggestions for facilities not included in RISEnergy which you would use for your research</td></tr>
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☐ Yes ☒ No</td></tr>
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<tr><td>Personal experience</td><td>Have you taken advantage of or benefited from the pro-active innovation support?
☐ Yes ☒ No</td></tr>
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I declare that the above provided information and especially that information on the number of days visited the RI is correct.

☒ I have read the RISEnergy privacy policy for participation in the RISEnergy TA and consent to participation and the associated data processing.

Your full name:

Your signature: