Title

Energy storage for grid-scale applications: technology overview, current technological options, and future challenges

Abstract

One of the most direct and effective ways to decarbonise human society is to lower the carbon content of the electricity we use, which is achieved by increasing the share of Renewable Energy Sources (RES) in the energy mix. As headliners for the transition towards a net-zero greenhouse gas emissions economy, the EU countries set very ambitious goals for the fast-approaching deadline of 2050, and while the goals for 2020 were broadly achieved (if not surpassed), much more is still to be done to meet the 2030 and 2050 deadlines in line with our ambitions.

Decarbonising electric energy becomes even more relevant when we realise that many promising strategies to achieve a net-zero greenhouse gas-emissions economy rely on electrification and that electric energy consumption is most likely to increase. In the future EU strategy, renewables will represent 50% to 70% of 2050 energy production, depending on the level of ambition we decide to pursue. We know that such RES share will mainly be represented by non-dispatchable RES, whose production is complex to forecast precisely, even in the short term, and it is impossible to control. It is widely acknowledged that energy storage will play a decisive role in managing RES variability, enabling renewable production to be dispatched. RES causes many issues compared to traditional fossil-fuel-based production, but these can be mitigated with the right storage technology. Different storage technologies are and will be required because of the distinct nature of the issues. However, while for power-intensive uses (forecast errors, balancing actions, frequency regulation) the technological landscape is dominated by one or two well-established options, for energy-intensive uses (load shifting) it is much more diverse. The truly emblematic energy-intensive storage technology is pumped-hydro, but most advanced countries struggle to find new sites for pumped-hydro facilities. This sparked intense research and development efforts that produced a vast range of interesting storage technologies based on entirely different concepts, mainly thermo-mechanical, than electrochemical storage (i.e., batteries).

The seminar will provide a comprehensive introduction to the issues that must be addressed to advance RES integration, identifying which storage technologies can address each problem. After this, the seminar will focus on energy-intensive uses of storage and on the newly proposed technologies to replace pumped hydro. The pros and cons of the reviewed technologies will be discussed, covering aspects ranging from practical and technological limitations to potential environmental impact and replicability. Finally, we will try to identify the future outlook of each technology, also factoring in some economic considerations.

Seminar Agenda

- First lesson (2 h). **Time: 9:30 – 11:30 – Date: 12 January 2026 – Classroom TBD + Online**
  - Introduction
    - The EU/global path towards decarbonizationion
    - RES-related issues and their classification as power-intensive and energy-intensive
  - Storage technologies for grid-scale applications (part 1):
    - Classification of technologies based on charging and discharging times
    - Overview of technologies for power-intensive tasks
    - Pumped hydro: technology overview, overview, limitations and possible solutions
- Second lesson (2 h). **Time: 9:30 – 11:30 – Date: 13 January 2026 – Classroom TBD + Online**
  - Storage technologies for grid-scale applications (part 2):
    - Electrochemical and thermo-mechanical concepts
    - Thermomechanical concepts
    - Practical applications and economic outlook

Author's short bio

Guido Francesco Frate received his Bachelor's and Master's degrees in Energy Engineering from the University of Pisa (Italy) in 2013 and 2016, respectively, and his PhD from the University of Pisa (Italy) in 2020, with a thesis titled "*Analysis of a pumped thermal electricity storage system with the integration of low-temperature heat sources*".

From 2020 to 2022, Guido Francesco was a postdoctoral researcher in the Department of Energy, Systems, Territory and Construction Engineering at the University of Pisa, where he became an Assistant Professor at the beginning of 2022. In 2022, Guido Francesco was a *Visiting Researcher* at the Centre for Energy Storage at the University of Birmingham (UK) for a period of three months, and, in 2023, Guido Francesco held the same position at the Laboratory of Applied Thermodynamics at the University of Liege (BE) for a similar period.

At the University of Pisa, Guido Francesco teaches *Fluid Machines* and *Energy Systems* in graduate and undergraduate engineering courses. He has been the co-relator for more than 20 Master's theses and cooperated with several PHD students.

Guido Francesco's research focuses on using traditional and innovative energy storage technologies (particularly power-to-heat-to-power and Carnot Batteries) to integrate renewables in energy systems; on the optimal management of energy systems; on the use of high-temperature heat pumps to electrify the process heat production in industry via waste heat upgrading or direct production; finally, on the modelling and simulation of components for innovative energy storage and power-production plants.

Guido Francesco co-authored more than 40 journal and conference papers in collaboration with national and international researchers and industrial partners. He presented at several national and international congresses in the EU and the USA. He participated in several nationally and internationally funded research projects on energy savings in commercial activities, Innovative power production systems, and hybrid electro-thermal energy storage technologies. Finally, Guido Francesco participated in and coordinated several research activities funded by companies to promote energy savings and develop new technologies for more sustainable power production.