IEA Technology Collaboration Programme

International Energy Agency
Technology Collaboration Programme on Energy Storage
(ES TCP)

# Task 37
# Smart Design and Control of Energy Storage Systems
# Executive Summary

SMART
TASK37

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Task Manager ES TCP Task 37:
Ryozo Ooka
The University of Tokyo
Japan

# AUTHORS


Ryozo Ooka, Institute of Industrial Science, The University of Tokyo

Fuzhan Nasiri, Concordia University

Ruchi Chaudhary, Cambridge University

Max Langtry, Cambridge University

Frederic Kuznik, INSA Lyon

Christian Obrecht, INSA Lyon

Alireza Afshari, Aalborg University

Alessandro Maccarini, Aalborg University

Samira Rahnama, Aalborg University

Parham Ahranjani Mirzaei, Aarhus University

Enrico Fabrizio, Politecnico di Trino

Maria Ferara, Politecnico di Trino

Mariagrazia Dotoli, Politecnico di Bari

Raffaele Carli, Politecnico di Bari

Fariborz Haghighat, Concordia University

Ken Takahashi, The University of Tokyo

Doyun Lee, The Korea Institute of Machinery and Materials

# CONTENT

# KEY MESSAGES AND POLICY RECOMMENDATIONS

The goal of this Task is to design, integrate, control, and optimize energy storage systems (ESS) across various scales, from buildings to power grids. This involves developing methods, optimization, and advanced control strategies to predict, evaluate, and improve ESS performance. This comprehensive review includes six subtasks, each providing essential insights for effective ESS deployment.

**Key Messages**

Task 37 of the IEA Energy Storage Technology Collaboration Programme (ES TCP) was established to deliver practical methods and tools for the smart design and control of energy storage systems (ESS), ranging from buildings to grid-level integration. The ultimate goal is to enable widespread, efficient deployment of ESS that improves energy system resilience, reduces operational costs, enhances integration of renewables, and supports decarbonization objectives.

This Task has produced a coordinated body of research, frameworks, and case studies that together offer new insights and actionable strategies for both technical stakeholders and policymakers. Outputs include a suite of design methodologies, performance benchmarking tools, control strategies, and modeling approaches—many of which leverage advanced technologies such as AI, IoT, and data-driven analytics. These outputs are intended for engineers, researchers, building designers, energy system operators, and policy advisors, and will be disseminated through this final report, peer-reviewed publications, and future annexes or collaborative projects within the ES TCP network.

The key achievements and new contributions of Task 37 are summarized below:

**1. Smart Data Analytics and IT Integration (Subtask 0)**

**What's new:** Developed a classification of predictive analytics specific to ESS, and established frameworks for integrating IoT, BMS, and BIM to support smarter control and lifecycle management.
**Expected benefits:** Improved system efficiency, more reliable performance predictions, and extended lifetime of ESS through enhanced monitoring and control.

**2. Forecasting Models for Control (Subtask A)**

**What's new:** Introduced cost-effective Direct Multi-Step (DMS) forecasting models that match more complex alternatives and demonstrated the practical application of Transfer Learning for ESS control.
**Expected benefits:** Reduced data collection costs and improved forecasting accuracy for operational decisions, leading to better grid integration and energy savings.

**3. Machine Learning for ESS Modeling (Subtask B)**

**What's new:** Highlighted the untapped potential of advanced machine learning—particularly Artificial Neural Networks—in modeling complex, nonlinear ESS behavior, including underexplored technologies like sorption storage.
**Expected benefits:** Faster, more flexible modeling for system designers and control engineers, supporting real-time diagnostics and adaptive control strategies.

### 4. Smart Design Methodology (Subtask C)

**What's new:** Delivered a comprehensive seven-step methodology for designing thermal energy storage (TES) systems, validated through multiple international case studies.
**Expected benefits:** Improved alignment between system design and application needs, resulting in optimized energy use and better return on investment.

### 5. AI-Based Control Systems (Subtask D)

**What's new:** Demonstrated the effectiveness of AI-driven predictive control systems in real-world settings, enhancing system responsiveness and user comfort during power disruptions.
**Expected benefits:** Higher system reliability, lower carbon footprints, and improved energy resilience in buildings and districts.

### 6. Cooperative Control at District/Grid Scale (Subtask E)

**What's new:** Provided a detailed typology of ESS control architectures and identified strategies for stabilizing microgrids and enhancing real-time grid responsiveness.
**Expected benefits:** Better integration of distributed storage, improved grid stability, and reduced vulnerability to outages or supply-demand imbalances.

## Policy Recommendations

In light of the findings from Task 37, several policy directions are recommended to support the effective deployment of smart energy storage systems across buildings, districts, and power grids. These recommendations aim to inform policymakers on enabling frameworks that can foster innovation, improve resilience, and advance energy sustainability.

To begin with, the integration of digital technologies—such as the Internet of Things (IoT), Artificial Intelligence (AI), and Building Information Modeling (BIM)—into energy storage systems should be a key focus of energy policy. Public investment and regulatory support can help accelerate the deployment of these technologies, ensuring better management, monitoring, and control of energy systems.

Furthermore, policymakers are encouraged to support data-sharing initiatives and the development of standardized frameworks that facilitate interoperability among energy systems. Such efforts will enhance forecasting and operational control, particularly when existing data and models can be reused through techniques like Transfer Learning. Reducing barriers to data access will enable broader use of forecasting tools that can optimize energy storage performance while minimizing implementation costs.

In the area of system design, policy should promote adaptive approaches that consider the diversity of buildings and energy infrastructures. Incentives for customized, application-specific design—especially in retrofitting existing buildings—can lead to more efficient and resilient energy systems. Supporting pilot projects and demonstration cases of advanced thermal energy storage (TES) design methods can serve as valuable benchmarks for wider adoption.

To optimize the operation of energy storage, investment in AI-based control systems should be encouraged. These systems are critical in increasing energy resilience, especially in the face of growing disruptions linked to climate change and energy demand fluctuations. Policymakers can play a crucial role by supporting research, establishing guidelines, and creating market incentives for resilient energy infrastructure that integrates smart storage solutions.

Lastly, as power grids evolve into more dynamic and decentralized systems, real-time control, protection mechanisms, and cybersecurity become essential. Policymakers should prioritize the development and deployment of quick protection devices and smart grid technologies, which are instrumental for ensuring stability and preventing system vulnerabilities. Cross-sector collaboration—between government, academia, and industry—will be key to realizing these advancements.

By adopting these policy directions, governments can help unlock the full potential of energy storage technologies, advancing climate goals, energy equity, and long-term system reliability.

General Recommendations for Deployment

1. Invest in Advanced Technologies:

    Prioritize IoT, AI, and ML integration in ESS for enhanced performance.

2. Customize Solutions:

    Tailor methodologies and models to specific applications and buildings.

3. Enhance Resilience and Stability:

    Focus on predictive and real-time control systems for improved resilience.

4. Collaborate and Share Data:

    Use Transfer Learning and collaborative approaches to minimize costs and leverage existing knowledge.

By implementing these recommendations, stakeholders can effectively design, optimize, and control energy storage systems, leading to more sustainable and efficient energy management across various scales.

# MAIN RESULTS IN A NUTSHELL

The general objective of this task is to address the design, integration, control, and optimization of energy storage systems (ESS) within buildings, districts, power grids, and local utilities. The focus is on developing advanced design methods, optimization techniques, and control strategies to effectively predict, evaluate, and improve the performance of buildings and districts when energy storage is available. This task consists of six subtasks, each providing critical insights for the deployment of energy storage solutions. Here are the main results and conclusions for each subtask.

1. Data Analytics and Information Technologies for Smart Energy Storage

- Critical Role of ESS: ESS are crucial for efficient energy management, involving complex variables that require accurate state and trend estimation for optimal operation and control.
- Integration with IoT: IoT technologies play a key role in integrating distributed energy storage (DES) systems, helping balance renewable energy supply and demand through effective design and operation.
- Importance of BMS and BIM: Building Management Systems (BMS) and Building Information Modeling (BIM) are essential for smart design and control features in ESS, enhancing efficiency and performance.

2. Forecasting for Control of Smart Energy Storage Systems

- Efficiency of DMS Models: Simple neural Direct Multi-Step (DMS) models perform similarly to complex Machine Learning (ML) models but with lower computational costs.
- Transfer Learning Benefits: Data collection requirements for new control systems can be minimized by reusing measurement data and trained models from existing buildings.
- Forecasting Challenges: Forecasting grid electricity price and carbon intensity is generally easier than predicting building electrical load, which varies in difficulty across different buildings.
- Data vs. Accuracy Trade-off: There is a trade-off between using less data (reducing costs) and achieving better prediction accuracy (reducing operational costs). Finding the optimal balance is crucial.

3. Data-driven Modelling of Energy Storage Devices using Machine Learning

- Underutilization of ML Potential: Current energy storage modeling often underutilizes the potential of modern ML.
- Focus on Sorption Technologies: Few studies focus on physical and chemical sorption, which requires precise control and has significant potential.
- Advantages of ANN: Artificial Neural Networks (ANN) handle highly non-linear problems better than traditional white-box approaches, which often lead to stiff differential equations.
- Applications Beyond Predictive Modeling: ML can be used for real-time learning, anomaly detection, and data mining, expanding its applications beyond predictive modeling.

4. Smart Design/Integration Methodology for Energy Storage Systems

- Seven-Step Design Methodology: A proposed seven-step design methodology can guide the process from describing the thermal process to defining TES geometry based on thermal application requirements and constraints.
- Discrepancies in Design Parameters: There is a discrepancy between design cases regarding input parameters to the proposed design methodology.
- Application Type Consideration: Including the type of application (retrofit or new construction) as a decisive factor in the design methodology is recommended for better alignment with specific needs.
- Need for More Applications: Additional applications are needed to validate and refine the design methodology.

5. Advanced Storage Control Applied to Optimize Operation of Energy Storage Systems

- Predictive Capabilities of AI: AI-based control systems can predict important factors like energy storage performance, weather conditions, and demand, optimizing energy storage for environmental and economic benefits while maintaining system stability.
- Enhanced Resilience: AI-based control improves building and district resilience during disruptions, adjusting energy use to maintain comfort and minimize the impact of power outages.
- Transformative Potential: Energy storage technology, combined with AI-based control, offers a transformative approach to sustainable energy management, significantly enhancing efficiency and reliability.

6. Cooperative Control of Building/District/Grid

- Challenges with Renewable Energy: Renewable energy sources are unpredictable, and energy demand varies, necessitating a consideration of costs and constraints for optimization.
- Microgrid Stability: Developing quick protection devices for stable microgrid operation during isolated events is a significant challenge that needs addressing.
- Real-time Control Needs: As power grids evolve into smarter systems, real-time control, mitigation, and protection become crucial.
- Vulnerability Prevention: Detecting and preventing vulnerabilities is essential to avoid financial and proprietary losses, ensuring the security and stability of energy systems.

Summary Recommendations

- Invest in IoT and AI Technologies: Enhance the integration and control of ESS by leveraging IoT and AI technologies.
- Tailor Solutions: Customize design methodologies and forecasting models to specific building characteristics and application types.
- Enhance Resilience: Focus on predictive and real-time control systems to improve system resilience and stability.
- Utilize Transfer Learning: Apply Transfer Learning to reduce setup costs and leverage existing data and models.

By implementing these strategies, stakeholders can optimize the design, control, and performance of energy storage systems, contributing to more sustainable and efficient energy management across various scales.

# EXECUTIVE SUMMARY

## 1 Short Description of Task 37

### 1.1 Objectives and Scope

The general objective of this Task is to address the design/integration, control, and optimization of energy storage systems within buildings, districts, power grids, and/or local utilities. The focus will be on the development of design methods, optimization, and advanced control strategies for effectively predicting, evaluating, and improving the performance of Buildings and districts when energy storage is available. The Task shall deal with the fundamental of smart technology and its application to energy storage systems in buildings, districts, and grids.

### 1.2 Organisational Structure

Project group managed by the Task Leader Ryozo Ooka.

Participating countries: Japan, Canada, UK, France, Denmark, Italy, Korea, China, Sweden, US, Norway, Turkey, Israel and Ireland.

The Task Leader reports to the ExCo of the TCP on a regular basis.

### 1.3 Beginning and End of Task

Start: May 2020. End of Task: June 2024.

### 1.4 Experts Meetings

| City | Country | Date | # Participants |
|---|---|---|---|
| Online | | 12 June 2020 | 39 |
| Online | | 10 July 2020 | 44 |
| Online | | 14 August 2020 | 35 |
| Online | | 25 September 2020 | 35 |
| Online | | 26 October 2020 | 30 |
| Online | | 27 May 2021 | 35 |
| Online | | 22 October 2021 | 32 |
| Online | | 6 May 2022 | 25 |
| London | UK | 18 October 2022 | 21 |
| Tokyo | Japan | 18 May 2023 | 23 |
| Turin | Italy | 27 October 2023 | 21 |
| Lyon | France | 1 June 2024 | 12 |

# 2 Summary of Subtasks

## 2.1 Subtask 0

This sub-task is mandated to investigate the state-of-the art smart tools and technologies to support integration, optimization, control and coordination of energy storage systems at/with various integration scales (building, district, and community), various operational & control scenarios (real-time vs predictive), various technologies (batteries, thermal storage, CAES, etc.), and various objectives (cost efficiency, resilience & self-reliance, renewables penetration, etc.).

This report provides a state-of-the-art review on emerging applications of smart tools such as data analytics and smart technologies such as Internet-of-things (IoT) in case of design, management and control of energy storage systems. In particular, we have established a classification of the types and targets of various predictive analytics for estimation of load, energy prices, renewable energy inputs, state of the charge, fault diagnosis, etc. In addition, the applications of information technologies, in particular, use of cloud, IoT systems, building management systems (BMS) and building information modeling (BIM) and their contributions to management of energy storage systems will be reviewed in detail. The paper concludes by highlighting the emerging issues in smart energy storage systems and providing directions for future research.

## 2.2 Subtask A

The prediction of energy demand in buildings and districts is a constraint that must be satisfied in control. Especially, the energy demand of buildings and districts varies significantly depending on the usage, composition of the energy system, change of weather, occupant behavior, and so on. There are many demand prediction models are previously proposed including IEA's achievement. This particular Annex will focus on prediction models that support smart control and operation of energy storage technologies.

This sub-task investigates the role of data in enabling high accuracy forecasting for smart energy storage systems by studying the performance of various prediction models in providing forecasts for a Linear MPC controller that operates batteries within a multi-building energy system simulation. Specifically, it examines the capability of different Machine Learning models to forecast electricity demand, grid electricity cost, and carbon emissions, considering how different aspects of the supporting data impact prediction performance and the implications for the joint design of forecasting models and data collection strategies.

## 2.3 Subtask B

The objective of subtask B is to analyze the numerical models developed at the component scale for optimization, design and control of energy storage systems integrated in buildings and districts. In order to carry out such analysis, a comprehensive and up-to-date set of information is mandatory. It was therefore decided to build a database gathering as much information as possible on recent or ongoing research works on energy storage systems, including (at least some) modeling attempts.

Research on the optimal use of energy storage systems includes approaches like Rule-based Control (RBC), Model Predictive Control (MPC), and Adaptive Control (AC), all of which rely on accurate and fast system models. Creating equation-based (white-box) models can be time-consuming and require engineering services, particularly when systems change. Grey-box modelling, which uses simple mathematical equations calibrated with data, and black-box modelling, which relies purely on data-driven methods, offer alternatives. With the rise of data availability, computing power, and machine learning algorithms, black-box modelling has gained significance. In this report, this sub-task is reviewing the existing literature on data-driven modelling of energy storage devices for buildings in Subtask B.

## 2.4 Subtask C

Recent research studies have focused on the optimal design of Thermal Energy Storage (TES) systems for different plants and processes, utilizing advanced optimization techniques. There are a wide range of TES technologies that can be integrated into a variety of thermal applications. Each TES technology has its own technical and economic characteristics that make it essentially suitable for a specific application. Identifying important factors and then matching an application with the most appropriate TES system is still a challenging issue. Subtask C discusses the challenges in identifying the most appropriate Thermal Energy Storage (TES) system for a specific application due to the technical and economic characteristics of each TES technology. A seven-step design methodology is proposed that can guide the process from describing the thermal process to defining the TES geometry based on the requirements and constraints of the thermal application. The steps in the proposed methodology include specifying the thermal process, thermal demand, storage technology, integration parameters, key performance indicators, optimization method, and optimization tools. The proposed methodology is implemented in seven different case studies to demonstrate its effectiveness in identifying the most appropriate TES system for a specific application. Although the case studies involve various types of applications with both sensible and latent thermal energy storage systems, the proposed design procedure is applicable. The design steps proposed in this subtask can serve as a foundation for developing a systematic approach for designing TES systems in future works.

## 2.5 Subtask D

Subtask D is intended to provide the latest findings on the smart control and operation strategies of energy storages into buildings and districts. Within the complex multi-source multi-energy systems that are exploited to ensure a full decarbonization of the building sector, the strategies used to control such storages may not be straightforward, as they should be set considering a large number of variables and uncertain inputs so that a multiple number of interrelated outputs are optimized.

In this subtask, the identification and review of recent studies concerning the control of energy storage integrated in systems for buildings, or group of buildings is performed. In particular, the report concentrates on papers that are not only purely theoretical or numerical studies, but where some experimental activities were carried out or where analysis are conducted based on real case-studies. This is particularly important in order to evaluate the effectiveness of the control strategies against real measurements. Thus, a systematic review process was implemented aimed at identifying the latest advancements in energy storage control, the emerging trends and the role of AI in shaping such trends, and future perspectives.

## 2.6 Subtask E

The main objective of this subtask is to represent all system components (in terms of their electrical or energetic inputs and outputs, efficiencies, technical constraints, static and dynamic behavior, costs, emissions) and propose optimal control and operation methods in power grid systems.

This subtask presents a comprehensive review of the existing studies regarding ESS in power distribution networks. The contributions of this work can be summarized as follows:

- This subtask discusses various issues related to the power quality of distribution networks and their mitigation scopes with ESSs. In detail, we present a systematic review of ESS studies published in journals or conference proceedings providing a comprehensive review of ESS integration in power distribution networks.
- We approach the review of relevant ESS papers through multiple angles, including technological, design, and optimization aspects. Additionally, we provide a detailed classification of the papers based on various criteria, such as the type of ESS used, the control strategy employed, and the application area. Our review categorizes the control architectures for ESSs and explains the advantages and challenges of developing practical operational strategies and solution techniques for different ESS applications.
- Differently from most of the recalled reviews, we show all the possible applications of ESS in power distribution grids such as frequency regulation, grid stability, voltage regulation, and ancillary services. Through the review, we identify the existing gaps in the literature and provide promising research directions to fill these gaps. We also highlight the correlation between articles considering all the possible ESS applications, recent advancements in storage technologies, and relevant control approaches available in the literature.

# 3 Interrelationships between Subtasks and their Contribution to the Overall Task

Each subtask of Task 37 is interconnected, collectively building a comprehensive framework for the smart design and control of energy storage systems. Figure 1 shows the interrelationship between subtasks. Subtask 0 establishes the foundation by exploring smart tools and data analytics technologies essential for predictive management. Building on this, Subtask A focuses on forecasting energy demand and supply—critical for enabling real-time control strategies envisioned in Subtask 0. Subtask B then leverages these forecasts by applying machine learning to develop component-level models that inform design and operational decisions. These models support Subtask C, which proposes a structured methodology to optimally design energy storage systems for specific building and district contexts. The design outputs feed directly into Subtask D, where advanced control strategies — especially AI-based systems—are developed to manage energy systems under real-world uncertainties. Finally, Subtask E scales these concepts to the grid level, addressing coordination across buildings, districts, and power grids. Together, these subtasks form a layered and interdependent approach that enables holistic optimization and integration of energy storage across all levels of the energy system.

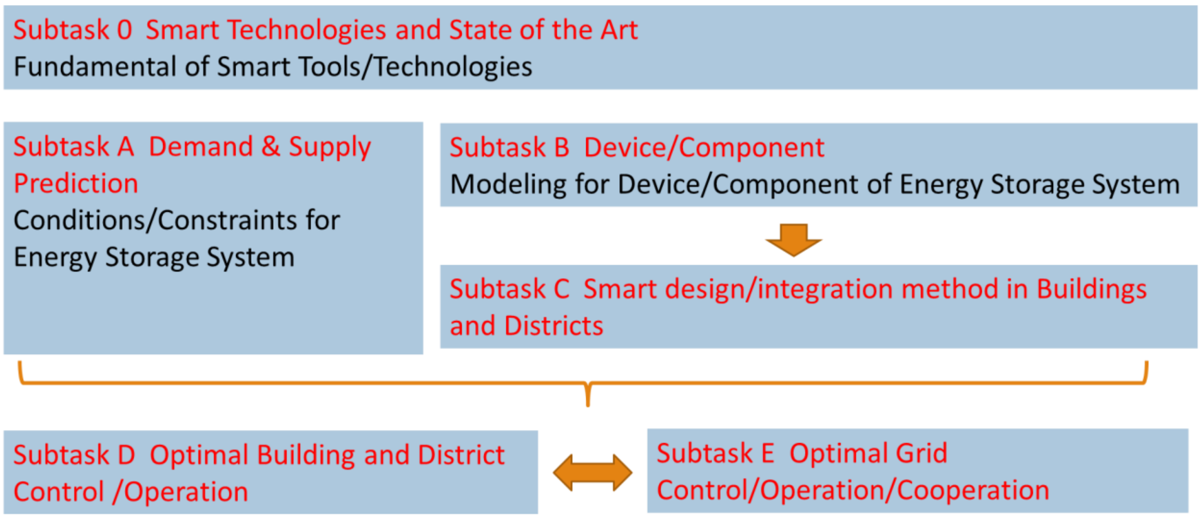


Figure 1: Interrelationship between subtasks

# 4 Comprehensive Results and Recommendations for Deployment

The primary goal of this Task is to address the design, integration, control, and optimization of energy storage systems within various scales, from buildings to power grids. The focus is on developing methods, optimization, and advanced control strategies to predict, evaluate, and improve the performance of energy storage systems in these contexts. This comprehensive review consists of six subtasks, each providing insights and conclusions essential for deploying effective energy storage solutions. Below is a summary of findings and recommendations for each subtask.

1. Data Analytics and Information Technologies for Smart Energy Storage

Main Conclusions:

- Energy Storage Systems (ESS) are critical for efficient energy management, requiring accurate state and trend estimation for optimal operation and control.
- IoT technologies are vital for integrating distributed energy storage (DES) systems, balancing renewable energy supply and demand.
- Building Management Systems (BMS) and Building Information Modeling (BIM) are essential for the smart design and control of ESS.

Recommendations:

- Invest in IoT technologies to enhance DES integration and operation.
- Implement BMS and BIM in the design and control phases of ESS to maximize efficiency and performance.

2. Forecasting for Control of Smart Energy Storage Systems

Main Conclusions:

- Simple neural Direct Multi-Step (DMS) models perform comparably to complex ML models with lower computational costs and better data efficiency.
- Transfer Learning minimizes data collection requirements by reusing data and trained models from existing buildings.
- Forecasting grid electricity price and carbon intensity is generally easier than predicting building electrical load, though the difficulty varies by building.

Recommendations:

- Use DMS models for efficient forecasting in ESS control systems.
- Apply Transfer Learning to leverage existing data and models, reducing setup costs.
- Tailor forecasting models to specific building characteristics for improved accuracy.

3. Data-driven Modelling of Energy Storage Devices using Machine Learning

Main Conclusions:

- Current energy storage modeling underutilizes modern ML potential.
- Few studies focus on physical and chemical sorption, despite its promise and need for precise control.
- ANN can handle highly non-linear problems, offering advantages over traditional white-box approaches.

Recommendations:

- Expand research on physical and chemical sorption technologies.
- Utilize ANN for modeling complex, non-linear energy storage systems.
- Match ML algorithms to specific system characteristics for better modeling accuracy.

4. Smart Design/Integration Methodology for Energy Storage Systems

Main Conclusions:

- The seven-step design methodology applies to various TES systems across different buildings.
- Input parameters vary significantly between design cases.
- The type of application (retrofit or new construction) should be a decisive factor in the design process.

Recommendations:

- Adopt the seven-step methodology for designing TES systems.
- Customize input parameters based on specific project requirements.
- Consider application type in the design phase to ensure optimal integration and performance.

5. Advanced Storage Control Applied to Optimize Operation of Energy Storage Systems

Main Conclusions:

- AI-based control systems can predict and optimize energy storage performance, weather conditions, and demand.
- These systems enhance resilience during disruptions, maintaining comfort and minimizing outage impacts.
- AI-based control and energy storage technology offer significant benefits for sustainable energy management.

Recommendations:

- Implement AI-based control systems to optimize energy storage operations.
- Focus on resilience improvements through predictive control strategies.
- Leverage AI to enhance both environmental and economic outcomes.

6. Cooperative Control of Building/District/Grid

Main Conclusions:

- Renewable energy sources are unpredictable, and energy demand varies, requiring cost and constraint consideration for optimization.
- Quick protection devices for stable microgrid operation during isolated events are necessary.
- Real-time control, mitigation, and protection are crucial as power grids evolve.
- Preventing vulnerabilities is essential to avoid financial and proprietary losses.

Recommendations:

- Develop and deploy quick protection devices for microgrid stability.
- Invest in real-time control and protection systems for smart grids.
- Enhance vulnerability detection and prevention mechanisms to safeguard energy systems.

General Recommendations for Deployment

- Invest in Advanced Technologies: Prioritize the integration of IoT, AI, and ML in ESS to enhance performance and control.
- Customize Solutions: Tailor methodologies and models to specific applications and building characteristics for optimal results.
- Enhance Resilience and Stability: Focus on predictive and real-time control systems to improve system resilience and stability.
- Collaborate and Share Data: Utilize Transfer Learning and collaborative approaches to minimize costs and leverage existing knowledge.

By implementing these recommendations, stakeholders can effectively design, optimize, and control energy storage systems, contributing to more sustainable and efficient energy management across various scales.