Pillars of Energy Flexibility: Demand-Side Response and Power-to-X

Ričards Stivriņš, Claudio Rochas, Agris Kamenders

Riga Technical university, Faculty of Natural Sciences and Technology

RTU FACULTY OF NATURAL SCIENCES AND TECHNOLOGY

Contact information:

Āzenes iela 12 – K1, LV-1048, Latvia

Ricards.Stivrins@rtu.lv

Demand-side response and storage is key for short-term, whereas Power-to-X technologies are indispensable for long-term flexibility and decarbonizing hard to electrify sectors.

This study reviews demand-side flexibility and Power-to-X technologies to evaluate their role in enabling energy system flexibility under high shares of renewable energy sources. It identifies key enabling factors and research gaps. Effective future energy systems require the integration of both demand-side flexibility and Power-to-X technologies, in line with energy storage, and sector coupling. Data-driven, real-time, and scalable solutions are essential for energy flexibility integration, to achieving a reliable and climate-neutral energy system.

Methodology

The review article includes the analysis of 42 distinct references, initial articles were identified via keyword searches (Demand-Side Response energy flexibility, power-to-x energy flexibility), upon which a snowball sampling technique was subsequently applied. The majority of sources are from high impact energy and engineering journals. Significant weight is given to reports from European Union bodies and energy agencies. Selected contemporary sources are utilized to provide real-time context on recent critical events and to track rapid developments in hydrogen market landscapes.

Energy Flexibility Enablers

	Demand response	Power-to-Hydrogen H_2	Power-to-Heat	Storage
Enabling technologies	• Heat pumps • HVAC systems • Smart thermostats & IoT controls • Building thermal mass	• Hydrogen storage • Electrolyzers • Fuel cells / gas turbines	• Heat pumps (air, ground, industrial) • Electric boilers (incl. electrode boilers) • Thermal energy storage	• Battery energy storage systems • Hybrid systems (battery, thermal, hydrogen)
Strengths/ Potentials	• Large, widely available flexibility source • Cost-effective and fast response • Enables load shifting (peak shaving)	• Long-term and seasonal storage • Enables decarbonization of industry & transport • Cross-sector integration	• Directly links electricity and heating sectors • Uses existing district heating systems • Strong short to medium term flexibility	• Frequency regulation and voltage support • Combining hybrid storage optimizes cost and performance • Enables aggregation and flexibility services
Weaknesses/ Limitations	• Depends on user comfort & behavior • Hard to quantify, generalize and scale • Requires smart control and data access	• High capital costs • Low overall round-trip efficiency • Infrastructure still underdeveloped	• Dependent on heat demand patterns • Limited long-term storage without large systems • Requires additional retrofitting of heating infrastructure	• Limited duration/scale/size • Battery cycle life and degradation. • High investment cost

Conclusion

- **Demand-Side Response** is confirmed as a **cost-effective, mature solution** for *short-term* flexibility, essential for managing immediate grid imbalances and negative pricing.
- **Power-to-X** technologies are the critical enablers for long-term and cross-sectoral flexibility, addressing seasonal storage and decarbonizing hard-to-electrify industries.
- Current models lack generalizability across different building types and climatic contexts; **Machine Learning** offers a path to scalable, data-driven forecasting.
- There is a deficit in models that integrate **real-time market signals**, user comfort constraints, and dynamic grid conditions simultaneously.
- Existing literature often individually analyses electricity, heat, and hydrogen sectors; a **unified, system-level framework** is urgently needed for effective sector coupling.
- Prioritize the co-location of **Renewable Energy Sources (RES)** with flexible loads to minimize curtailment and grid congestion.