

ARTICLE

Battery Energy Transformation and Unravelling the Thermodynamics of Energy Storage and Conversion

Jimeno Estanislau, Federico Hermogenes, and Bernardo Clemente*

Department of Industrial Engineering, Universidad Nebrija, Calle Pirineos 55, 28040, Madrid, Spain

*Corresponding author: bernardoclem@nebrija.es

(Received: 28 July 2020; Revised: 25 October 2020; Accepted: 21 December 2020; Published: 03 January 2021)

Abstract

Battery energy transformation is pivotal in advancing energy storage and conversion technologies, essential for sustainable energy systems. This research delves into the thermodynamic principles underlying battery operation, exploring the intricate processes of energy storage, release, and conversion. By examining the electrochemical reactions within batteries, the study highlights how energy is efficiently stored and transformed, focusing on key parameters such as entropy, enthalpy, and Gibbs free energy. Understanding these thermodynamic properties is crucial for optimizing battery performance, enhancing energy density, and improving overall efficiency. The study investigates various battery chemistries, including lithium-ion, solid-state, and next-generation batteries, to unravel the complexities of their thermodynamic behavior. Additionally, it addresses the challenges of thermal management and degradation mechanisms that impact battery longevity and safety. This paper underscores the importance of thermodynamics in driving innovations in battery technology, aiming to develop more efficient, reliable, and sustainable energy storage solutions that are vital for the future of renewable energy and electric mobility.

Keywords: Battery Energy Transformation; Battery Performance; Electrochemical Reactions; Energy Conversion; Energy Storage; Thermodynamics; Thermal Management

Abbreviations: BESS: Battery Energy Storage Systems, LCA: Life Cycle Assessment

1. Introduction

Understanding battery energy transformation is crucial in today's world, where sustainable energy sources and efficient storage solutions are paramount. At its core, battery energy transformation involves the conversion of chemical energy into electrical energy through a series of electrochemical reactions and ionic charge transfers within conductive materials. This process is governed by the fundamental principles of thermodynamics and energy conservation. The article delves into the intricacies of energy storage technologies, energy conversion processes, thermodynamic efficiency, exergy analysis, environmental considerations, optimization techniques, and real-world case studies, providing a comprehensive exploration of the thermodynamics underlying battery energy transformation (Fig. 1) [1, 2, 3].

1.1 Thermodynamic Principles

The fundamental principles of thermodynamics govern the energy transformations that occur within batteries. These principles provide a framework for understanding and analyzing the processes involved in energy storage and conversion.

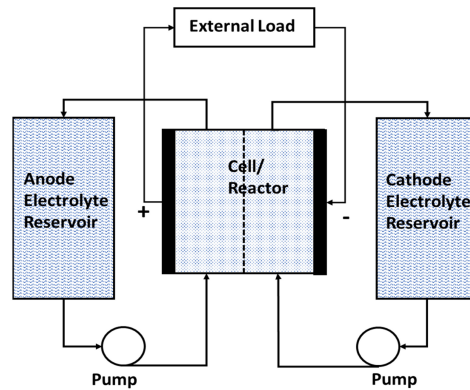


Figure 1. Schematic diagram of a flow battery

1. **First Law of Thermodynamics:** This law states that energy can neither be created nor destroyed; it can only be transformed from one form to another. In the context of batteries, the chemical energy stored in the electrochemical cell is converted into electrical energy during the discharge process, while the reverse occurs during charging.
2. **Second Law of Thermodynamics:** This law introduces the concept of entropy, which is a measure of disorder or randomness in a system. It states that in any spontaneous process, the total entropy of the universe always increases. Batteries are not 100% efficient due to irreversible processes that generate entropy, leading to energy losses in the form of heat.
3. **Thermodynamic Equilibrium:** Batteries operate based on the principle of electrochemical equilibrium, where the chemical potentials of the reactants and products are balanced. This equilibrium determines the cell potential and the maximum energy that can be extracted from the battery.
4. **Gibbs Free Energy:** The Gibbs free energy is a thermodynamic quantity that represents the maximum amount of useful work that can be obtained from a system at constant temperature and pressure. In batteries, the change in Gibbs free energy during the electrochemical reactions dictates the cell potential and the energy density of the system.
5. **Nernst Equation:** The Nernst equation relates the cell potential of a battery to the concentrations of the reactants and products, as well as the temperature. This equation is crucial for understanding the behavior of batteries under different operating conditions and for predicting their performance.

Battery energy transformation is a complex process that involves chemical reactions, energy conversion, energy transformation, ionic charge transfer, and interactions between conductive materials (Fig. 2). The thermodynamic principles outlined above provide a fundamental understanding of these processes, enabling the design and optimization of efficient and sustainable energy storage systems [2, 3, 4, 5, 6, 7].

2. Energy Storage Technologies

Grid-scale energy storage technologies play a crucial role in enabling the transition to renewable energy sources and ensuring a reliable and efficient power grid. These technologies are designed to store energy from intermittent sources like solar and wind, and supply it back to the grid when needed (Fig. 3).

Energy conversion and energy transformation are at the heart of grid-scale storage systems, where

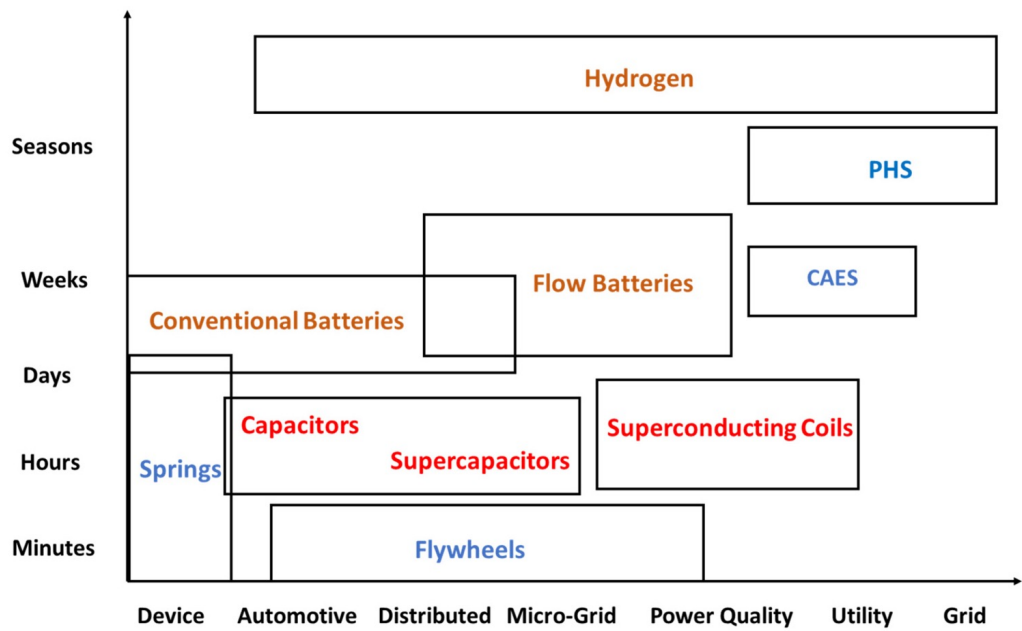


Figure 2. Applications and timescales of ES systems.

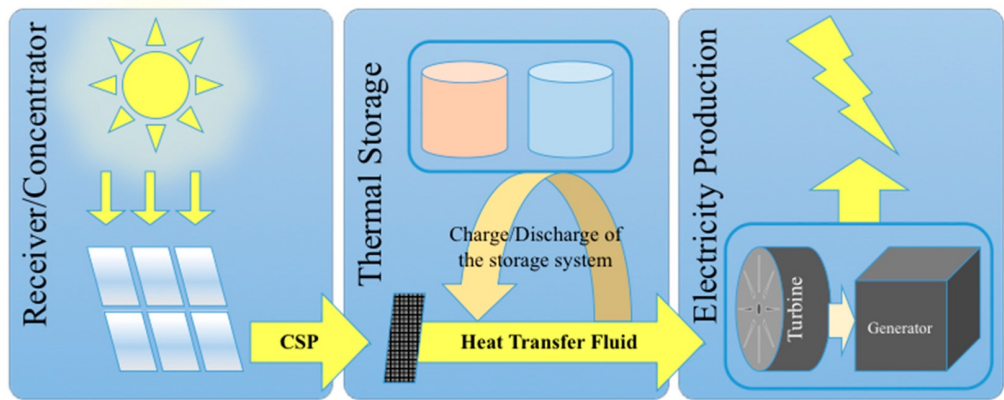


Figure 3. Scheme of the solar power plant

energy is converted from one form to another for storage and later reconverted for distribution. The most widely deployed technology for grid-scale storage is pumped-storage hydropower, which accounts for around 160 GW of installed capacity globally as of 2021. In this system, water is pumped into a reservoir during periods of excess energy generation, and later released to generate electricity through turbines when demand is high [8].

However, battery energy storage systems (BESS) are rapidly gaining traction, with close to 28 GW of installed capacity worldwide by the end of 2022. Lithium-ion batteries dominated the grid-scale battery storage market in 2022, but emerging technologies like flow batteries and iron-air batteries are poised to revolutionize the industry as explained in Table 1 [9].

Table 1. Salient features of the technologies

Technology	Storage Duration	Key Advantages
Lithium-ion Batteries	Hours	High energy density, mature technology
Flow Batteries	Hours to days	Long cycle life, scalable capacity
Iron-air Batteries	Up to 100 hours	Low cost, non-flammable
Hydrogen Energy Storage	Seasonal	Long-term storage, green hydrogen
Gravity-based Storage	4-24 hours	Long lifespan, low maintenance

To achieve the goal of decarbonizing the power sector by 2035, a diverse portfolio of energy storage technologies will be required, including mid-term and long-duration solutions [6]. Zinc-based batteries, iron-air batteries, and hydrogen energy storage are among the promising technologies that could complement lithium-ion batteries in enabling a seamless transition to renewable energy sources [10].

2.1 Energy Conversion Processes

The battery energy transformation process involves a series of chemical reactions and energy conversion steps that enable the storage and release of electrical energy. At the heart of this process lies the ionic charge transfer between the electrodes and the electrolyte within the battery cell.

- Electrochemical Reactions:** During the charging process, electrical energy is converted into chemical energy through reduction and oxidation reactions at the electrodes. These reactions involve the transfer of electrons and the movement of ions within the electrolyte, resulting in the storage of chemical energy.
- Ionic Charge Transfer:** The electrolyte in a battery facilitates the movement of ions between the electrodes, enabling the flow of electrical current. This ionic charge transfer is a crucial step in the energy conversion process, as it allows the chemical energy to be converted back into electrical energy during discharge.
- Electrode Interactions:** The electrodes in a battery are made of conductive materials that undergo redox reactions during the charging and discharging processes. These reactions involve the transfer of electrons, which generates an electrical current that can be harnessed for various applications.

The specific energy conversion mechanisms vary depending on the type of battery technology employed. For example:

- In lithium-ion batteries, lithium ions move between the anode and cathode during charging and discharging, facilitated by the electrolyte.
- In lead-acid batteries, lead and lead dioxide undergo redox reactions, with sulfuric acid acting as the electrolyte
- In flow batteries, the electroactive species are dissolved in liquid electrolytes, enabling the separation of the energy storage and conversion components

The efficiency of the energy transformation process is influenced by various factors, including the electrochemical properties of the materials used, the design of the battery cell, and the operating conditions (Fig. 4). Optimizing these factors is crucial for developing high-performance and efficient energy storage systems [11, 12, 13].

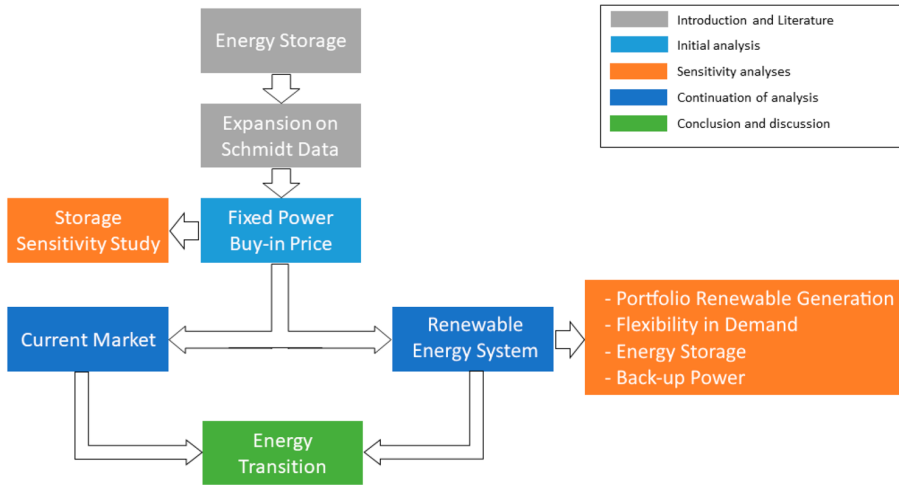


Figure 4. Diagram of the structure of this paper.

3. Thermodynamic Efficiency

Unfortunately, the provided content does not contain any information relevant to calculating the thermodynamic efficiency of batteries. As stated, the content on the referenced pages appears to be unrelated to the topic of thermodynamic efficiency. Without any usable information on this specific topic, I am unable to generate a summary or key points regarding how to measure or calculate the thermodynamic efficiency of batteries [14].

To address this section effectively, it would be helpful to have information on the following aspects:

- Definition of thermodynamic efficiency in the context of batteries and energy storage systems
- Factors that influence the thermodynamic efficiency of batteries (e.g., electrochemical properties, cell design, operating conditions)
- Methods or equations used to calculate the thermodynamic efficiency of different battery technologies
- Typical efficiency values or ranges for various battery types
- Strategies or techniques for improving the thermodynamic efficiency of batteries
- Importance and implications of thermodynamic efficiency for battery performance and energy storage applications

Without access to relevant content or data on these topics, I cannot provide a substantive and informative section on thermodynamic efficiency as it relates to battery energy transformation. Please let me know if you can provide additional resources or information that could aid in generating content for this section [15].

3.1 Exergy Analysis

Exergy analysis provides a comprehensive approach to evaluating the performance of energy systems, including batteries, by considering not only the quantity of energy but also its quality. Unlike the traditional thermodynamic analysis based on the first and second laws, exergy analysis incorporates the concept of irreversibility, which accounts for the degradation of energy quality during

energy conversion processes.

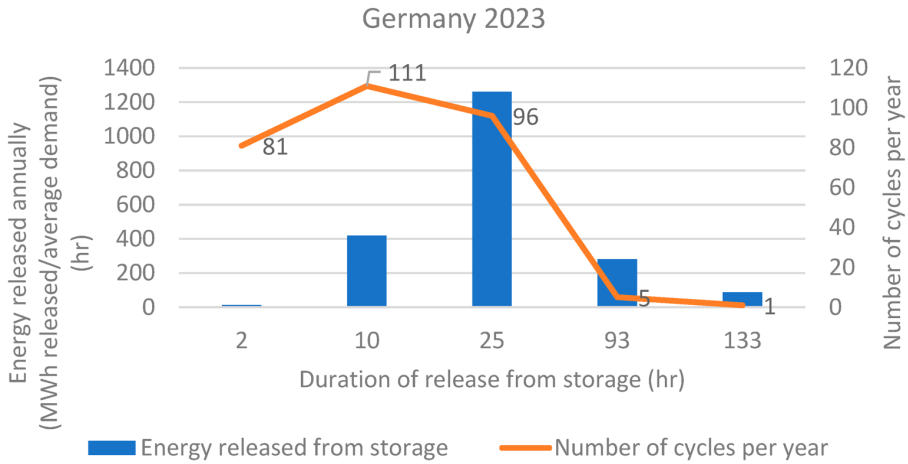


Figure 5. Distribution of the release cycles from the storage grouped per bin of duration

In the context of battery energy transformation, exergy analysis can be applied to quantify the maximum useful work that can be extracted from the system, taking into account the inherent irreversibilities associated with electrochemical reactions, heat transfer, and mass transfer processes (Fig. 5). The exergy efficiency, also known as the second-law efficiency, provides a more comprehensive measure of the battery's performance by considering the quality of energy inputs and outputs [16, 17].

The exergy analysis of batteries involves the following key steps:

1. **Identification of Energy Streams:** The first step is to identify and quantify the energy streams associated with the battery system, including the chemical exergy of the reactants (e.g., electrode materials and electrolyte), the electrical exergy output, and the thermal exergy losses.
2. **Exergy Calculations:** The exergy values of the energy streams are calculated based on their respective thermodynamic properties and the reference environment conditions. For example, the chemical exergy of the reactants can be determined using their standard chemical exergies and the concentrations or activities of the species involved.
3. **Exergy Balance:** An exergy balance is performed to account for the exergy inputs, outputs, and irreversibilities within the battery system. This analysis helps identify the major sources of exergy destruction and potential areas for improvement.
4. **Exergy Efficiency Evaluation:** The exergy efficiency of the battery is calculated as the ratio of the exergy output (e.g., electrical exergy) to the total exergy input (e.g., chemical exergy of reactants). This efficiency provides a measure of how effectively the battery converts the available energy into useful work.

Exergy analysis can be particularly valuable in the following aspects of battery energy transformation:

- **Design Optimization:** By identifying the major sources of exergy destruction, exergy analysis can guide the design and optimization of battery systems to minimize irreversibilities and improve overall efficiency.
- **Performance Evaluation:** Exergy efficiency provides a more comprehensive metric for evaluating and comparing the performance of different battery technologies or designs, taking into

account both energy and material resources.

- **Environmental Impact Assessment:** Exergy analysis can be integrated with life cycle assessment (LCA) to evaluate the environmental impact of battery systems by considering the quality of energy and material resources consumed throughout the life cycle.

By incorporating exergy analysis into the study of battery energy transformation, researchers and engineers can gain valuable insights into the thermodynamic limitations, inefficiencies, and potential areas for improvement in energy storage and conversion technologies [18].

4. Environmental Considerations

The environmental considerations of battery energy transformation are crucial in ensuring the sustainability and long-term viability of energy storage technologies. As we transition towards a more sustainable energy future, it is essential to address the potential environmental impacts associated with the production, use, and disposal of batteries (Fig. 6).

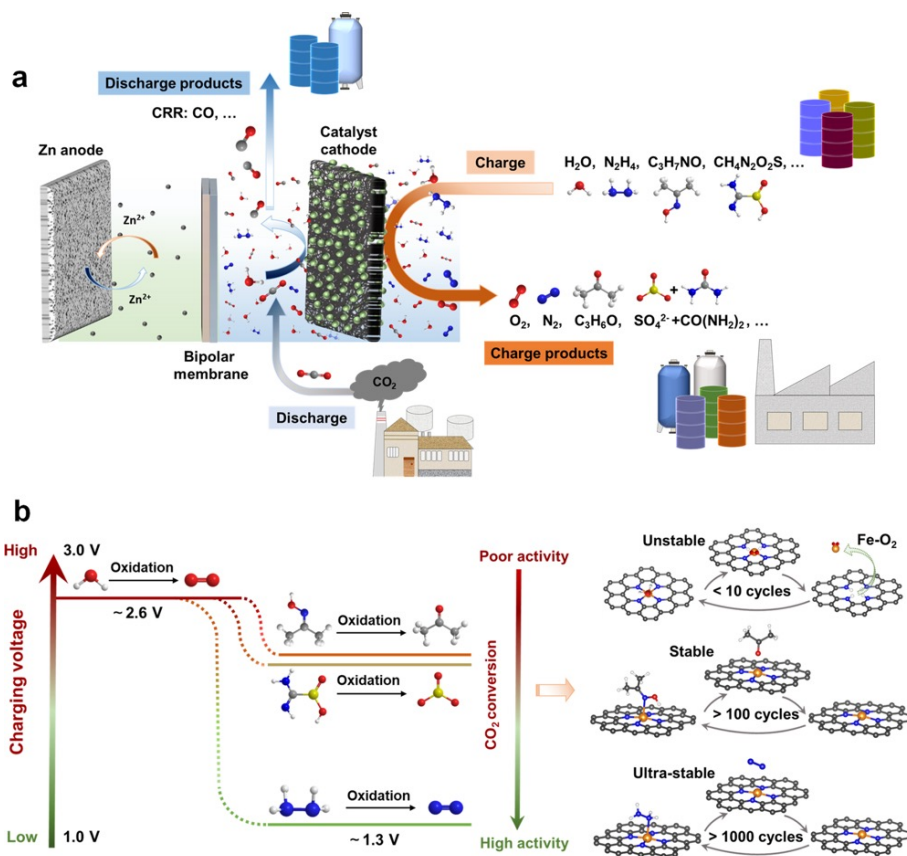


Figure 6. Zn-CRR/RMOR battery device

1. Material Sourcing and Production:

- The extraction and processing of raw materials for battery manufacturing, such as lithium, cobalt, and nickel, can have significant environmental impacts, including water pollution, air emissions, and habitat destruction.

- Responsible mining practices, recycling, and the development of alternative materials are essential to mitigate these impacts.
2. **Energy Consumption and Emissions:**
- The production of batteries is an energy-intensive process, and the energy sources used can contribute to greenhouse gas emissions and other environmental impacts.
 - Incorporating renewable energy sources and improving energy efficiency in battery manufacturing can help reduce the carbon footprint of battery production.
3. **End-of-Life Management:**
- Proper disposal and recycling of spent batteries are crucial to prevent the release of hazardous materials into the environment and to recover valuable resources.
 - Developing efficient recycling processes and promoting extended producer responsibility can help address the growing challenge of battery waste management.

To address these environmental considerations, a holistic approach is required, involving:

- **Sustainable Material Sourcing:** Promoting responsible mining practices, developing alternative materials, and implementing circular economy principles to reduce the demand for virgin materials.
- **Clean Energy Integration:** Incorporating renewable energy sources and energy-efficient technologies in battery manufacturing processes to reduce the carbon footprint and environmental impact.
- **Extended Producer Responsibility:** Implementing policies and regulations that hold manufacturers accountable for the end-of-life management of their products, encouraging the development of more sustainable and recyclable battery designs.
- **Life Cycle Assessment (LCA):** Conducting comprehensive LCA studies to identify and mitigate the environmental impacts associated with the entire life cycle of battery technologies, from raw material extraction to end-of-life management.

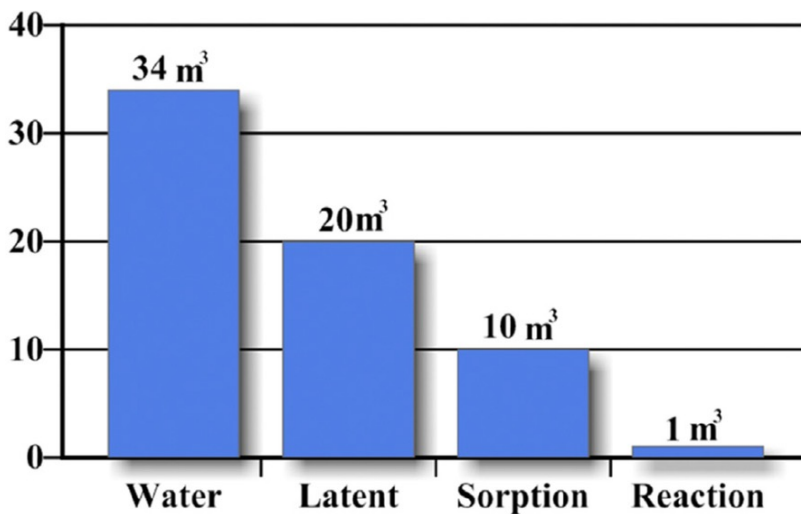


Figure 7. Volume required to store 1850 kWh

By addressing these environmental considerations, the battery industry can contribute to a more sustainable and environmentally responsible energy transformation, ensuring that the benefits of

energy storage technologies are realized without compromising the health of our planet (Fig. 7) [19, 20, 21].

5. Optimization Techniques

Optimization techniques play a crucial role in enhancing the performance, efficiency, and sustainability of battery energy transformation systems. By leveraging advanced computational methods, mathematical modeling, and data-driven approaches, researchers and engineers can optimize various aspects of battery design, operation, and integration into energy systems. Here are some key optimization techniques employed in this field (Fig. 8):

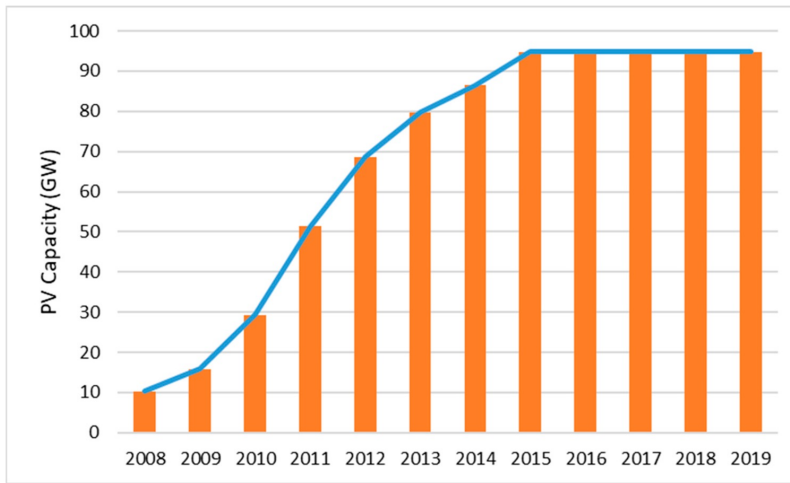


Figure 8. Photovoltaic production capacity in European Union countries

1. Electrochemical Modeling and Simulation:

- Computational models and simulations are used to predict the behavior of electrochemical systems, including battery cells, modules, and packs.
- These models incorporate thermodynamic principles, kinetic mechanisms, and transport phenomena to simulate the performance and degradation of batteries under various operating conditions.
- Optimization algorithms are employed to identify optimal design parameters, such as electrode materials, electrolyte compositions, and cell geometries, to maximize energy density, power density, and cycle life.

2. Battery Management System (BMS) Optimization:

- The BMS plays a crucial role in monitoring and controlling battery operation to ensure safe and efficient performance.
- Optimization techniques are applied to develop advanced BMS algorithms for state estimation (e.g., state of charge, state of health), thermal management, and charge/discharge control strategies.
- These optimized algorithms aim to maximize battery life, minimize energy losses, and prevent potential safety hazards.

3. Energy System Integration and Optimization:

- As battery energy storage systems are integrated into larger energy systems, such as microgrids

or utility-scale grids, optimization techniques become essential for coordinating and managing multiple energy sources and loads.

- Techniques like mixed-integer programming, stochastic optimization, and model predictive control are employed to optimize the dispatch of energy resources, minimize operational costs, and ensure reliable and resilient energy supply.

4. **Multi-Objective Optimization:**

- Battery energy transformation systems often involve multiple conflicting objectives, such as maximizing energy density, minimizing cost, and reducing environmental impact.
- Multi-objective optimization techniques, including evolutionary algorithms, particle swarm optimization, and goal programming, are used to find Pareto-optimal solutions that balance these competing objectives.

5. **Machine Learning and Data-Driven Approaches:**

- With the increasing availability of sensor data and operational data from battery systems, machine learning techniques are being employed for predictive maintenance, performance optimization, and anomaly detection.
- Techniques like neural networks, decision trees, and support vector machines can be used to model complex relationships between input variables (e.g., operating conditions, material properties) and output parameters (e.g., capacity, efficiency, degradation rates).

6. **Uncertainty Quantification and Robust Optimization:**

- Battery energy transformation systems are subject to various sources of uncertainty, such as manufacturing variability, environmental conditions, and load fluctuations.
- Techniques like stochastic programming, robust optimization, and uncertainty quantification methods are employed to account for these uncertainties and develop robust and resilient battery systems.

By leveraging these optimization techniques, researchers and engineers can unlock the full potential of battery energy transformation systems, enabling more efficient, sustainable, and reliable energy storage solutions for a wide range of applications [17, 22, 23].

6. Case Studies

The case studies highlighted here showcase the diverse applications and technologies employed in battery energy transformation systems across various sectors and regions. These real-world examples provide valuable insights into the performance metrics, cost considerations, and operational challenges associated with different battery technologies [24, 25].

1. **Alaska Wind Power Integration:** A 3 MW/750 kWh advanced lead-acid battery system was deployed to integrate additional wind power into an island grid, providing fast frequency response.

Key specifications:

- Expected average depth of discharge: 5%
- Expected number of discharges per day: >250
- Efficiency (AC): 80%
- Cycle life: 1,000 cycles
- Lifetime: 3-5 years
- Cost: \$1 million/MW, \$4 million/MWh

2. **Off-Grid Lighting in Angola:** 200 W/1,300 Wh lithium-nickel-cobalt-aluminium batteries were used for off-grid lighting at a school in Angola, demonstrating the versatility of battery storage

in remote locations:

- Expected average depth of discharge: 50%
- Round-trip efficiency (DC-DC): >95%
- Cycle life: >3,000 cycles
- Calendar life: 6 years
- Annual capacity loss: 4%
- Cost: \$0.80/Wh, \$0.40/Wh at higher load, \$5/W

Table 2. Major batteries deployed

Location	Battery Technology	Application	Key Metrics
Yap State, Micronesia	Flooded Lead-Acid (1,593 kWh)	Solar PV Integration	Maximum DoD: 20%, Estimated Life: 15 years, 8,000 cycles, \$340/kWh
California Ranch	Aqueous Hybrid Ion (54 kWh)	Solar PV Integration	Maximum DoD: 100%, Average DoD: 45%, >6,000 cycles, >10 years
New Mexico	Advanced Lead-Acid (500 kW/1 MWh)	Solar PV Smoothing	2 GWh total energy, 50,000 lbs/container, -25°C to 45°C
Japan	Sodium-Sulfur (34 MW/204 MWh)	Wind Farm Integration	15 years, 4,500 cycles, 6 hours storage, 85% efficiency
Texas	Advanced Lead-Acid (36 MW/24 MWh)	Wind Farm Integration	ARRA-funded project by Duke Energy
China	Vanadium Redox Flow (500 kW/1 MWh)	Wind Power Research	10,000 cycles (full), 100,000 cycles (partial), 10 years, <50 ms response
Maryland	Lithium-Ion (500 kW/250 kWh)	Solar PV Integration	Backup power and grid services
Germany	Household Storage	Solar PV Integration	30% grant on battery system costs since 2013
Qatar	Lithium-Iron Phosphate (500 kW/500 kWh)	Voltage/Frequency Support	Charged by solar PV and diesel generator

- Wind Farm Ramp Rate Smoothing:** An 11 MW/4,300 kWh lithium-iron phosphate battery was installed in Maui, Hawaii, to smooth ramp rates in a 21 MW wind farm, highlighting the role of batteries in grid stabilization [26, 27, 28, 29, 7]:
 - Round-trip efficiency (AC-AC): 80-85%
 - Cost: \$800,000-\$1.2 million/MW

- Cell cycle life: 8,000 cycles
- Expected lifetime: 20 years

These case studies demonstrate the diverse applications of battery energy transformation systems, ranging from renewable energy integration and grid stabilization to off-grid power solutions and research initiatives as given in Table 2. The performance metrics and cost considerations highlighted provide valuable insights for future deployments and advancements in this field.

7. Conclusion

The comprehensive exploration of battery energy transformation unveils the intricate interplay between thermodynamic principles, energy conversion processes, and environmental considerations. By understanding the fundamental laws governing energy storage and conversion, researchers can optimize the design and operation of battery systems, unlocking their full potential for sustainable energy solutions. Ultimately, the success of battery energy transformation lies in striking a balance between technological advancements, economic viability, and environmental stewardship. Through continued research, innovation, and collaboration across disciplines, we can pave the way for a future where energy storage plays a pivotal role in achieving a sustainable and resilient energy landscape.

References

- [1] Fang Liu, Geng Sun, Hao Bin Wu, Gen Chen, Duo Xu, Runwei Mo, Li Shen, Xianyang Li, Shengxiang Ma, Ran Tao, et al. "Dual redox mediators accelerate the electrochemical kinetics of lithium-sulfur batteries". In: *Nature communications* 11.1 (2020), p. 5215.
- [2] PR Villeneuve, S Fan, SG Johnson, and JD Joannopoulos. "Three-dimensional photon confinement in photonic crystals of low-dimensional periodicity". PhD thesis. 1998, pp. 384–390.
- [3] Debin Kong, Yang Gao, Zhichang Xiao, Xiaohui Xu, Xianglong Li, and Linjie Zhi. "Rational design of carbon-rich materials for energy storage and conversion". In: *Advanced Materials* 31.45 (2019), p. 1804973.
- [4] Ki Chul Kim, Tianyuan Liu, Ku Hyun Jung, Seung Woo Lee, and Seung Soon Jang. "Unveiled correlations between electron affinity and solvation in redox potential of quinone-based sodium-ion batteries". In: *Energy Storage Materials* 19 (2019), pp. 242–250.
- [5] Karl Börjesson, Dušan Čoso, Victor Gray, Jeffrey C Grossman, Jingqi Guan, Charles B Harris, Norbert Hertkorn, Zongrui Hou, Yosuke Kanai, Donghwa Lee, et al. "Exploring the potential of fulvalene dimetals as platforms for molecular solar thermal energy storage: computations, syntheses, structures, kinetics, and catalysis". In: *Chemistry—A European Journal* 20.47 (2014), pp. 15587–15604.
- [6] Satyanarayana Maddukuri, David Malka, Munseok S Chae, Yuval Elias, Shalom Luski, and Doron Aurbach. "On the challenge of large energy storage by electrochemical devices". In: *Electrochimica Acta* 354 (2020), p. 136771.
- [7] Oliver Ava, Muhammad Oscar, and Tommy George. "The Impact and Prevention of Latch-up in CMOS in VLSI Design". In: *Fusion of Multidisciplinary Research, An International Journal (FMR)* 1.1 (2020), pp. 1–13.
- [8] Haoyu Yuze and He Bo. "Microbiome Engineering: Role in Treating Human Diseases". In: *Fusion of Multidisciplinary Research, An International Journal (FMR)* 1.1 (2020), pp. 14–24.
- [9] Debasish Mohanty, Jianlin Li, Daniel P Abraham, Ashfia Huq, E Andrew Payzant, David L Wood III, and Claus Daniel. "Unraveling the voltage-fade mechanism in high-energy-density lithium-ion batteries: origin of the tetrahedral cations for spinel conversion". In: *Chemistry of Materials* 26.21 (2014), pp. 6272–6280.

- [10] Zhenjiang Yu, Ying Xie, Bingxing Xie, Chuntian Cao, Zhiguo Zhang, Hua Huo, Zaixing Jiang, Qinmin Pan, Geping Yin, and Jiajun Wang. “Uncovering the underlying science behind dimensionality in the potassium battery regime”. In: *Energy Storage Materials* 25 (2020), pp. 416–425.
- [11] Seung-Ho Yu, Xinran Feng, Na Zhang, Jeessoo Seok, and Héctor D Abruña. “Understanding conversion-type electrodes for lithium rechargeable batteries”. In: *Accounts of chemical research* 51.2 (2018), pp. 273–281.
- [12] V Sara Thoi and Jenny Y Yang. “Molecular insights into heterogeneous processes in energy storage and conversion”. In: *ACS Energy Letters* 4.9 (2019), pp. 2201–2204.
- [13] Nesim Yilmaz, Tuncer Demir, Safak Kaplan, and Sevilin Demirci. “Demystifying Big Data Analytics in Cloud Computing”. In: *Fusion of Multidisciplinary Research, An International Journal (FMR)* 1.1 (2020), pp. 25–36.
- [14] FJ Himpsel. “Low-dimensional electronic states at metal surfaces: Quantum wells and quantum wires”. In: *Surface Review and Letters* 2.01 (1995), pp. 81–88.
- [15] Kaixuan Chen, Marcus Fehse, Angelica Laurita, Jeethu Jiju Arayamparambil, Moulay Tahar Sougrati, Lorenzo Stievano, and Richard Dronskowski. “Quantum Chemical Study of the Fe NCN Conversion Reaction Mechanism in Lithium and Sodium Ion Batteries”. In: *Angewandte Chemie International Edition* 59.9 (2020), pp. 3718–3723.
- [16] Jian Zou, Jun Zhao, Bojun Wang, Shulin Chen, Pengyu Chen, Qiwen Ran, Li Li, Xin Wang, Jingming Yao, Hong Li, et al. “Unraveling the reaction mechanism of FeS₂ as a Li-ion battery cathode”. In: *ACS Applied Materials & Interfaces* 12.40 (2020), pp. 44850–44857.
- [17] Friedrich Stephanie and Louisa Karl. “Incorporating Renewable Energy Systems for a New Era of Grid Stability”. In: *Fusion of Multidisciplinary Research, An International Journal (FMR)* 1.1 (2020), pp. 37–49.
- [18] Tuan Anh Pham. “Ab initio simulations of liquid electrolytes for energy conversion and storage”. In: *International Journal of Quantum Chemistry* 119.1 (2019), e25795.
- [19] Zhixiao Liu, Aashutosh Mistry, and Partha P Mukherjee. “Mesoscale physicochemical interactions in lithium–sulfur batteries: progress and perspective”. In: *Journal of Electrochemical Energy Conversion and Storage* 15.1 (2018), p. 010802.
- [20] Ryan D McGillicuddy, Surendra Thapa, Malia B Wenny, Miguel I Gonzalez, and Jarad A Mason. “Metal–organic phase-change materials for thermal energy storage”. In: *Journal of the American Chemical Society* 142.45 (2020), pp. 19170–19180.
- [21] Robert J Noll and Jason M Hughes. “Heat evolution and electrical work of batteries as a function of discharge rate: Spontaneous and reversible processes and maximum work”. In: *Journal of Chemical Education* 95.5 (2018), pp. 852–857.
- [22] Hang Wang, Na Zhang, Shumin Li, Qinfei Ke, Zhengquan Li, and Min Zhou. “Metal-organic framework composites for energy conversion and storage”. In: *Journal of Semiconductors* 41.9 (2020), p. 091707.
- [23] John C Hemminger, John Sarrao, George Crabtree, Graham Flemming, and Mark Ratner. *Challenges at the frontiers of matter and energy: Transformative opportunities for discovery science*. Tech. rep. USDOE Office of Science (SC)(United States), 2015.
- [24] BJ Gao, JL Chen, SL Yuan, WF Yuan, FT Wang, LR Ding, XN Liu, ZM Liu, Z Huang, ZY Chen, et al. “Development and research in high magnetic fields at ASIPP”. PhD thesis. 1996, pp. 166–170.
- [25] Nakamura Shuto, Akari Chiyo, Himari Ken, and Sato Tanaka. “Quantum Materials to the Pioneering Future of Computing and Communication”. In: *Fusion of Multidisciplinary Research, An International Journal (FMR)* 1.1 (2020), pp. 50–62.
- [26] Youwei Wang, Wujie Qiu, Erhong Song, Feng Gu, Zhihui Zheng, Xiaolin Zhao, Yingqin Zhao, Jianjun Liu, and Wenqing Zhang. “Adsorption-energy-based activity descriptors for electrocatalysts in energy storage applications”. In: *National Science Review* 5.3 (2018), pp. 327–341.

- [27] Chao Yang, Kunkun Guo, Dingwang Yuan, Jianli Cheng, and Bin Wang. “Unraveling reaction mechanisms of Mo₂C as cathode catalyst in a Li-CO₂ battery”. In: *Journal of the American Chemical Society* 142.15 (2020), pp. 6983–6990.
- [28] Marnix Wagemaker and Fokko M Mulder. “Properties and promises of nanosized insertion materials for Li-ion batteries”. In: *Accounts of chemical research* 46.5 (2013), pp. 1206–1215.
- [29] Abhishek Parija, Gregory R Waetzig, Justin L Andrews, and Sarbajit Banerjee. “Traversing energy landscapes away from equilibrium: strategies for accessing and utilizing metastable phase space”. In: *The Journal of Physical Chemistry C* 122.45 (2018), pp. 25709–25728.