Economics of Electric Energy Storages in Electricity Distribution

J. Lassila, V. Tikka, J. Haakana, and J. Partanen

***Abstract*— The role of energy storages in modern smart grid environments is evident. The increasing proportion of uncontrollable renewable energy sources in electricity systems brings new requirements for energy storage solutions. However, even though the demand for energy storages is obvious, their economic feasibility has not been addressed in detail so far. Yet, the issue is highly relevant to distribution system operators (DSOs). Critical questions are, for instance, whether energy storages are technically feasible and whether there is demand for them in the system where the storages should be located, what the size of the storages should be, and how the cost-optimised operation of the storages should be managed. To be able to answer these questions, the economics, technical behaviour and constraints of energy storages have to be understood. This paper presents the principles of the economic feasibility analysis of battery energy storage systems (BESS) in a distribution network. The results are based on analyses of the development of the economic value of a distribution system and the lifetime costs of the BESS's. The findings help DSOs to analyse the economic feasibility of energy storages in their network environment.**

***Index Terms*— Energy storage, storage economics, distribution system operator, network planning**

I. INTRODUCTION

An objective of the global smart grid programs is to raise the efficiency of electricity distribution systems. One way to achieve this is to promote efficient operation of the electricity distribution capacity. The management of renewable energy sources and distributed energy resources plays a significant role in the efficient future smart grids. In particular, stationary and mobile energy storages will be among the key issues in the smart grids. There are several stakeholders that are interested in the storage of energy (Table I). The table shows that the interests and expectations related to energy storages vary between stakeholders. Targets such as peak shifting [1, 2], frequency control [3] and island operation [4] have been discussed in numerous publications. An example of efficient operation of the distribution infrastructure is the release of power capacity by peak shifting. Another example is securing continuous power delivery in the case of grid interruptions. Both functions can be managed with electric energy storages that also provide a means to defer a distribution upgrade. These functions are discussed in more detail in the paper.

The cost-efficient implementation and operation of energy storages as part of smart grids requires understanding not only of the economics of energy storages and electricity networks but also of the expectations of different stakeholders with respect to energy storages. Table II lists some functionalities expected of energy storages.

TABLE I
STAKEHOLDER EXPECTATIONS OF ENERGY STORAGES (+++ MAIN ISSUE, ++ IMPORTANT ISSUE, + MINOR ISSUE).
TSO/DSO = TRANSMISSION/DISTRIBUTION SYSTEM OPERATOR.

	Reserve for power balance	Energy cost optimisation	Back-up during grid interruptions	Power peak-cut
TSO	+ + +	+		+ + +
DSO		+	+ + +	+ + +
Retailer		+ + +		+ +
Customer		+ + +	+ + +	+
DG		+ + +		+

TABLE II
REQUIREMENTS AND PROPERTIES OF DIFFERENT ENERGY STORAGE TARGETS (P = POWER, E = ENERGY).

	Operation frequency	Length of storage period	Orienta-tion
Reserve for power balance	Continuous	Very short	P
Energy cost optimisation	Daily	Hours, days	E
Back-up source/ storage during grid interruptions	Rarely (avail: continuous)	Days, weeks	E + P
Power peak cut	Daily, weekly	Hours, days	E + P

TABLE III
LITERATURE REVIEW ON EVS AND ELECTRICITY DISTRIBUTION
(+++ = MAIN THEME, ++ = IN AN IMPORTANT ROLE, + = MENTIONED IN THE PUBLICATION, ○ FOCUS ON OPERATOR PERSPECTIVE AND CONTENT).

Publication	Operator perspective					Content			Energy system perspective									DG			Business perspective			Storage technology perspective					Other		
	TSO	DSO	Retailer	Customer	DG	Theoretical	Simulation + case	Case (application)	Load leveling (peak shaving), time shifting	System capacity needs	Voltage quality, regulation	Renewables integration	Black start, islanding	Frequency regulation	Supply reliability	Supply reserve capacity	As a part of microgrid	Wind (farms)	Solar	Other DG	Energy arbitrage	Forecast accuracy (DG)	T&D upgrade deferral	Chemistry	Power electronics	Life-time (modelling)	Techno-economic analyses	Protection, safety	Price development	Energy policies, CO2	Electric vehicles
[5] Bragard et al. (2010)				o			o		+		+	++			+			+	++		+	++		++	+++	+	+			+	+
[6] Chen et al. (2012)						o			+			++		+		+		++				++				++	+++				
[7] Dicorato et al. (2012)					o		o		+			++						+++			+	++				++	+++				
[8] Hill et al. (2012)		o			o		o		++		++	+++	++	++	+				+++		++	++			+						
[9] Liang et al. (2010)					o		o		++			++						+++									+			+	
[10] Manz et al. (2012)	o	o	o		o	o		o	+	++	+	++	+	++	+	+		++	+		++	+	++	+	+	+	+++			+	+
[11] Miller et al. (2010)					o		o		++			++	+	+++			+	++	+		+			+	+		++				
[12] Paska et al. (2009)					o	o			+	+	++	++	+	+	+	+		++	+					++	++		++	+		+	
[13] Such and Hill (2011)	o				o				+	+		++	+	++				+++						+	+		+			+	
[14] Tant et al. (2012)				o	o		o		++		+++	++							++					+	++	++	+++				
[15] Whittingham (2012)						o		o	+			+		+	+		+							+++		+		+	++		++
[16] Wong et al. (2011)		o				o			++	+	+			+	+									+			++	+		+	++

The differences presented in Tables I and II have to be taken into account in the economic feasibility analysis of energy storages. The operation frequency may vary from continuous to daily or weekly based operation depending on the storage operator and application. In this paper, the focus is on distribution-level challenges and opportunities for storing energy.

Table III provides a literature review considering battery energy storage systems (BESS) and distribution networks. In the table, publications are grouped under various themes and perspectives such as operator, energy system, business and technology. It has to be borne in mind that the publications presented in the table do not fully cover the research area. Nevertheless, the literature samples show that although several scientific papers have been published on BESS's over the past few years, their economic effects on the electricity distribution business have mostly been neglected (see e.g. the column *Business perspective* and *T&D upgrade deferral* in Table III).

The paper focuses on peak shifting, supply reliability, and cost-optimised operation of the electricity distribution capacity with a BESS. The results are generic and can thus be used in the estimation of the lifetime costs of batteries in island operation as well as in peak shifting and peak cutting applications. The same principles can be partly adopted to electric vehicles and vehicle-to-grid operation. In all applications, the lifetime costs of the operation of batteries have to be determined taking into account that they depend, for instance, on the number of discharging cycles.

The target of the paper is to explain and illustrate the economic feasibility analysis of BESS in distribution systems. Hence, the paper helps distribution system operators (DSOs) to analyse the overall economics and feasibility of energy storages in their distribution networks, and to pinpoint installation targets for energy storages in the network. The findings also help DSOs in the cost-efficient operation of energy storages in the long run.

II. BACKGROUND OF ANALYSES

Network development strategies and investment decisions are based on techno-economic analyses. In the analyses, the benefits of investments are compared with the lifetime costs of the distribution system. It is common to compare different development technologies with each other to find the most feasible solution. For instance, when renovating an old feeder, the renovation alternatives to be considered could be for instance a traditional overhead line or underground cable technology. The former costs less as a one-time investment, but the lifetime outage costs can be higher because of a lower reliability. In addition, cost analyses have to be conducted for energy storages. A meticulous analysis of the possible benefits of energy storages as well as their lifetime costs is also required. With BESS's, the case is anything but straightforward. The benefits can be defined by network analyses. For instance, when the original load curve and peak cutting potential as well as the monetary value of the distribution capacity are known, it is possible to determine the economic gain of the energy storage from the network perspective. However, it is more difficult to define the lifetime costs of batteries because the costs strongly depend on the operating environment.

III. PROBLEM DESCRIPTION

The focus in the paper is on the development of a methodology for economic feasibility studies on the distribution network capacity and supply reliability. The key is to find out whether there is overall economic rationale for energy storages in distribution systems. In other words, the question is whether the benefits gained from the released distribution capacity and improved reliability are higher than the costs of the use of energy storages. The main steps of the methodology are presented in Fig. 1.

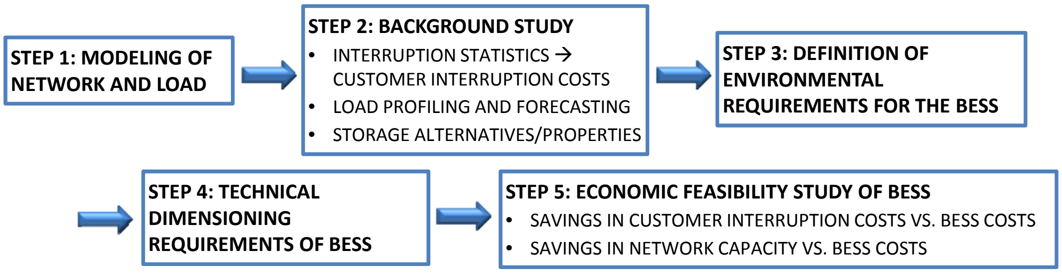

Fig. 1. Main steps in the energy storage methodology.

A. Required information and subtasks

Optimisation of the distribution capacity and reliability can be described by the cost function

$$\min \int_0^{t_1} \left(C_{\text{Inv-Net}}(t) + C_{\text{Opex-Net}}(t) + C_{\text{Inv-Storage}}(t) + C_{\text{Opex-Storage}}(t) + C_{\text{CIC}}(t) \right) dt \tag{1}$$

where

$C_{\text{Inv-Net}}(t)$	investment costs of the network
$C_{\text{Opex-Net}}(t)$	operational costs of the network
$C_{\text{Inv-Storage}}(t)$	investment costs of the energy storage
$C_{\text{Opex-Storage}}(t)$	operational costs of the energy storage
$C_{\text{CIC}}(t)$	customer interruption costs
t_1	lifetime

$C_{\text{Opex-Storage}}$ can be defined as a function of investment costs and capacity of the energy storage and allowed charging cycles over the storage lifetime.

The BESS operational cost can be described as

$$C_{\text{Opex-Storage}}(t) = c_{\text{Electricity}}(t) \cdot P_{\text{Bat-Loss}}(t) + C_{\text{Maintenance}} \tag{2}$$

where

$c_{\text{Electricity}}$	price of electricity
$P_{\text{Bat-Loss}}$	power losses of the battery
$C_{\text{Maintenance}}$	maintenance cost of the BESS

$$P_{\text{Bat-Loss}}(t) = P_{\text{Bat}}(t) \cdot \left[1 - \eta_{\text{Bat}}(t) \cdot \eta_{\text{Converter}}(t)\right] + \frac{dE_{\text{Self-Disch}}}{dt} \tag{3}$$

where

P_{Bat}	charging or discharging power
η_{Bat}	efficiency of the battery
$\eta_{\text{Converter}}$	efficiency of the converter
$E_{\text{Self-Disch}}$	self-discharging energy

$$\eta_{\text{Bat}}(I_{\text{Bat}}(t)) = 1 - \frac{I_{\text{Bat}}(t)^2 \cdot R(SOC(t), CC(t), CL(t), I_{\text{Bat}}(t), T(t))}{P_{\text{Bat}}(t)} \tag{4}$$

where

I_{Bat}	charging/discharging current
R	internal resistance of battery
SOC	state of charge
CC	cycle count
CL	calendar life
T	temperature

Internal resistance R is a combination of different factors, for instance battery state of charge, cycle count (CC), calendar life (CL), charging/discharging current and ambient temperature. All these factors are highly relevant in the analysis, and should therefore be defined with care. The total effect of the battery efficiency is not significant during one cycle, but in the long run, it may become a crucial factor in the feasibility analysis. In this analysis, the battery efficiency is assumed constant and independent of ambient circumstances. The efficiency of the power electronics poses an additional challenge to the BESS, and thus, a typical efficiency curve of the converter is not suitable for a low power. The converter may have a rather high efficiency rating, but the typical efficiency is only valid for the nominal operating current. In the case of an actual application, the nominal operating point is seldom exploited in full.

B. Battery Energy Storage in the operation and asset management of a DSO

BESS includes several interesting aspects to be considered in the context of electricity systems. As decentralised storage systems, BESS would affect the management of the distribution grid in a number of functional areas, including energy management, system services and internal business of the DSO [17]. In this paper, the focus is on the security of supply and power peak cut. The overall limit value for the economic feasibility of a BESS can be determined by

$$\textit{Lifetime savings} > \textit{costs of the storage use.} \tag{5}$$

There are several factors that affect the overall feasibility of BESS in an electricity distribution network. For instance, the higher is the number of interruptions (permanent and non-permanent, momentary), the better is the overall feasibility of the BESS from the perspective of the security of supply (assuming that faults do not occur so often that there is not enough time to recharge the storage). On the other hand, the longer an interruption lasts, the larger an energy storage is required (dimensioning of the BESS). A summary of an analysis of this kind is presented in Table IV from the perspectives of a BESS, the supplying network and an electricity end-user. However, when reading the table, it has to be taken into account that the direction of each effect is not always definitive but may vary depending on cross effects between different factors.

TABLE IV
EFFECTS OF DIFFERENT FACTORS ON THE FEASIBILITY OF A BATTERY ENERGY STORAGE SYSTEM, BESS (↗ = INCREASING, ↘ = DECREASING, - = NO EFFECT OR MINOR EFFECT).

		Dimensioning of the BESS	Life-time of the BESS	Operational costs of the BESS	Overall feasibility of the BESS
	Battery energy storage system (BESS)				
Higher..	Efficiency, power electronics	↘	↗	↘	↗
	Efficiency, battery	↘	↗	↘	↗
	Investment price of battery storage (€/kWh)	↘	-	-	↘
	Cycle life	-	↗	-	↗
	Supplying network				
Higher..	Number of permanent faults	-	↘	↗	↗
	Duration of permanent faults	↗	↘	↗	↘
	Number of non-permanent faults	-	↘	↗	↗
	Price of the network capacity (€/kW)	↗	-	-	↗
	Price of the electricity (€/kWh)	-	-	↗	↘
	Customer (load)				
Higher..	Peak power/peak energy -ratio	↗	-	-	↗
	Amount of stored energy	↗	↘	↗	↘
	Peak frequency	-	↘	↗	↗
	Unit cost of interruption (€/kW, €/kWh)	↗	-	↗	↗

The reason for the low utilisation rate of BESS is their high purchase price and limited lifetime. In average, the price of an energy unit in a battery (charging, discharging) is about 20 cent/kWh [18]. With the most recent battery solutions, the price is as low as 10 cent/kWh. If/when the price of an energy unit can be brought down to 2–4 cent/kWh, which is reached for instance with 15 000 charging events and a 400–500 €/kWh investment price, the application potential of batteries will be significant in the grids in the future.

In the paper, definitions for the economic feasibility are given. The definitions are illustrated by case studies to delineate the meaning and role of different background data and parameters used in the studies. Because of the strong correspondence with the parameters, sensitivity analyses are also performed.

IV. BESS AS A BACK-UP ENERGY SOURCE AND STORAGE DURING A GRID SUPPLY INTERRUPTION

The security of supply plays a critical role in electricity distribution. Industrial electricity customers, in particular, are highly interested in and dependent on uninterrupted electricity supply. Even a short (momentary) interruption, caused by a high-speed auto-reclosing operation, may lead to significant economic losses for instance in the process industry. In this section, the feasibility of a battery storage system is studied from the perspective of the security of supply. In Fig. 2, the principle of a BESS in a supply reliability application is illustrated.

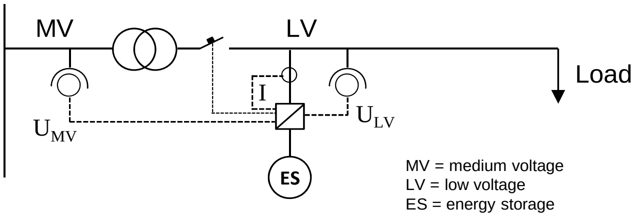

Fig. 2. BESS in a supply reliability application.

In principle, there are two main solutions to provide high-level supply reliability for the electricity end-user. In the first solution, the supplying grid is built with high-reliability technology. For a DSO operating in a rural area, this would require a weatherproof and meshed network structure. In the second alternative, high-level reliability is provided locally at the customer-end by a UPS (uninterruptible power supply) and energy storages.

The research questions related to the economic feasibility of storages in terms of supply reliability are:

- How do we determine the balance between an improvement in reliability and the costs of a storage?
- What is the optimum size of a storage in terms of power (kW) and capacity (kWh) with respect to the customer load and reliability of the supplying grid?
- How should long interruptions be managed by the storage, and what is the maximum interruption duration that the energy storage should cover?

The economic feasibility of a BESS in a reliability of supply application can be estimated by cost analyses where the number of grid interruptions (both short and long ones), customer interruption cost savings (CICS) as well as investment and operational costs of the energy storage are taken into account. CICS describe the change in customer interruption costs before and after the installation of the energy storage. An energy storage is economically feasible if the CICS are higher than the costs of the storage, and on the other hand, if the costs of the reliability improvement by a traditional network renovation method (for instance by underground cabling) are higher than the costs of an energy storage.

$$\int_0^{t_1} CICS(t)dt \geq \int_0^{t_1} C_{\text{Inv-Storage}}(t) + C_{\text{Opex-Storage}}(t)dt \tag{6}$$

Customer interruption cost (CIC) can be defined by [19]

$$CIC = \frac{E}{8760\ \text{h}} \cdot \{n_{\text{u}} \cdot c_{\text{un}} + t_{\text{u}} \cdot c_{\text{ud}} + n_{\text{p}} \cdot c_{\text{pn}} + t_{\text{p}} \cdot c_{\text{pd}} + c_{\text{hsar}} \cdot n_{\text{hsar}} + c_{\text{dar}} \cdot n_{\text{dar}}\} \tag{7}$$

where

E	annual energy, kWh
n_{u}	number of unexpected interruptions
c_{un}	unit cost for the number of unexpected interruptions, €/kW
t_{u}	duration of unexpected interruptions, h/a
c_{ud}	unit cost for the duration of unexpected interruptions, €/kWh
n_{p}	number of planned interruptions
c_{pn}	unit cost for the number of planned interruptions, €/kW
t_{p}	duration of planned interruptions, h/a
c_{pd}	unit cost for the duration of planned outages, €/kWh
c_{hsar}	unit cost for high-speed auto-reclosing, €/kW
n_{hsar}	number of high-speed auto-reclosings
c_{dar}	unit cost for delayed auto-reclosing, €/kW
n_{dar}	number of delayed auto-reclosings

A. Definition of fault duration for the energy storage dimensioning process

Considering the dimensioning of the storage capacity, the duration of expected interruptions plays a crucial role. The size of the energy storage is strongly dependent on the value of energy not supplied (ENS). For instance, if the power demand during an interruption is 100 kW and the interruption lasts for an hour, a minimum of 100 kWh output capacity would be required from the storage to be able to survive the supply interruption. In an actual case, the duration of interruptions similarly as their annual number is a highly statistical factor.

When considering the application of a BESS to improve the reliability of supply, reliable interruption statistics of interruptions have to be gathered from the case network. By the statistical data, possible savings in customer interruption costs can be defined. As seen from (7), the costs and possible savings in the CIC can be calculated based on several reliability factors. The current level of the CIC depends strongly on the feeder type and structure; whether it is an overhead line and located in a forest or by the roadside, or the feeder is built by underground technology. In addition, it is relevant to the cost analysis whether the feeder is a radial or meshed structure and whether it includes any distributed automation devices such as pole- or pad-mounted switchgear and remote-controlled disconnectors. The initial fault and interruption statistics reflect the situation in the present network, and thus, it is necessary to assess the state of the customer-end after the energy storage has been installed to the network. This can be carried out by the simulation methodology developed for the medium-voltage network interruption analysis described in more detail in [20] and [21]. The simulation requires adequate fault statistics including fault numbers and repair duration data. In the following example, the statistics include over 5000 actual fault events from a medium-voltage network. In the energy storage feasibility analysis, it is essential to determine both the number and duration of interruptions. Thus, the possible benefits can be defined. Figure 3 presents the fault distribution applied in this study.

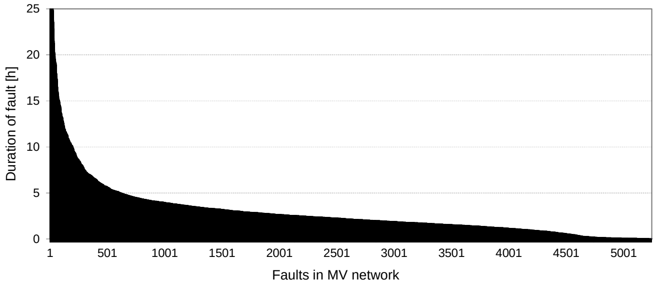

Fig. 3. Distribution of faults in a MV network for an eight-year period.

The simulation provides interruption durations for each network section, and thus, distribution substation specific data can be gathered. This together with the customer load profile curves forms the basis for the feasibility analysis of an energy storage installation. The principles of the interruption analysis model are illustrated in Fig. 4.

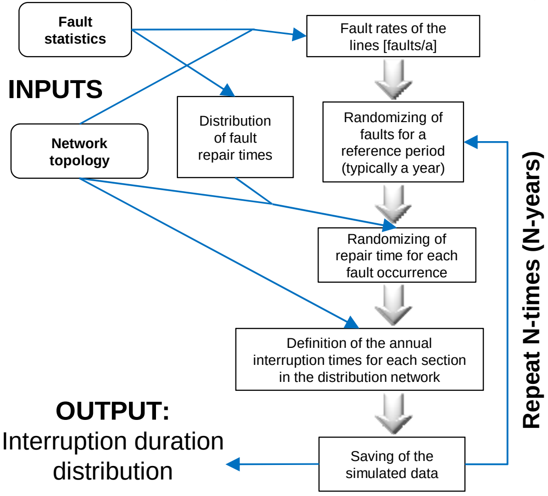

Fig. 4. Fault simulation sequence applied to the analyses [20].

A statistical perspective is included in the studies by Monte Carlo simulations. By the simulation, the performance of the network can be determined for instance for 1000 loops, where each loop corresponds to an example year in the analysis. In the simulations, an annual value for the ENS is defined. If the fault statistics available contain the durations of actual interruptions, the statistics can also be used to model the ENS, and thus, simulations are not required. This value describes the total amount of energy that cannot be supplied to the end-customer. If the annual ENS is zero, the energy storage covers all the interruptions caused by faults in the network.

$$ENS_{\text{annual}} = \frac{\sum_{i}^{N} \left(ENS_{i} - E_{\text{storage}} \right)}{N} \tag{8}$$

where

ENS_{annual}	annual energy not supplied from the grid
ENS_{i}	energy not supplied during a fault occurrence i
N	number of Monte Carlo simulation loops or the coverage of statistics in years

In the analysis, it is assumed that the storage can be fully charged before each fault in the network so that the whole capacity of the storage can be used to supply power during the interruption. The annual ENS is used to determine the average interruption duration experienced by the electricity end-users. It is defined as

$$t_{\text{avg,fault}} = \frac{ENS_{\text{annual}}}{P_{avg} \cdot n_{\text{avg,year}}}, \tag{9}$$

where

$t_{\text{avg,fault}}$ average interruption duration
P_{avg} average power during an interruption
$n_{\text{avg,year}}$ average number of interruptions experienced with the storage capacity E_{storage}

The effective number of interruptions, after the energy storage (ES) has been installed to the network, is defined as

$$n_{\text{avg,year}} = \frac{\sum n_2}{\sum n_1} n_{\text{avg}}, \tag{10}$$

where

n_1 number of interruptions experienced without an ES
n_2 number of interruptions experienced when there is an ES with a capacity E_{storage}
n_{avg} average number of interruptions without an ES

B. *Interruption management in the case network*

With the presented simulation methodology and interruption management equations, an analysis is carried out for an actual distribution network in Finland. The background information of the network is given in Fig. 5. Based on the network data and the fault frequencies, simulated interruption statistics for the case secondary substation are obtained. There are several remote-controlled disconnectors and backup connections on the feeder. There is relay automation only at the beginning of the feeder (at the primary substation).

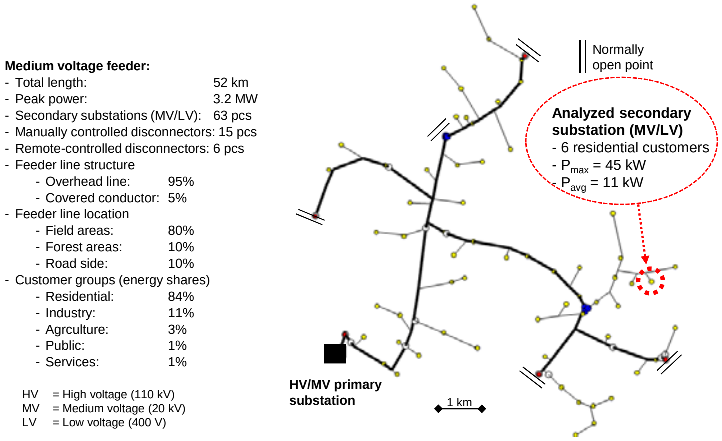

Fig. 5. Case network considered in the analysis.

Fig. 6 shows the curve of energy not supplied during the simulated individual faults for the secondary substation under consideration. The interruption lengths vary from 10 minutes to 9 hours and the ENS values from 0.25 kWh to 150 kWh depending on the interruption. The figure is a derivative from the interruption simulation process described in Fig. 4 and the load profile of the secondary substation under study.

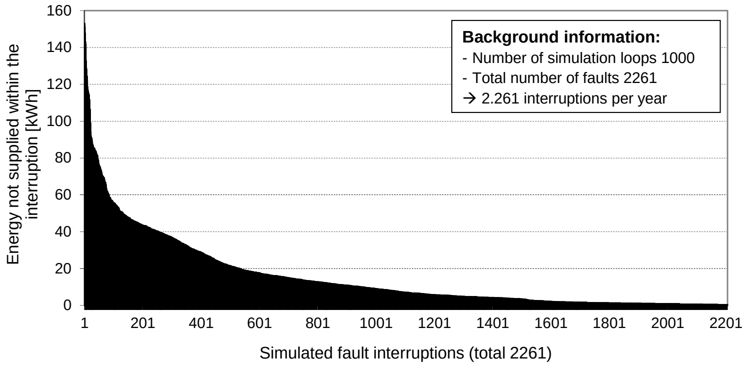

Fig. 6. ENS values within simulated interruptions for the case substation.

Fig. 7 presents threshold curves for the economic feasibility with BESS unit prices from 250 €/kWh to 1000 €/kWh for an energy storage installation in the case network as a function of backup supply duration and number of permanent faults applying the ENS data presented in Fig. 6, (1) and (7–10). Thus, in Fig. 7 the ENS profile remains the same while the number of permanent interruptions varies. The curves do not describe the optimal size of the BESS but they show the maximum duration of the backup supply from the energy storage, and thereby the maximum size of the BESS with which the installation is still viable. The optimal size of the BESS is somewhere below the threshold curve. The figure shows that the profitability of the BESS is quite low if only the reduction in permanent faults is considered. For instance, the break-even battery size of a 0.5-hour backup supply with the unit price of 500 €/kWh is around 7 faults/a (point a in Fig. 7). The economic feasibility of the BESS increases significantly if momentary interruptions are included in the CIC (dashed line). With the previous unit price and number of permanent faults, the break-even battery size would be approx. 1.1 hours (point b in Fig. 7). The momentary interruptions in the network under study contain an average of 20 high-speed auto-reclosings and five delayed auto-reclosings per year. The lifetime of the BESS is 10 years and the interest rate is 5% in the study.

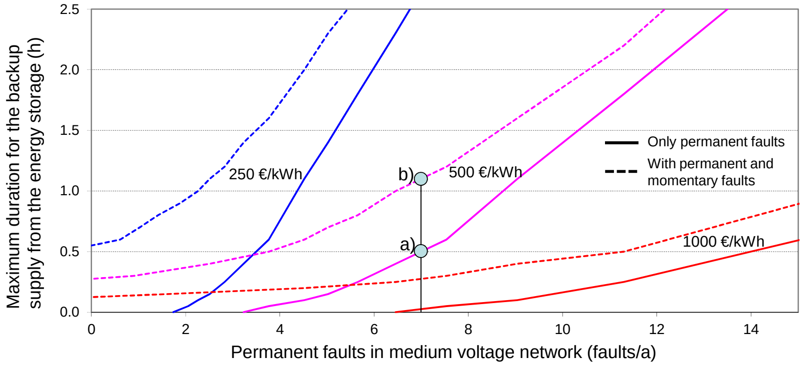

Fig. 7. Threshold curves for the installation of storages as a function of duration of backup supply with interruption of average power, number of faults and price of the BESS.

With the present battery prices (for instance 1000 €/kWh), the economic incentives to reduce long interruptions are relatively low. If the momentary interruptions are taken into account, the profitability of the BESS improves. If the frequency of permanent faults is higher and the battery prices are lower, the feasibility is significantly improved.

The reduction in the number of long interruptions depends on the size of the BESS. Nevertheless, a considerable number of long interruptions can also be avoided with a relatively small BESS capacity. An estimation of the reduction in the supply interruptions in the case network is given in Fig. 8, which illustrates interruption reductions with different BESS capacities. As much as 45% of the long interruptions can be avoided with a 0.5-hour storage capacity. However, in the case of small-size energy storages, a problem of insufficient power capacity may arise, because the BESS may not be able to supply enough power to the load. This power capacity requirement is a challenge also with momentary faults.

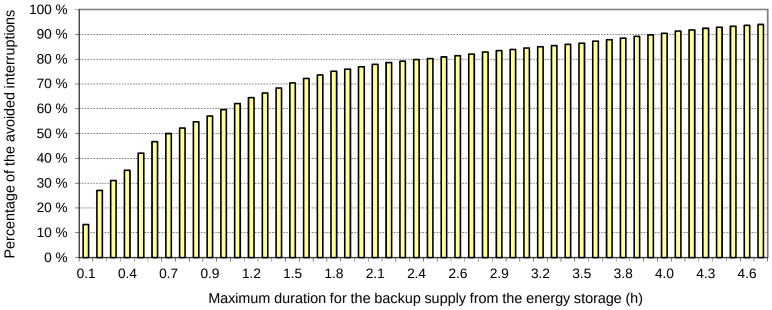

Fig. 8. Interruptions avoided with different BESS capacities (the capacity of the BESS defined by the average power of interruptions).

V. BESS IN POWER PEAK-CUT AND LOAD LEVELING

There are incentives to consider energy storages as a means to shave the peak and to smooth the load curves. The research questions related to the economic feasibility of energy storages in the power peak cut and load levelling are:

- How is the economic balance between the peak-cut (ΔP) and costs of the energy storage defined?
- What is the economic size of an energy storage in the sense of power (kW) and capacity (kWh) related to the base load in the network?
- How should an economic comparison be made between distributed (e.g. customer level) and centralised (e.g. medium-voltage feeder or primary substation level) peak cut operation?

Similarly as in the previous case, there are several factors affecting the feasibility of a BESS in a power peak cut and load levelling application (Table IV).

In (11)–(13), the conditions for the charging and discharging processes are presented. Equation (12) is based on the assumption that charging is started immediately after the peak cut [18] and the system load level (base load added by charging power) does not exceed the cut level during the charging process. Charging and discharging powers may also be limited by the BESS specifications.

$$E_{\text{discharge}} = \begin{cases} \int_{t1}^{t2} (P(t) - P_{\text{cut}})\, dt, \text{if } \begin{cases} P(t) > P_{\text{cut}} \\ P(t) - P_{\text{cut}} \le P_{\text{discharge}} \end{cases} \\ \int_{t1}^{t2} P_{\text{discharge}}\, dt, \text{if } 0, \text{if } P(t) - P_{\text{cut}} \ge P_{\text{discharge}} \\ 0, \text{if } P(t) \le P_{\text{cut}} \end{cases} \tag{11}$$

$$E_{\text{charge}} = \begin{cases} \int_{t1}^{t2} (P_{\text{cut}} - P(t))\, dt, \text{if } \begin{cases} P(t) < P_{\text{cut}} \\ P_{\text{cut}} - P(t) \le P_{\text{charge}} \end{cases} \\ \int_{t1}^{t2} P_{\text{charge}}\, dt, \text{if } 0, \text{if } P_{\text{cut}} - P(t) \ge P_{\text{charge}} \\ 0, \text{in all other cases} \end{cases} \tag{12}$$

$$E_{\text{discharge}} = \eta \cdot E_{\text{charge}} \tag{13}$$

where

$E_{\text{discharge}}$	energy needed for a peak decrease
t_1, t_2	start and end times
$P(t)$	load of the system
P_{cut}	cut level
E_{charge}	energy charged to the battery
$P_{\text{discharge}}$	discharging power limit (limited by the system and/or BESS propertie
P_{charge}	charging power limit (limited by the system and/or BESS properties)
η	$\eta_{\text{Converter}}$ x η_{Bat}

The theory related to the feasibility of peak cut actions can be illustrated by simple analytical methods. Fig. 9 shows two load peaks, both of which have a total energy of one unit. The two upper images show the actual measured load curves while the two lower images below show the simplified peak load shapes. The target is to demonstrate how the peak shape affects the application of a peak cut.

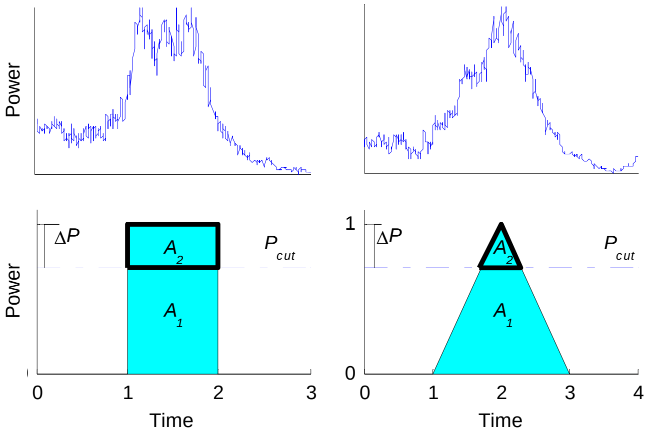

Fig. 9. Square load peak vs. triangle-shaped peak load. Both examples have the same surface area of 1.

In the case of a square-shaped load peak, the storage capacity increases linearly as the peak cut level is increased. In a triangle-shaped peak instead, the dependency of the peak cut level and the storage size is a square. Fig. 10a illustrates the dependency of the peak cut level and the energy required from the storage to the load. The economic feasibility analysis can be carried out based on knowledge about the load profile, for instance peak cut sensitivity and parameters related to the power supply. Fig. 10b shows how the peak load shape can affect the economic feasibility of a BESS used for a peak cut in a distribution grid. A peak cut seems to be the more economically feasible, the sharper the peak load spike gets. On the other hand, a square peak may also serve the purpose if the duration of the peak is short enough. Thus, the peak cut sensitivity, that is, the energy to Δ power ratio is dependent on the peak duration. Network costs are based on capacity costs, in other words, how much assets have been built to be able to transmit certain power through the network to the electricity end-user.

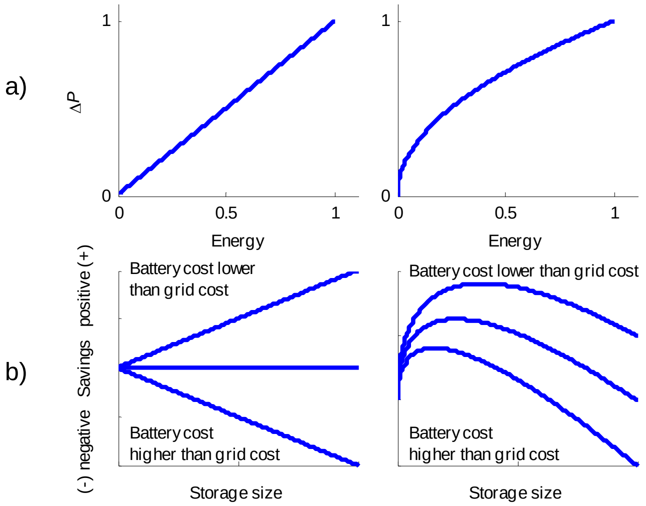

Fig. 10. Upper curves: Dependencies of the peak cut level and the energy required from the storage to the load in the cases illustrated in Fig. 9. Lower curves: Economic feasibility of a battery energy storage system in two theoretical cases. Savings take into account the released network capacity and the costs of the battery system.

A. *Peak cutting in the case network*

The case area consists of 100 electricity customers living in apartment houses, and the area is located in Southern Finland. The consumption consists of everyday household appliances excluding heating (Fig. 11).

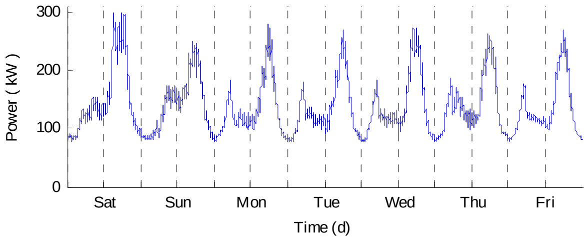

Fig. 11. Example: Load curve in wintertime for the case network.

The load varies significantly between day- and night-time. The difference between the peak and the low-load hours is almost 2/3 of the peak load. A peak operating time curve derived from an annual load curve is not an adequate tool for assessing the applicability of a BESS to a particular network but an actual load curve is needed. However, a peak operating curve may serve as a basis for considering the need for further investigations on the topic.

Fig. 12 illustrates some results related to the economic feasibility analysis of a BESS in the case network. It can be seen that the break-even point varies significantly depending on the battery unit price. The grid investment cost is treated as an average marginal cost [18].

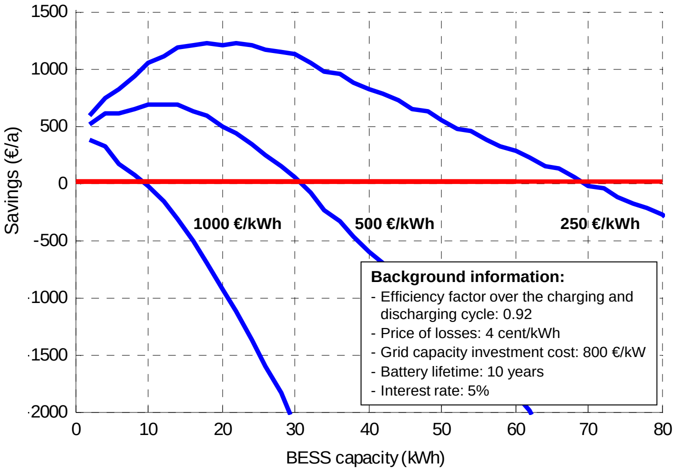

Fig. 12. Example: Feasibility study of a BESS in the case network.

With the present battery prices, the economic incentives to reduce peaks by BESS's are relatively low. However, if the BESS prices decrease, their economic feasibility will improve significantly. In the case network with a price of 250 €/kWh for the BESS, annual savings would be 1250 €/year with a 20 kWh energy storage at maximum.

VI. CONCLUSIONS AND DISCUSSION

Energy storages will be part of the future electricity distribution systems. An increasing proportion of uncontrollable renewable energy sources in the electricity system together with the growing requirements for the security of supply create pressure to store energy. So far, the prices of energy storage systems have been so high that there has been no economic rationale for energy storages in distribution networks.

In the paper, methodology related to peak shaving and supply reliability applications has been presented. The study shows that the economic feasibility of a BESS can be determined if there is reliable and adequate technical and economic background information available. As the results show, the economic incentives to improve supply reliability or reduce power peaks by BESS's are relatively low with the present battery prices. However, the prices are decreasing and the technological properties of batteries show an improving trend. These promote the economic feasibility of BESS's in electricity distribution. In addition to the price development, the economic feasibility can be enhanced if the BESS is simultaneously employed for several purposes such as peak cutting, supply reliability and renewable integration. However, this kind of a multi-purpose application was not in the focus of the paper.

In the study, intelligent load control has not been considered. This could provide an opportunity to decrease the electricity demand during an interruption, and thus, the capacity of the energy storages could be extended to serve electricity end-users during longer interruptions than without intelligent load control.

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Jukka Lassila received the M.Sc. and D.Sc. (Tech.) degrees in electrical engineering from Lappeenranta University of Technology (LUT), Finland, in 2000 and 2009, respectively.

He is a Post Doctoral Researcher at LUT and is also Director of Asset Vision Ltd., a consultant company. His main area of interest is electricity distribution systems, especially strategic planning of networks and network effects of electric vehicles and energy storages.

Ville Tikka was born in Savitaipale, Finland, in March 1984. He received his M.Sc degree from LUT in 2010.

Since then he has been a Doctoral Student at LUT. His main area of interest is modelling of the grid effects of electric mobility.

Juha Haakana was born in Ruokolahti, Finland, in December 1984. He received the M.Sc. degree from LUT, Lappeenranta, Finland, in 2008.

Since then, he has been a Doctoral Student at LUT. His main area of interest is strategic development of electricity distribution systems.

Jarmo Partanen received the D.Sc. (Tech.) degree in electrical engineering from Tampere University of Technology, Finland, in 1991.

He has been a Professor at LUT, Lappeenranta, Finland, since 1994. He is currently the Head of the Institute of Energy Technology at LUT. His main fields of interest are smart grids, electricity market, RES and regulation of electricity distribution business.