

SUSTAINABILITY COMPARISON OF ENERGY STORAGE AND DEMAND RESPONSE USING THE LEVELISED COST FRAMEWORK

Jacob Thrän, Imperial College London, j.thran22@imperial.ac.uk

Tim Green, Imperial College London

Robert Shorten, Imperial College London

Overview

To achieve net zero ambitions, the power sector will have to find replacements for the carbon-emitting dispatchable generators that have traditionally been providing the required flexibility to reliably deliver electricity. Two candidates for providing clean short-term flexibility are energy storage, such as batteries, and demand response, i.e. consumers shifting their electricity consumption temporally to support the grid. Both have seen their technology landscape change rapidly within the last decade. Energy storage solutions have been making huge leaps in commercial viability thanks to cost reductions in various technologies, most notably Lithium-ion batteries [1]. Demand response, on the other hand, has experienced renewed interest thanks to new end-uses like transport and heating being electrified, referring to the recently increasing uptake of electric vehicles (EVs) and heat pumps (HPs).

EVs can automatically vary the time at which they are charging (smart charging), or even deliver electricity back to the grid from their batteries, dubbed vehicle-to-grid (V2G). Heat pumps are also able to shift their power intake in time. One way they can achieve this flexibility is by temporally diverging from the house's temperature setting, i.e. using the heated space of the house as a type of thermal storage (smart heating). Another way for heat pumps to provide flexibility is by coupling them with a thermal storage tank (HP + TS).

These different demand response schemes as well as various storage technologies are all able to provide mostly the same flexibility services to grid stakeholders (e.g. reserve services or energy arbitrage). For that reason, they are likely going to compete with each other for the service provision with their success determined by their relative financial competitiveness. For policymakers and stakeholders to make informed decisions about energy storage and demand response, they must be able to compare the costs of different technologies. Comparing the respective social and environmental impact of storage and DR may further be of interest to policymakers so that they can optimise the sustainability of the different options, including any adverse environmental or social effects. This work comprehensively compares the costs of different DR schemes with the most competitive storage technology, as identified by [1]. Grid services can be identified as a function of duration and frequency of activations, and this analysis will be the first to illustrate the effect of frequency and duration on the competitiveness of different DR technologies. Additionally, this work quantifies the environmental costs of DR and qualitatively assesses social impacts.

Methods

The costs of these four different DR technologies are compared using the levelised cost of demand response (LCODR) framework [2]. Contrasting the resulting LCODR estimations to literature values from [1] for the levelised cost of storage (LCOS) permits the identification of the most competitive technology. This process is carried out for a range of activation durations and frequencies, illustrating how technologies' competitiveness is a function of the grid application they are used for and its activation requirements.

For the environmental assessment, a life-cycle assessment (LCA) was carried out for all DR equipment needed to provide a grid service. The data was taken from the ecoinvent database [3], and where possible accessed and processed via the CCaLC2 [4],[5]. In addition to the life-cycle evaluation of components that directly form part of the DR equipment, secondary effects are also discussed. One example of this is the increased tyre abrasion from heavier EVs with bigger batteries that may result from V2G. Shifting heat pump usage to where it is cheaper may also cause more nighttime activity which would reduce their efficiency as the coefficient of performance (COP) decreases. The environmental assessment of storage systems is taken from the results of [6].

Social impacts of demand response uptake are merely discussed qualitatively by referring to the relevant literature [7], [8].

Results

The results show that HP + TS is by far the cheapest DR scheme for any activation duration or frequency, and also outcompetes any storage technology. Smart heating without sizeable thermal storage, on the other hand, is more expensive than any other DR or storage solution thanks to the high number of participants required and their expensive compensation needs. Smart charging and V2G fall in between those two and are competitive with storage in some grid applications.

Preliminary results for the environmental assessment suggest that HP + TS has a bigger carbon footprint than any other DR scheme, although still much lower than any of the electrical energy storage systems. Smart charging has the lowest carbon footprint because it requires very little additional equipment. Smart heating similarly requires little equipment but the shift to nighttime heating requires more energy due to a lower COP. Heavier batteries from V2G usage are shown to increase tyre abrasion and thereby human toxicity potentials but it is difficult to quantify the impact with precision. The social impacts of demand response are often found in its potential for routine disruption which does not apply to the proposed DR schemes as they have little to no impact on the consumers' lives. External tampering with consumers' heating preferences may seem like a socially impactful policy but meaningful safeguards can be proposed to counter this.

Conclusions

Demand response is an alternative to energy storage for providing flexibility in power systems. Its costs in environmental, social and economic terms can be assessed using the levelized cost framework. This identifies the most financially competitive DR setup and permits an impact comparison in the social and environmental dimensions. All DR results are contrasted to the literature for storage which reveals that EV-based DR is sometimes financially competitive with storage. In contrast, heat pumps with thermal storage are much cheaper for any application that they are suited for. Environmental impacts of DR are generally lower than those of storage except for the human toxicity potential when specifically considering increased tyre abrasion from larger EV batteries used for V2G. This analysis of the sustainability of DR and storage provides energy system stakeholders with information about the financial and societal costs of both flexibility options.

References

- [1] Schmidt, O., Melchior, S., Hawkes, A., & Staffell, I. (2019). Projecting the future levelized cost of electricity storage technologies. *Joule*, 3(1), 81-100.
- [2] Thrän, J., Green, T.C., & Shorten, R. (2025). Levelised Cost of Demand Response: Estimating the Cost-Competitiveness of Flexible Demand. *SSRN Electronic Journal*. <https://ssrn.com/abstract=5101018>
- [3] ecoinvent. Ecoinvent Database. Retrieved January 8, 2025, from <https://ecoinvent.org/database/>
- [4] Azapagic, A. (2015). CCaLC2 software. Retrieved January 8, 2025, from <http://www.ccalc.org.uk>.
- [5] Azapagic, A., Stichnothe, H., Gujba, H., Espinoza-Orias, N., Jeswani, H., & Amienyo, D. (2017). CCaLC: Carbon Calculations over the Life Cycle of Industrial Activities.
- [6] Mostert, C., Ostrander, B., Bringezu, S., & Kneiske, T. M. (2018). Comparing electrical energy storage technologies regarding their material and carbon footprint. *Energies*, 11(12), 3386.
- [7] Darby, S. J., & McKenna, E. (2012). Social implications of residential demand response in cool temperate climates. *Energy Policy*, 49, 759-769.
- [8] Murtagh, N., Gatersleben, B., & Uzzell, D. (2014). A qualitative study of perspectives on household and societal impacts of demand response. *Technology Analysis & Strategic Management*, 26(10), 1131-1143.