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The Use of Battery Storage for Increasing the Hosting Capacity of the Grid for Renewable Electricity Production

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SUMMARY
This paper defines a step-by-step systematic decision making process to define operant conditions and applications for which battery storage is an option for electrical power grids. The set of rules is based on a number of research studies performed by the authors focusing mainly on sub-transmission grids. Battery storage is expensive so the focus in this paper is on comparing storage with other ways of achieving the same increase in the hosting capacity (HC) of grid. The approach is to find niche applications for which battery storage has unique advantages i.e. it provides a unique alternative for grid operator planning, which is unachievable in other ways.
The first step is to assess the grid's capacity to host new loads or production. This constitutes a baseline for evaluation of improvements from storage. The next step is to define applications for battery energy storage. Integrating new loads/production without increasing the hosting capacity may result in reduced performance and ultimately loss of production or consumption. The cost and severity of exceeding the hosting capacity will also affect the type of solution required. After this define the conventional planning solutions that would be adopted without storage option available. Such measures may include upgrading of transformer or construction of new power line. Curtailment, tariff based incentives or contracted load shedding as well as techniques like dynamic line rating can also be included in the comparison at this stage. Based on assessments of these alternatives it is possible to compare increase in hosting capacity with and without storage as well as comparing gains with storage to what can be achieved with conventional grid planning options or other novel methods.
It is also important to investigate the regulatory framework and constraints regarding ownership and operation of a battery energy storage. Should the grid operator own the battery storage? Or should the task be outsourced on a service contract or the service purchased in the market place? Storage capacity may only be utilized during certain periods. Can all or part of the storage capacity or the power electronic inverters perform additional functions and increase the return on investment for the installation? Regulatory aspects regarding the possibilities for different actors to pursue such additional income streams should be included in the assessment to correctly determine the return of investment of battery storage.
The final step should include control algorithm development, tested in a flexible but realistic environment and should establish whether the system actually delivers the predicted outcomes when exposed to real-time data. This may require building a pilot installation as a research and development activity before commercial deployment.

KEYWORDS
Energy storage, batteries, hosting capacity, grid planning

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1. Introduction

Energy storage has received much attention within the power engineering field during the last few years. Most of this attention has been towards new battery storage technologies like lithium-ion rather than the pumped hydro that today constitutes the vast majority of storage capacity in the electrical grid. Despite much research and dozens of small scale field trials the cost for storage capacity from batteries in the megawatt range is still substantial.

This paper outlines a road map towards the adoption of energy storage focusing on singling out applications where battery storage can produce benefits and additional ancillary services not possible to achieve by other means. The steps are given in Table 1; each step is described in detail in the subsequent sections together with key findings from the author's research into electric energy storage sizing, regulatory framework and control. The initial focus of the evaluation is a technical evaluation followed by the regulatory and economical aspects and finally on the feasibility of the required control schemes.

Table 1 Step-by-step approach to applying battery storage

Section	Step
2	Determine the grid hosting capacity
3	Define applications for battery energy storage
4	Estimate consequences of operating the grid without hosting capacity increase
5	Compare increase in hosting capacity using storage and other methods
6	Assess regulatory aspects and additional income stream
7	Evaluate technical feasibility of proposed storage scheme
8	Verify maturity of solution
	Full scale deployment

2. Determine the grid hosting capacity

The hosting capacity (HC) is defined as the maximum amount of new load or production that can be connected without endangering the reliability or quality for other customers [1]. The HC is a transparent and objective method for quantifying and comparing the amount of Distributed Energy Resources (DER) that can be integrated into the grid. It can be calculated for individual locations but also for a larger area (e.g., the distribution grid behind an HV/MV transformer). HC enables a fair and objective discussion between stakeholders. The concept has been recommended by the European energy regulators [2] and the European grid operators [3] and many researches, also including EPRI in the US [4]. It has gained popularity as a way to quantify the performance of future electricity grids (the "smart grid"). The hosting capacity approach also enables assessment of the suitable power ratings and capacity as well as optimal placement of storage within an electrical grid [5].

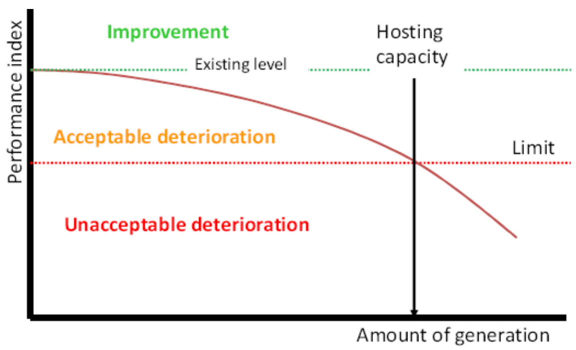

Figure 1. In the hosting capacity approach a power quality performance index is considered. With the increase of production (or loads) an acceptable deterioration of power quality is defined. When the generation (or load) increases further the performance index will reach a limit beyond which the deterioration is unacceptable. This limit to the amount of new generation is taken as hosting capacity for the studied performance index. Hosting capacities for several performance indices are to be studied to find the overall limits to new generation (or loads).

The HC is dependent on the selected performance indices. The impact of additional generation of DER in a grid can be quantified by using a set of performance indicators including power quality measurements like voltage magnitude, voltage dips as well as overcurrent limits in the distribution grid. The use of a performance index to determine the HC is illustrated in Figure 1 from [1] and has been further developed by the authors in [6] [7].

To meet today's battery life-time limitations, identify applications that require storage cycles of hours to maximum a few days. The performance indices that limit the HC can normally be improved by shifting the active load onto these time scales. If the HC is limited by rare and prolonged events storage of part of the power flow for a couple of hours will do little to improve the overall situation. Suitable locations for the storage will be where the overall HC limit shows a large sensitivity to the value of these performance limits.

Evaluation of a grid's hosting capacity is dependent on realistic power flow time-series within the grid. Hourly time resolution, or preferably 10-minute averages, are required to evaluate the gains in hosting capacity from battery energy storage. Such data is commonly available at transmission and sub-transmission level in Sweden. Otherwise the first step towards defining applications for storage would be to implement such measurements and log the data during a time period of at least a year.

3. Define applications for battery energy storage

Energy storage can be used for a number of potential applications. These applications can be characterised by the timescale of the phenomena. In Figure 2 the characteristic time scale of different applications are shown together with examples of storage technologies suitable for the same timescale.

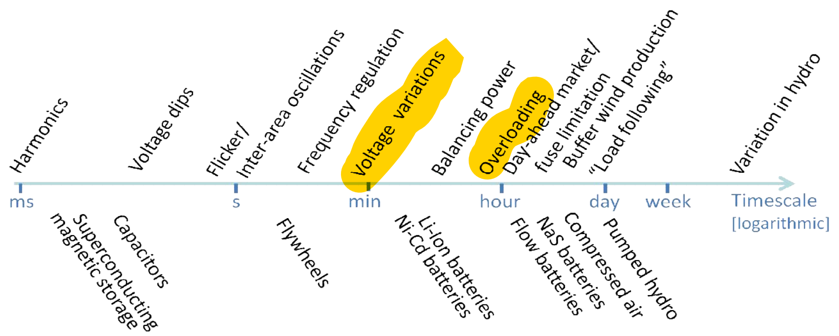

Figure 2. Applications and storage technologies characterised by their typical time scales.

Besides time-scale, a distinction should also be made between the duration of the required storage cycle's versus the time-interval between cycles. In Figure 3 the vertical axis shows the time between cycles while the horizontal axis gives the required storage duration.

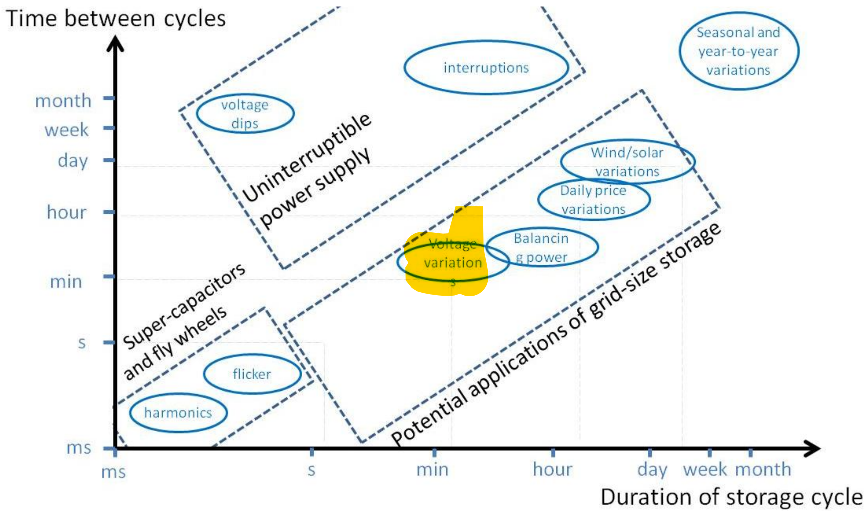

Figure 3. Selection of suitable storage technologies due to interval and duration of required storage cycles

A third distinguishing factor is between applications that require large power ratings and those that require relatively higher storage capacity (higher MWh to MW ratio). The required storage capacity is given by integrating over time the power that is to be removed or supplied to the grid. Batteries can consist of either stacks of individual cells (e.g. lithium-ion storage) or flow batteries where chemically active components are dissolved in liquids and the capacity can be relatively cheaply expanded with bigger tanks. For lithium-ion batteries (which are currently gaining much attention) the cost will be driven by capacity rather than power requirements, thus excluding the applications on the far right of Figure 2 and Figure 3.

Other influencing factors in the selection of appropriate applications for battery storage are acceptable losses per cycle, number of deep and shallow storage cycles. For battery storage the current lifetime of most commercially available grid size storage technologies will imply that frequent cycling (above a few times per day) will lead to unacceptable short life time of the battery. Thus the applications on the far left of Figure 3 and Figure 3 can be excluded from further study.

Dimensioning storage for the extreme cases can seldom be justified. As shown in [5] a 4 MWh storage can eliminate 40% of overloading resulting from a wind park simulated as 67 MW installed capacity compared to the hosting capacity of 56 MW. To handle the entire overload from the worst situation in a three year period would require 160 MWh for a 60 hour period of near continuous overproduction during an autumn storm. In such situations, an alternative to storing the surplus energy production that cannot be delivered to the grid is curtailment. Curtailment of production involves reducing the power output from certain energy resources at times when there is a risk of overloading a transformer or some other component. In the case of wind power the pitch angle of the rotor blades can be altered to "spill wind". The wind will then pass without optimum energy capture, thus reducing the power output of the wind turbine. The ability to curtail the production implies that all overloading does not have to be taken care of by the storage unit and a design decision is required as to how much to store and how much to curtail. Such assessments will be largely economic and based on technical results defining when an increased storage size gives diminishing returns per storage unit.

4. Estimate consequences of operating the grid without hosting capacity increase

When loads or production exceed the hosting capacity one or several performance indexes are exceeded (see section 2). This can imply unacceptable voltages and current, fines for exceeding regulatory requirements, shortened equipment life-time or even exploding transformers and blackouts.

Traditional grid planning is based on the N-1 operational criterion, which ensures a high reliability of transmission and subtransmission grids. However this sets a severe limit to the amount of wind power that can be connected because of the need for spare capacity in the grid. If the reserve could be made available in another way, e.g. by reducing consumption or production, this could result in a more cost effective alternative than providing energy storage. Using curtailment schemes, dynamic line rating or special protection systems a large increase in hosting capacity is possible without increasing the risk of overloading, as has been shown in [8]. In effect, part of the HC risk is converted into economic risk and this is taken on by the wind-park owner through loss-of-production during periods with overload.

5. Compare increase in hosting capacity using storage and other methods

Conventional grid planning solutions include upgrading transformers or constructing new power lines. Such solutions constitute a bench-mark for comparison when evaluating the gains from the new emerging technologies such as grid-scale energy storage.

Different planning levels or changes in regulation can also alter what is considered acceptable. If a grid operator adopts tariff-based incentives or contracted load shedding, the measures' efficiency at resolving hosting capacity violation(s) can be assessed. It is then feasible to include in these comparisons, technologies such as dynamic line rating or controlled production curtailment.

The reduction in overloading with battery storage is shown in Figure 4 (take from [5]).

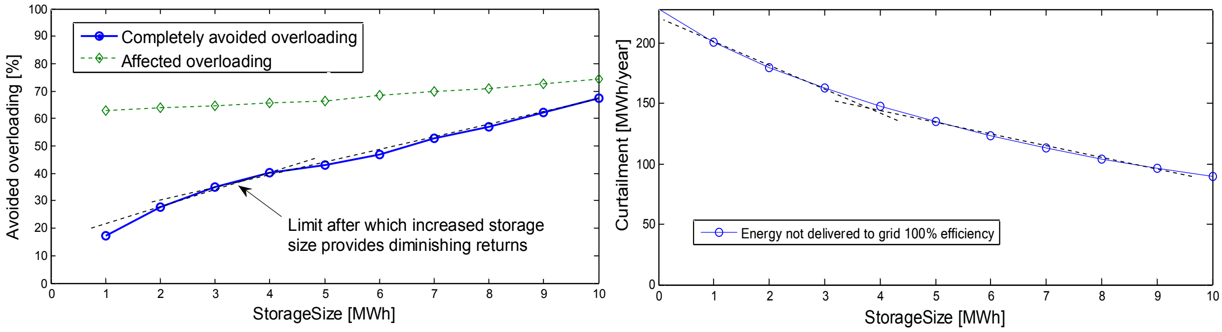

Figure 4. Avoided overloading (left) from wind power with energy storage in a 10 MVA 40/10 kV transformer in central Sweden. The corresponding decrease in required curtailment is shown to the right. In both figures the point of diminishing return is indicated [5].

While the reduction of overloading constitutes improvement of performance index a direct gain in hosting capacity results from the possibility to gradually curtail the production, rather than from the storage installation itself (as the storage will not eliminate all instances of overloading).

Our second case is from an assessment of a virtual power plant in which storage and hydro power are coordinated to compensate for solar photovoltaic's and wind power prediction errors in order to meet spot market [9]. Again a part of the gain can be ascribed to the battery energy storage and part to the new dispatch policy for the existing hydro-plant and reservoir, see Figure 5. Maybe only the improvement due to hydro power is economically viable? However the storage can also absorb power while the run-off hydro plant and reservoir can only delay power dispatch in an over production situation. The refurbishment of the plant to a pumped hydro installation would be a substantial investment but may still be as efficient as, and cheaper, than the here described battery storage with several MWh of capacity.

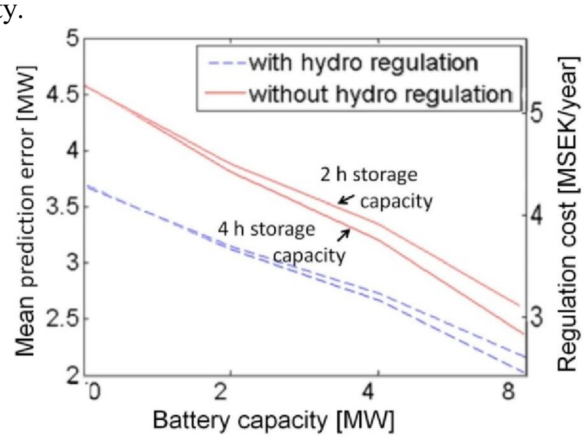

Figure 5. Reduction of prediction error from wind and solar production when included in an aggregation of different DER into a so called virtual power plant with an existing hydro reservoir and different battery storage sizes. The two upper (solid/red) curves are with only battery storage [9].

Our research shows that battery storage can be the better solution when the need to decrease power flows occurs often (daily) and for short periods. If the need to reduce power flows occurs seldom (e.g. a few times per year) controlled curtailment is probably a better alternative as the power not delivered to the grid will only be a fraction of the total annual production.

It is important in the assessment not to restrict the investigation too much to the present cost of storage. Instead the aim of the assessment should be to compare the potential with and without storage in the grid. During this step the amount of storage that is reasonable to be installed in the grid is assessed through comparison with other alternatives. In this way, the most appropriate solution to obtain the same gain in hosting capacity is found. Knowledge of the full potential with storage can still be valuable, allowing quicker adaptation if and when prices for storage decrease.

6. Assess regulatory aspects and additional income stream

Despite harmonisation attempts at the European level, the regulatory framework is still largely national. Different countries have different constraints to what a grid operator can own and operate. The regulatory framework regarding storage in Sweden is assessed in [10]. Economic incentives available for the construction of battery storage may vary and only be available for specific legal identities. Two other relevant questions are: Does the regulatory framework allow the grid operator to own the storage? Do current incentives make it more profitable for producers or aggregate-ors to operate the storage? Depending on the outcome of these questions it might make sense to rent ancillary services from a third party that use the storage for arbitrage on spot or regulation market.

Again from [9] Figure 6 shows the use of storage resources for three applications using both battery storage and hydro reservoir. While dark patches indicate frequent uses, other applications may only occasionally require the battery storage as is the case for the middle application in the figure.

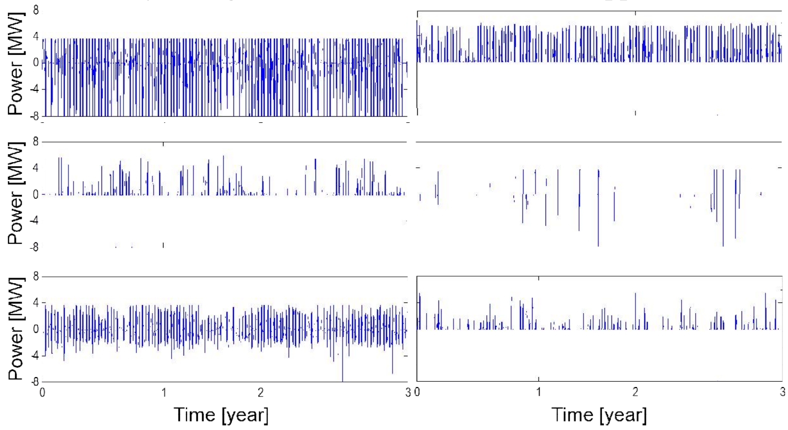

Figure 6. Time use of the hydro and battery storages for three studied ancillary services. Top row shows balancing with battery as primary storage (left) and hydro reservoir as secondary storage (right). Middle row: peak monthly reduction with reservoir as primary storage (left) and battery as secondary storage (right). Bottom row: loss minimisation with battery as primary storage (left) and reservoir as secondary (right). In the simulations only one application is applied at a time [9].

During this stage it should be evaluated if storage can provide additional ancillary services or emergency support such as Uninterrupted Power Supply (UPS) to prioritise loads or black-start possibilities of smaller grids. Such opportunities to add value could complement the main application and allow part of the investment to be added to the grid operator cost base included in use of grid tariffs.

In situations where planning permissions take a long time, battery storage is often the only option. Mobile storage in the 1 MWh range can be used as a temporary measure and then moved to other locations once the grid has been strengthened.

7. Evaluate technical feasibility of proposed storage scheme

The efficient usage of storage requires development of control algorithms and integration of the storage into existing grid operator dispatch practices. This requires development efforts that can be undertaken using small or even simulated storages operated under realistic conditions and using actual planned communication infrastructure. The dispatch of the storage needs to be decided. Is it by the storage owner, aggregator or to be integrated with grid owners control procedures? Can the storage be operated only with knowledge of local parameters (such as grid frequency, power factor and local voltage) or are remote measurements and market related data required for its operation?

The dispatch of any storage is an optimisation issue. It must withhold sufficient battery charge to be available when most required (similar to achieving a high capacity credit, an indicator for the reliability of a generation type to be available during peak demand hours). Yet still the storage must not be kept idle for minor situations when its services could still benefit the grid (similar to achieving a high utilization factor, a metric that can be assigned a generator or a power transformer).

If the choice has fallen on multiple distributed storage installations rather than one large central unit there is also a need for distributed or coordinated control of individual storage units. The verification that the actual control procedures and operation algorithms can fulfil the expected targets can be achieved also in smaller field prototypes. Due to the difficulties in accurately assessing state-of-charge of some battery technologies also battery management system may impact storage performance in a way not foreseen in theoretical studies as they try to preserve life-time of the batteries.

8. Verify maturity of solution

This paper has outlined a step-by-step approach to the full scale deployment of energy storage by a grid operator. A similar step-by-step procedure for research and development is outlined below. A focused R&D strategy on behalf of the research funders can help to mature and commercialize the use of battery storage within electrical grids. The required cost reduction of battery storage is likely to be driven from other fields, mainly electric cars but possible also combined PV inverter and batteries that are beginning to enter the market and may well be soon offered as modular MV substation solutions. Meanwhile research focus should be on dedicated programs focusing on successively higher steps on the below list:

1. Develop methods for quantifying and comparing gain in HC from storage
2. Find other applications of storage and quantify their value in such a way that it can be added to the gain in HC from storage
3. Apply these methods to a range of typical and atypical systems to get insight into the kind of applications / systems /situations where storage will be an advantage compared to other methods
4. Develop suitable control algorithms for storage to increase HC and for the other applications, including methods to optimize between conflicting applications in the same storage installation
5. Test those algorithms through simulations and (where needed) in laboratory experiments
6. Test the successful algorithms in a flexible but realistic environment
7. Test the successful algorithms in a real-world environment, where possible in parallel with conventional methods, to gain confidence
8. Deploy storage in a real-world situation where it is needed

Activities directly targeting full scale demonstration without sufficient understanding of previous steps are likely to lead to weak or missed business case. The above steps should help ensure that grid operators and public funding is used cost-effectively. Over time the research should be required to produce more concrete and usable results corresponding to the later steps on the above list, thus giving gradual and incremental long term development.

Conclusions

The percentage of production from variable energy sources is growing and it is becoming ever harder to obtain permission for traditional grid planning alternatives. Battery storage is an additional option that can be added to the grid operator solution portfolio. It is important to gain experience with storage technology for it to be effectively and cost efficiently applied when the need arises.

The step-by-step procedure outlined in this paper can determine circumstances and applications for which battery storage is a grid planning option providing unique benefits not possible to achieve by other means.

A positive return on investment assessment will today likely require the use of multiple applications of the same storage installation. This implies that the ownership of the storage may need to be outside of the grid operator with grid support options and ancillary services contracted.

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