



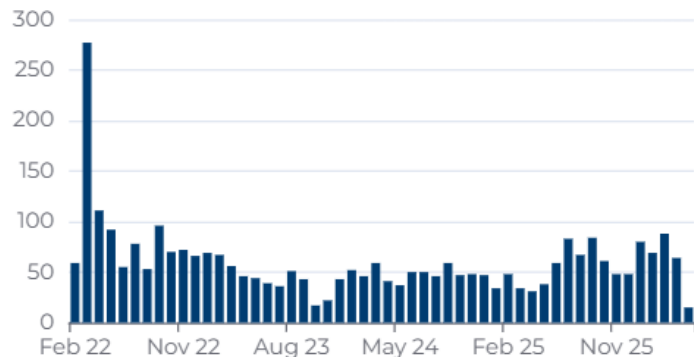
CLUSTER MODELING OF HYBRID HOSPITAL ENERGY SYSTEMS: RESILIENCE ASSESSMENT UNDER WARTIME CONDITIONS

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National Academy of Sciences of Ukraine

Background and Motivation

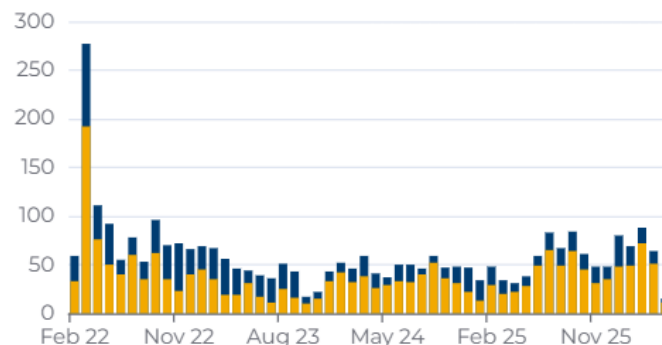
3095 total attacks on health care



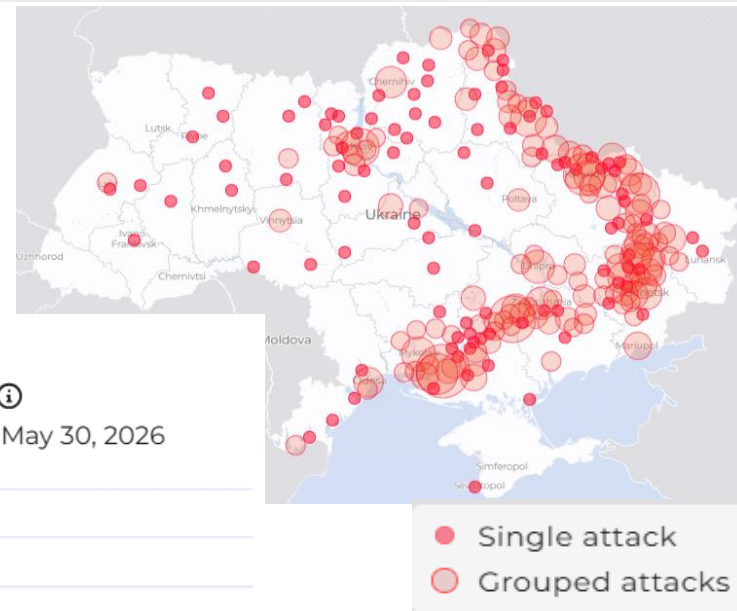
1632 attacks damaged or destroyed hospitals
462 health workers killed
476 health workers injured

2016 of 3095 attacks

damaged health infrastructure ⓘ
between February 24, 2022 and May 30, 2026



1632 attacks damaged or destroyed hospitals
77 health workers killed
308 health workers injured



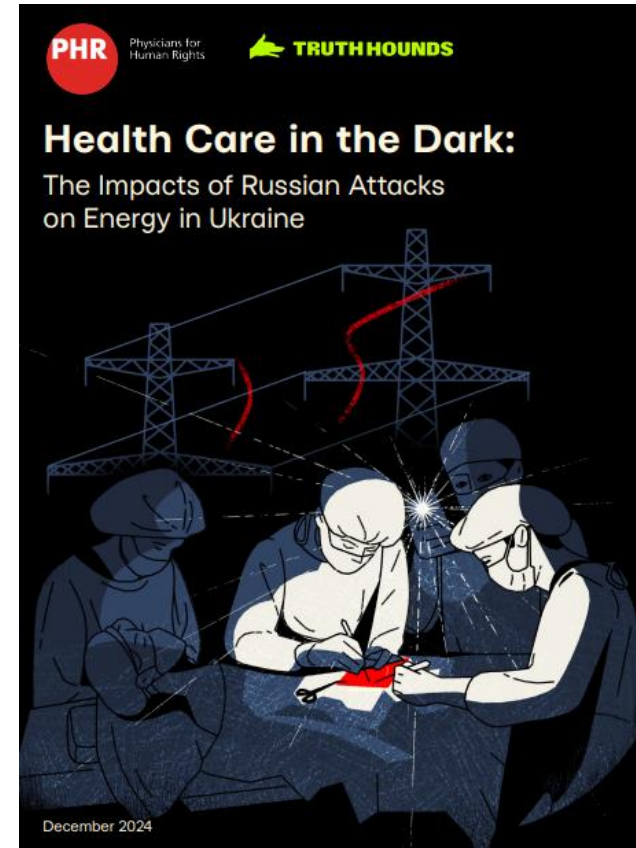
This map is a joint undertaking:

1. eyeWitness to Atrocities (eyeWitness),
2. Insecurity Insight,
3. Media Initiative for Human Rights (MIHR),
4. Physicians for Human Rights (PHR)
5. Truth Hounds,
6. Ukrainian Healthcare Center (UHC).

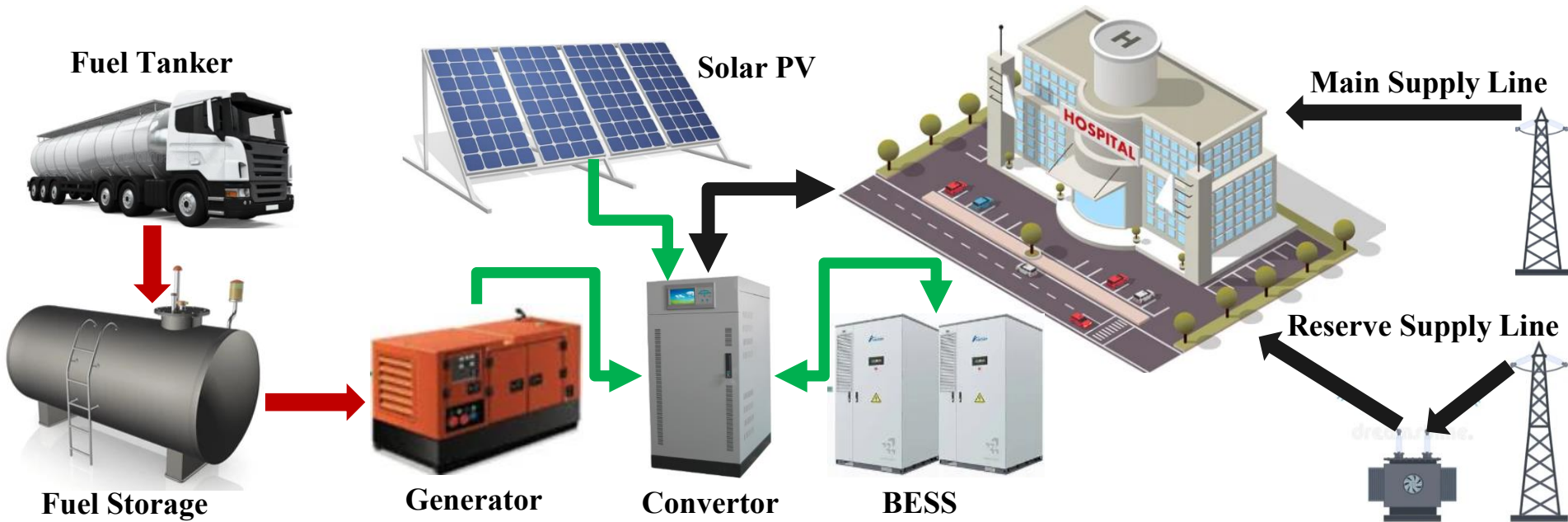
<https://www.attacksonehealthukraine.org/>

Background and Motivation

- Devastating consequences of Russian attacks on energy for Ukrainian healthcare institutions.
- Mismatch between existing hospital energy supply systems and wartime conditions.
- Absence of adequate resilience assessment models for hospital power supply systems.



Hospital Energy Supply Systems



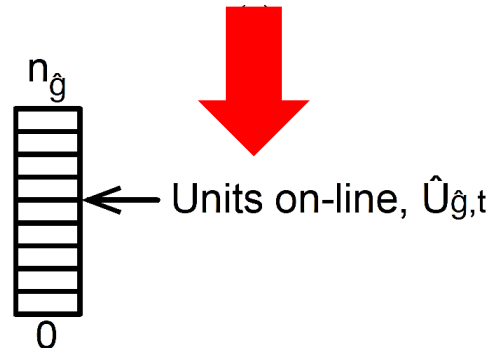
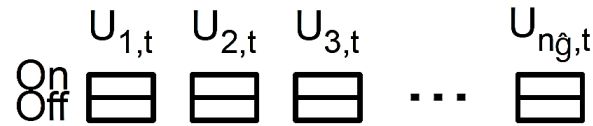


Challenges in Assessing the Resilience of Hospital Energy Supply Systems

- **Additional costs** arising from unmet electricity demand and the need to compensate for shortages.
- **Adaptation to varying outage scenarios**, including both short-term interruptions and prolonged disconnections, each with different impacts on system resilience.
- **Logistical constraints in fuel supply and load management**, which determine the feasibility of using backup energy sources.

Cluster Model of Energy Systems: MILP Problem

Boolean state variables for power units



Integer state variables for power units

Cluster Model of Energy Systems: MILP Problem

S. Saukh, A. Borysenko,

Clustered MILP models for resilience assessment of power system

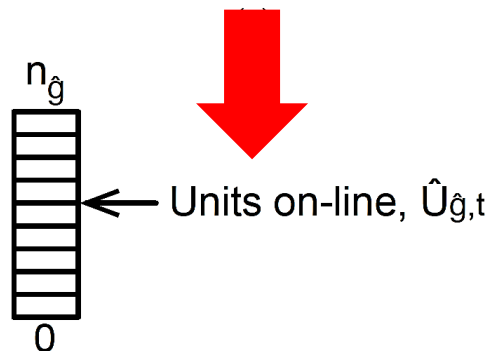
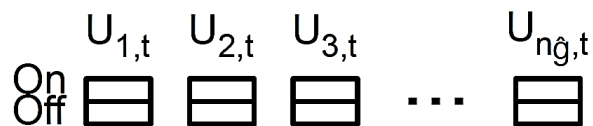
operating under systematic terrorist attacks, Energy Reports, Volume 15, 2026,

MILP Performance Comparison: Traditional vs Clustered EPS Models (results obtained for 2024).

Quarter	Solve Time (s)	Solve Time Reduction (%)	Objective function value ($\times 10^{10}$)	Objective Gap (%)
	Traditional → Clustered		Traditional → Clustered	
Q1	4029.84 → 774.63	80.8 %	2,38846 → 2,38578	0.112 %
Q2	328.55 → 48.78	85.2 %	3,15978 → 3,15696	0.089 %
Q3	45.97 → 15.72	65.8 %	4,66330 → 4,66144	0.040 %
Q4	78.13 → 17.11	78.1 %	2,55505 → 2,55483	0.009 %

Cluster Model of Energy Systems: MILP Problem

Boolean state variables for power units



Integer state variables for power units

- 1). The balance equation of quantities of generators in the start-up, load and stop modes

$$y_t - x_t = u_t - u_{t-1}, \quad t > 1$$

- 2). Upper limit of the total number of generators in the start-up and stop modes

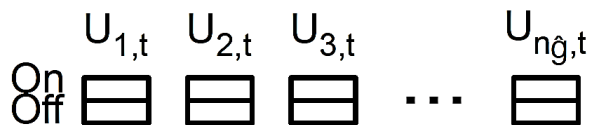
$$y_t + x_t \leq |F|$$

- 3). Upper limit of the number of generators operating in load mode

$$u_t \leq |F|$$

Cluster Model of Energy Systems: MILP Problem

Boolean state variables for power units 4). Operating costs for generators in load mode



$$C_t = \left(\bar{c} u_t + \sum_{\omega \in \Omega} \tilde{c}_{\omega} \cdot \tilde{p}_{\omega,t} \right) \partial t$$

5). The upper limit of the variable part of the load of generators that are in the load mode

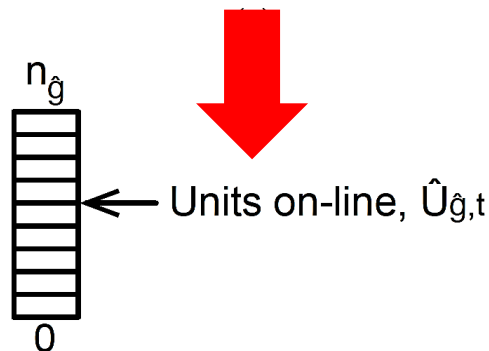
$$\tilde{p}_{\omega,t} \leq \Delta P \cdot u_t$$

6). Upper limit on the generator load in a load mode

$$p_t \leq \bar{P} \cdot u_t$$

7). Lower limit on the generator load in a load mode

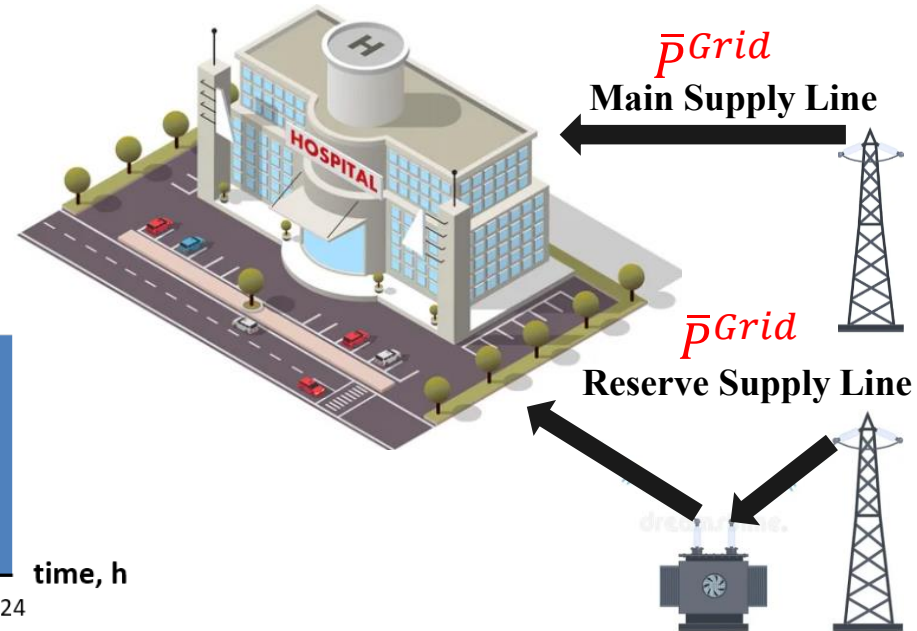
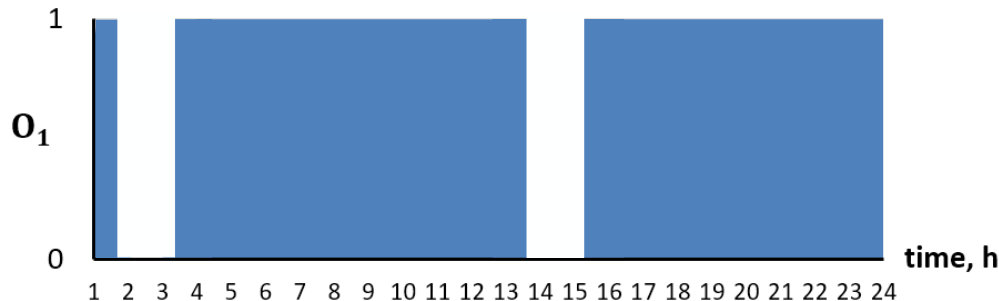
$$p_t \geq \underline{P} \cdot u_t$$



Integer state variables for power units

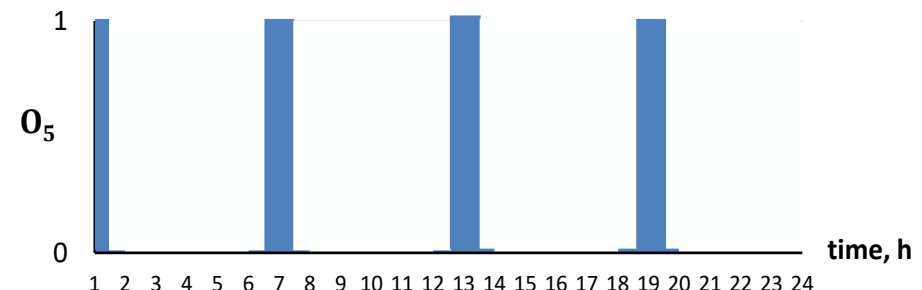
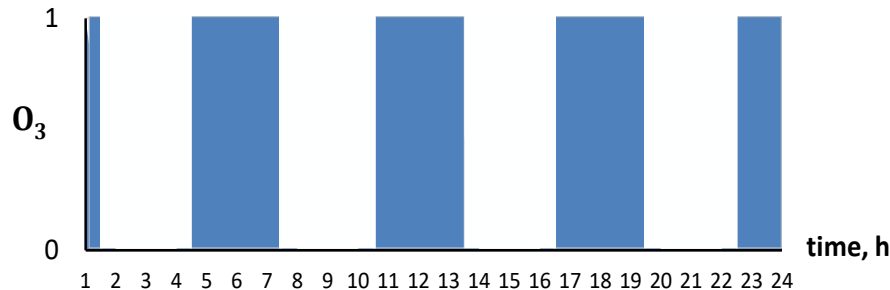
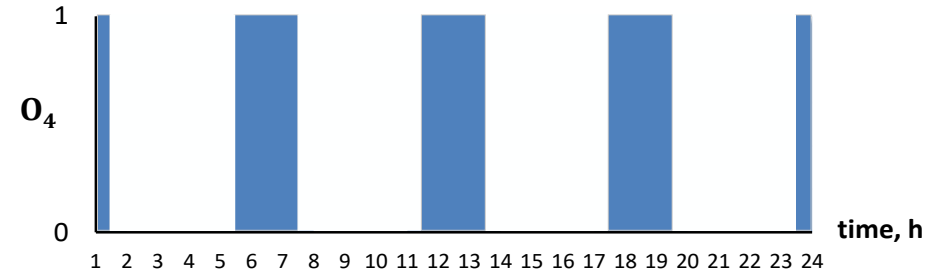
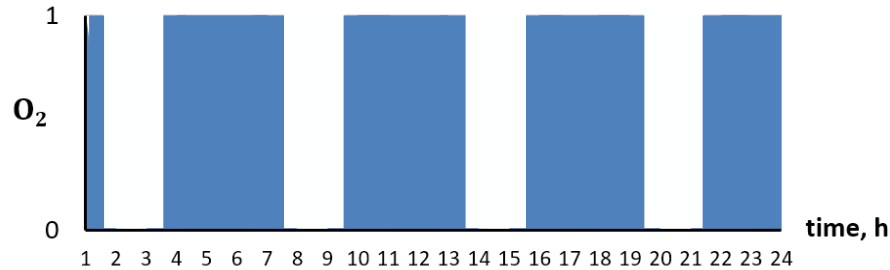
Cluster Model of Hospital Hybrid Energy Systems: Outage Scenarios

$$p^{Grid} \leq O_V \left(\Delta T \left\{ \frac{t}{\Delta T} \right\} \right) \bar{p}^{Grid}$$





Cluster Model of Hospital Hybrid Energy Systems: Outage Scenarios



Cluster Model of Hospital Hybrid Energy Systems: Critical Loads

Uninterrupted supply to essential areas and equipment

$$0 \leq \Delta l_t \leq l_t - l_t^{Critical}$$



Cluster Model of Hospital Hybrid Energy Systems: Cost on Unloading

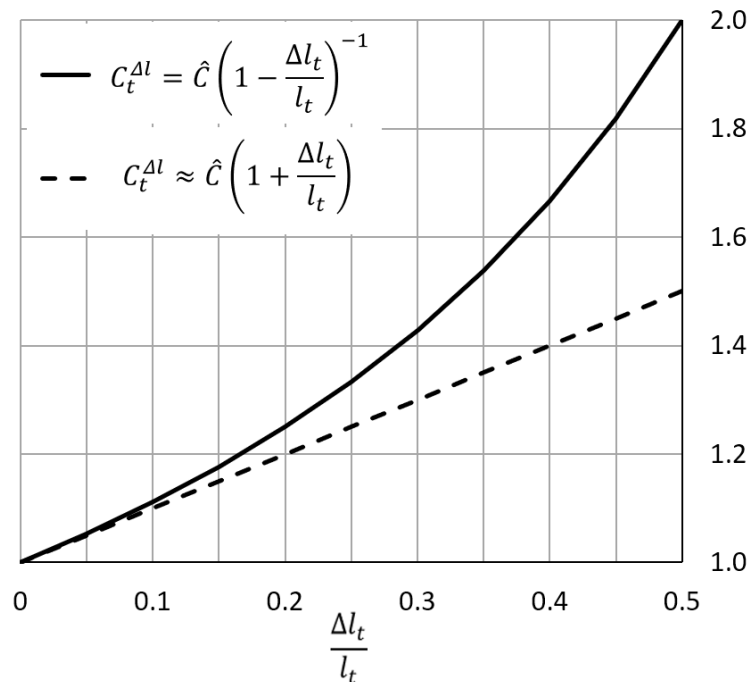
Estimating residential outage costs under inclining block electricity rates in China

Kang H. C., Cheng Y.-S., Qi H.S., Woo C.-K. (2025, November).

$$c_t^{Al} = \hat{c} \left(1 - \frac{\Delta l_t}{l_t} \right)^{-1}$$

Modeling tasks formulated as a MINLP problem

$$\sum_{t \in T} c_t^{Al} \Delta l_t + \sum_{t \in T} (C_t + C_t^{SU} + C_t^{SD}) \rightarrow \min$$



Cluster Model of Hospital Hybrid Energy Systems: Fuel Balance and Supply Requirements

Fuel Balance

$$F_t^S - F_{t-1}^S = F_t^D - F_t^C$$

Requirements for fuel reservation

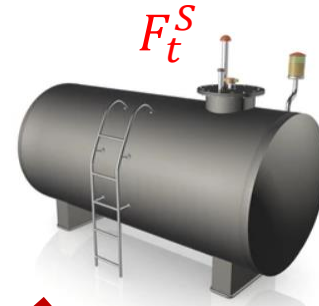
$$F_{min}^S \leq F_t^S \leq F_{max}^S$$

Logistical constraints on fuel supply volumes

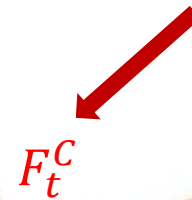
$$\sum_{t \in \Delta D} F_t^D \leq F_{max}^D \quad \forall \Delta D \in T$$



Fuel Tanker



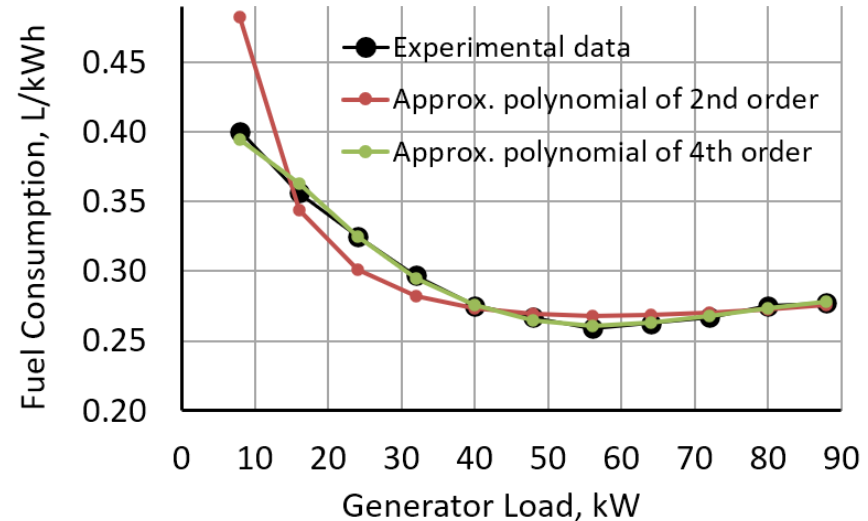
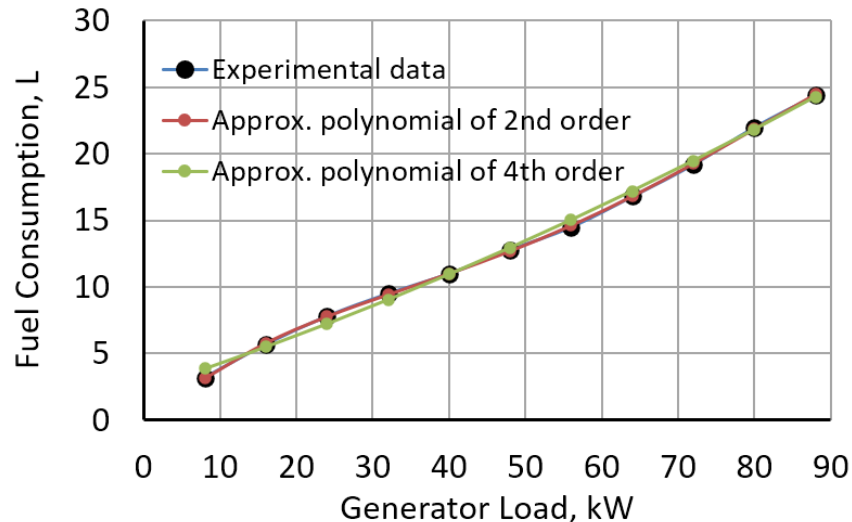
Fuel Storage



Generators



Cluster Model of Hospital Hybrid Energy Systems: Approximating Generator Cost Characteristics



Cluster Model of Hospital Hybrid Energy Systems: Piecewise-Linear Approximation of Generator Cost Char.

$$\sum_{t \in T} C_t^{\Delta l} \Delta l_t + \sum_{t \in T} (\mathbf{C}_t + C_t^{SU} + C_t^{SD}) \rightarrow \min$$

$$\mathbf{C}_t = \left(\bar{C} u_t + \sum_{\omega \in \Omega} \tilde{C}_\omega \cdot \tilde{p}_{\omega,t} \right) \partial t$$

$$\tilde{p}_{\omega,t} \leq \Delta P u_t$$

$$p_t = \underline{P} u_t + \sum_{\omega \in \Omega} \tilde{p}_{\omega,t}$$

Parameters of linear functions:

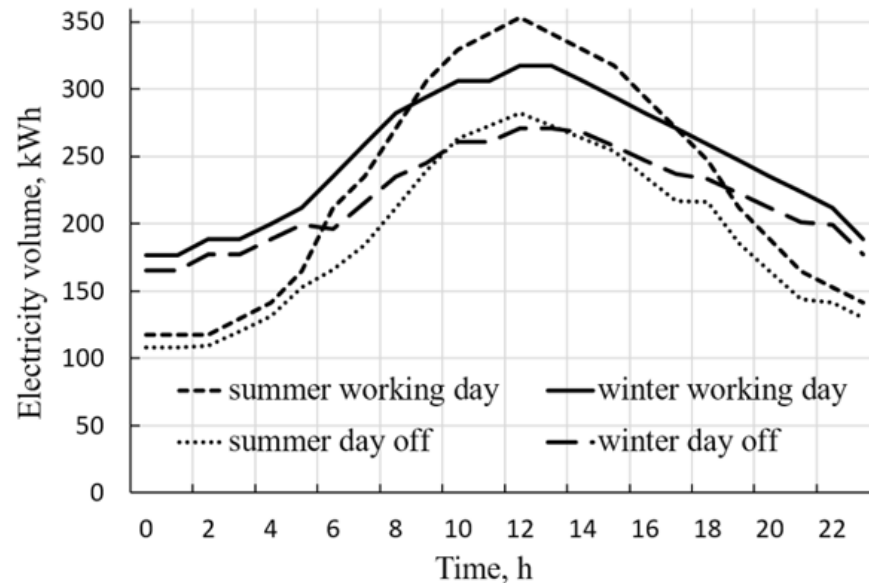
$$\bar{C} = \left(\left((a_4 \underline{P} + a_3) \underline{P} + a_2 \right) \underline{P} + a_1 \right) \underline{P} + a_0$$

$$\tilde{C}_\omega = ((4a_4 \mu_\omega + 3a_3) \mu_\omega + 2a_2) \mu_\omega + a_1$$

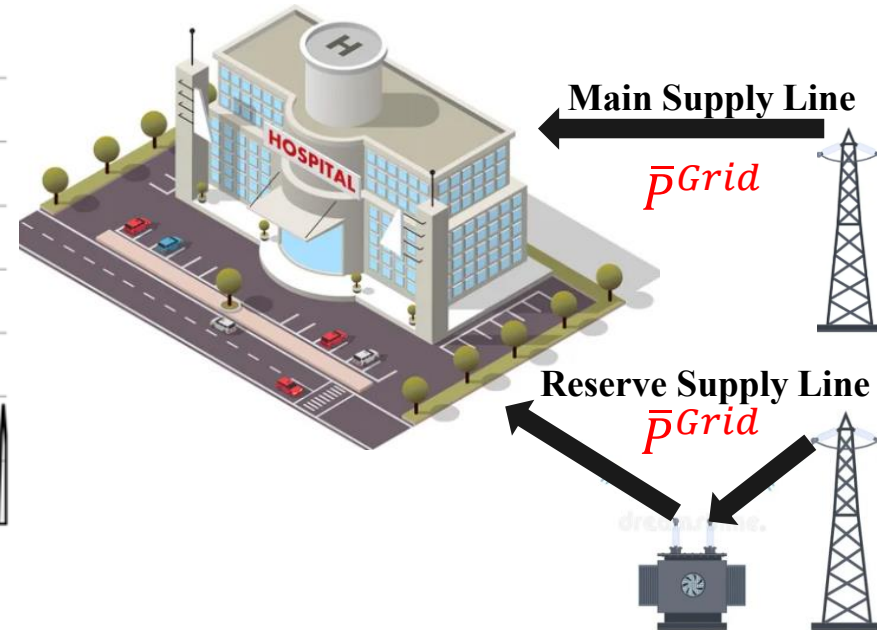
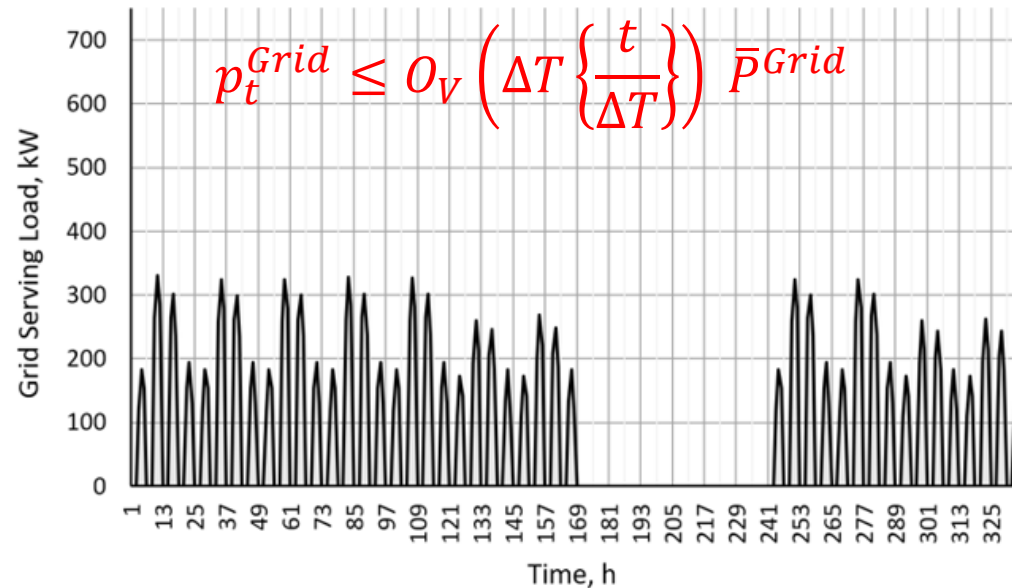
$$\mu_\omega = \underline{P} + \left(\omega - \frac{1}{2} \right) \Delta P$$

$$\omega \in \Omega, \quad \Delta P = (\bar{P} - \underline{P}) / |\Omega|$$

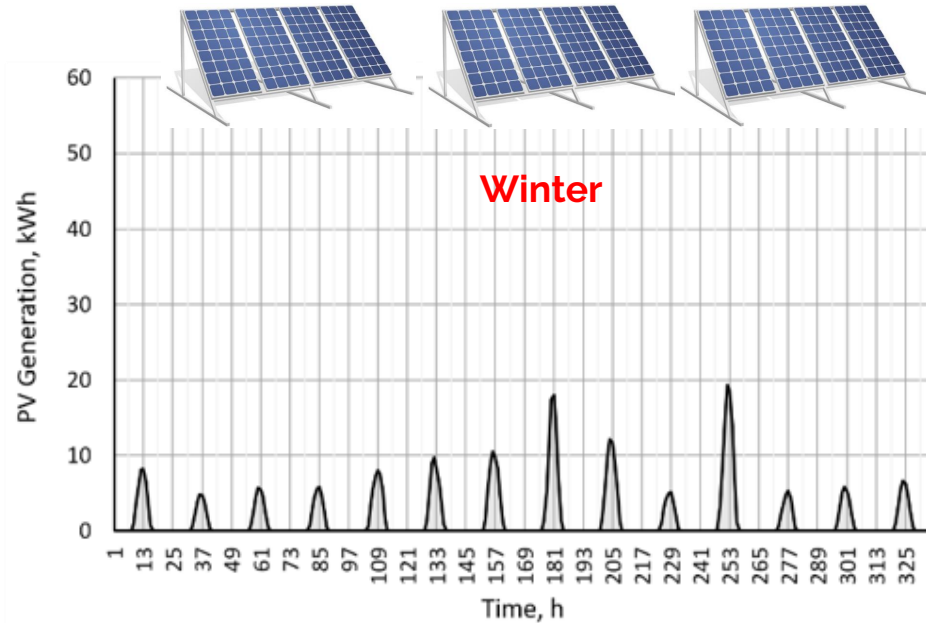
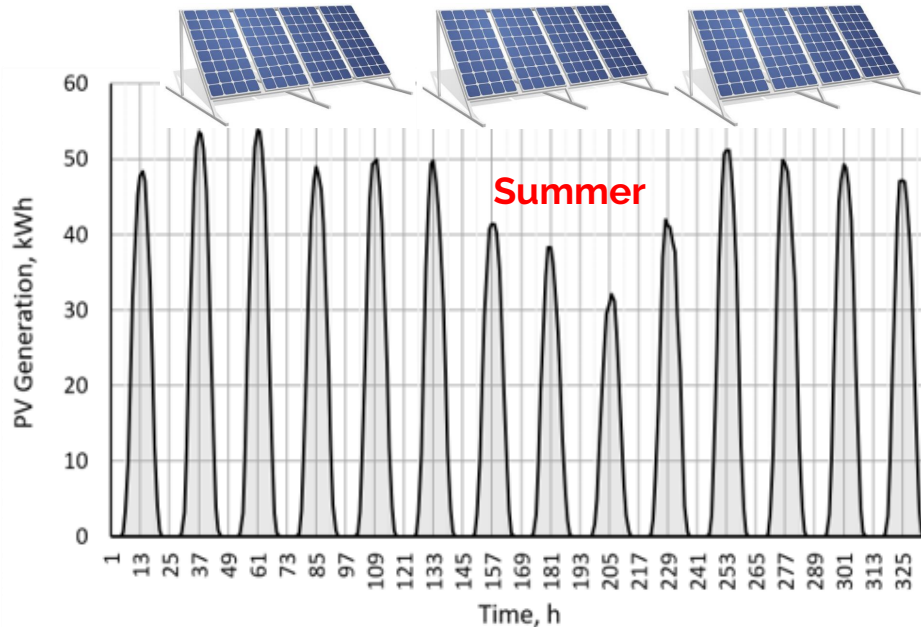
Cluster Model of Hospital Hybrid Energy Systems: Results of Load Regime Modeling



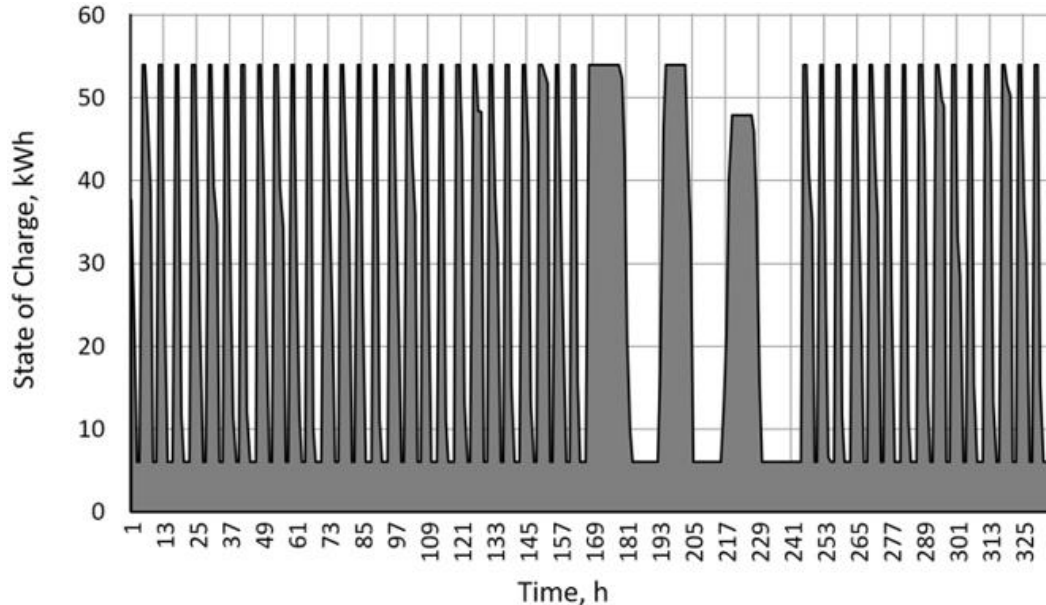
Cluster Model of Hospital Hybrid Energy Systems: Results of Grid Serving Load Regime Modeling



Cluster Model of Hospital Hybrid Energy Systems: Results of Solar PV Load Regime Modeling



Cluster Model of Hospital Hybrid Energy Systems: Results of BESS Regime Modeling

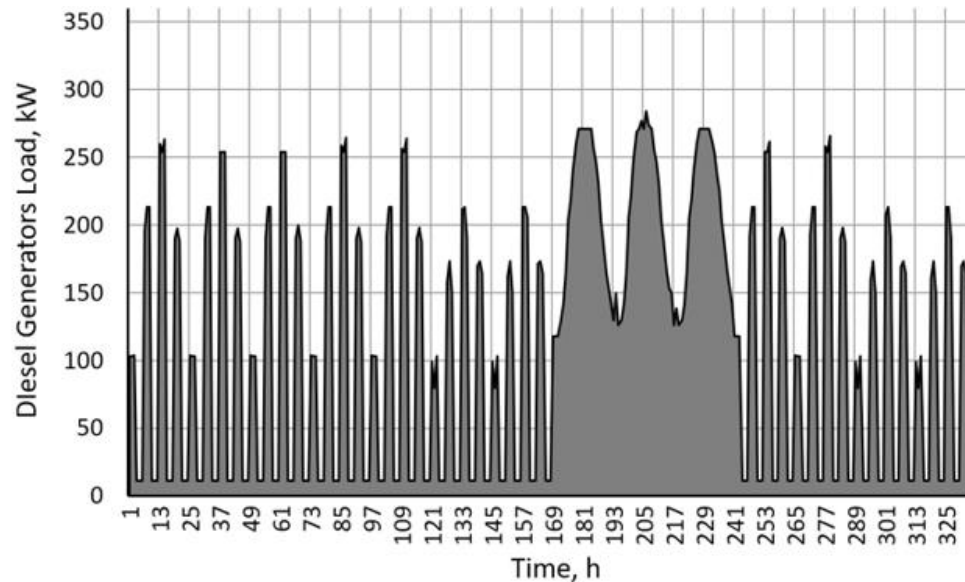


60 kWh



BESS

Cluster Model of Hospital Hybrid Energy Systems: Results of Generators Load Regime Modeling



2 x 88 kW

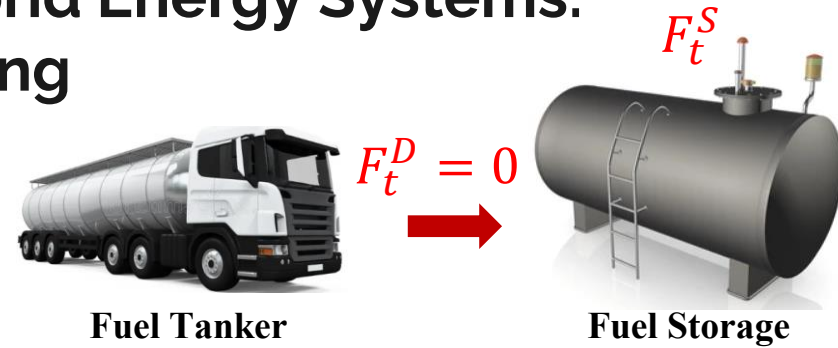
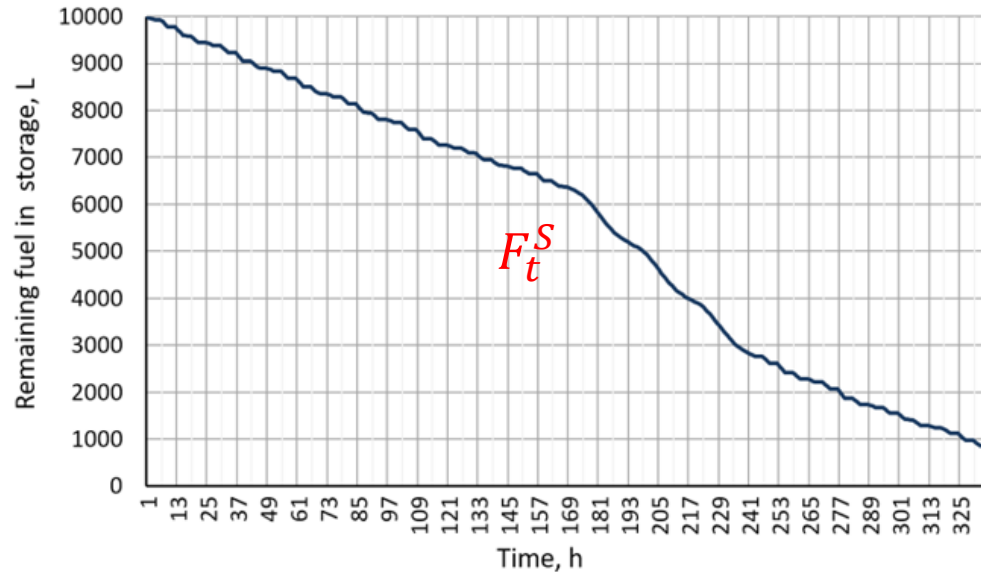


2 x 120 kW



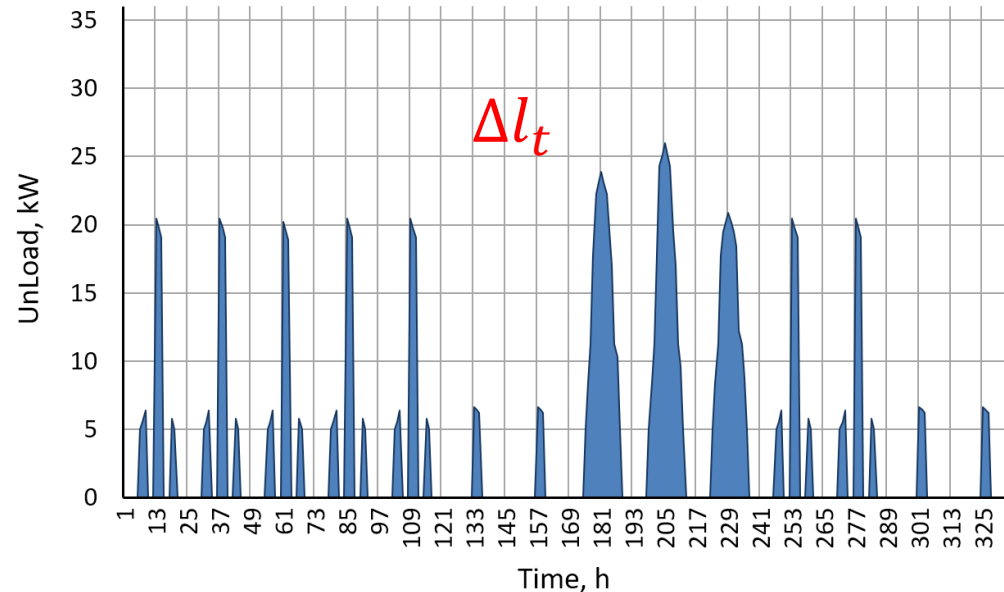
Generators

Cluster Model of Hospital Hybrid Energy Systems: Results of Fuel Supply Modeling



Cluster Model of Hospital Hybrid Energy Systems: Results of Unload Regime Modeling

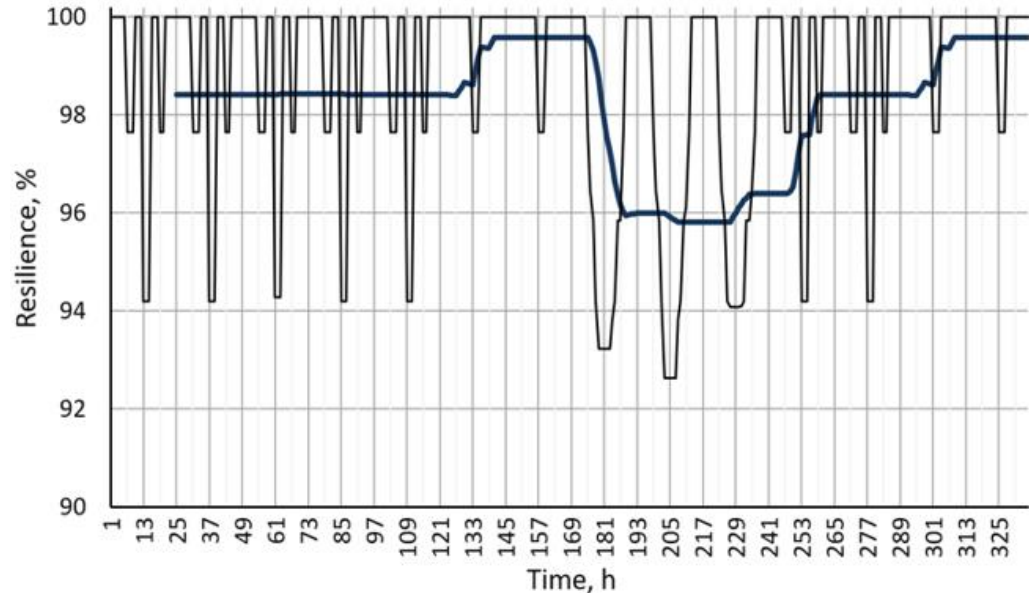
Cardiac Operations During Blackout at the Heart Institute, Kyiv



<https://heart.kyiv.ua/operacziyi-u-temryavi-v-instituti-serczya/>

Resilience Analysis of Hospital Hybrid Energy Systems:

$$\mathbb{R}_{t,\Delta T} = \sum_{t-\Delta T}^t (l_t - \Delta l_t) / \sum_{t-\Delta T}^t l_t, \quad t > \Delta T$$





Conclusions

- A cluster model of hybrid hospital energy systems (HHES) was developed to assess resilience under wartime conditions.
- The model incorporates scheduled and emergency outages, reduced BESS efficiency at extreme temperatures, and fuel supply constraints.
- Key innovations:
 - Representation of both outage types for realistic hospital load regimes.
 - Simplified cost–demand dependence enabling mixed integer quadratic programming.
 - Refined diesel fuel modeling with higher-order polynomials and piecewise linear approximation.
- Simulations show large-scale BESS integration cuts diesel use by ~50% during scheduled outages and ~30% during prolonged emergencies.
- Energy storage during grid connection significantly enhances hospital resilience.
- The model serves as both a quantitative assessment tool and a methodological basis for crisis energy management solutions.



Q&A

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