Electric Cars as Energy Storages – Case Study from Nordic Country

Jukka Lassila, Ville Tikka, Juha Haakana and Jarmo Partanen, Lappeenranta University of Technology*
(*) jukka.lassila@lut.fi (Tel: +358 50 5373636)
P.O. Box 20, 53851 Lappeenranta, Finland

Abstract

The present development trends in the transport and energy sectors pose challenges to the existing electricity distribution infrastructure. An objective of the global Smart Grid programs is to improve the efficiency of electricity distribution systems. Efficiency can be improved for instance by implementing energy storages to the grid and cutting the load peaks by feeding power on peak hours from the energy storages to the grid. Electric vehicles with vehicle-to-grid properties provide an opportunity to meet this challenge. Cutting of power peaks has a positive effect on the network dimensioning and costs, and finally, on the electricity distribution fees paid by the electricity end-users.

In this paper, the challenge is approached from the economic perspective of an electricity distribution company. In the paper, a case study related to charging and discharging of electric cars in an actual electricity distribution network is introduced. The focus is on the discharging perspective. The paper answers, for instance, such questions as to what the feasible level of energy storages (batteries) is in the distribution system, and how it is defined. The results show that there are economic incentives for bidirectional energy storages. The paper provides tools for a network analyzer to determine the feasibility of energy storages in different cases.

Introduction

The transport is taking a significant role in the development of electricity distribution. Several scenarios forecast a significant growth in the number of electric vehicles (later EVs) in the coming decades. This is not only a challenge but also an opportunity for the distribution infrastructure. Appropriately coordinated charging adjusts the load for the moments when the base load is most suitable for the charging, for instance in night-times. This load optimization requires intelligence (smart grids) implemented into the distribution system but also in the EVs, and on the other hand, different kinds of (economic) incentives for the EV users to follow the recommendations or restrictions for the charging. Grid to Vehicle (later G2V) and network effects have been discussed for instance in [1]-[3]. The economic consequences of EV charging for the distribution business have been discussed for instance in [4].

The next revolutionary step in the electrification of transportation is the option to operate EVs as energy storages on the grid, in other words, Vehicle to Grid (later V2G). This provides an opportunity for the engineers to increase the efficiency of the distribution system. The challenge of the existing power systems has been the large daily variation in the load levels; the power demand in the grid may vary tens or even hundreds of percents over the day. When the network dimensioning is based on the peak power, the overall efficiency can be rather low from the capacity point of view. For instance in the low-voltage networks, the peak operating times vary from 1500 to 2500 hours per year. The efficiency of the network can be improved by charging vehicle batteries at low-load moments and discharging them during peak hours. This releases network capacity, and reinforcement investments can be avoided or delayed.

With our case example, the target of the paper is to provide information and tools for asset managers and network engineers in electricity distribution companies to determine the economic effects of EVs and energy storages. By these tools, the key is to find out whether there is overall economic justification for the V2G process in distribution systems. In other words, are the benefits arising from the released distribution capacity higher than the costs of the use of energy storages (batteries)? With the case network, the paper demonstrates what kind of background information is needed and how it is used in the network analysis. The first useful results of economic effects can be achieved with a rather low amount of data. The results show that there are economic incentives for bidirectional energy storages, especially as the battery technology is constantly developing. The main steps of the methodology developed in this work are presented in Fig. 1.

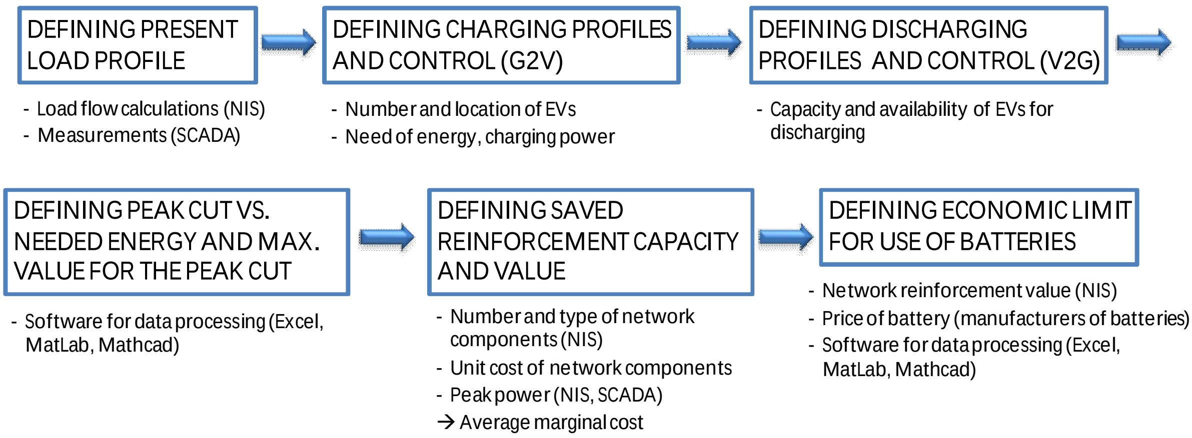
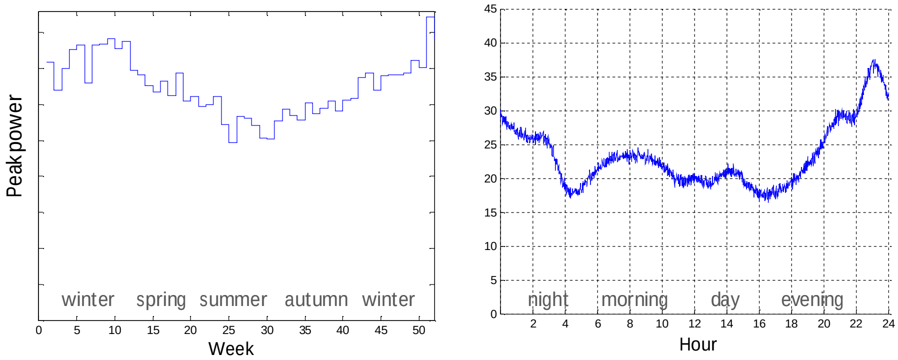


Fig. 1. Main steps and information sources in the economic feasibility study. NIS = Network Information System

Background for the studies

The case area of the study is located in Finland. The case company operates in a rural area. For this study, a low-voltage network with residential customers is chosen. The customers have residential houses heated by electricity (direct electric heating and electric heating with a water storage, heat recovery). Typical annual and daily load curves are presented in Fig. 2.



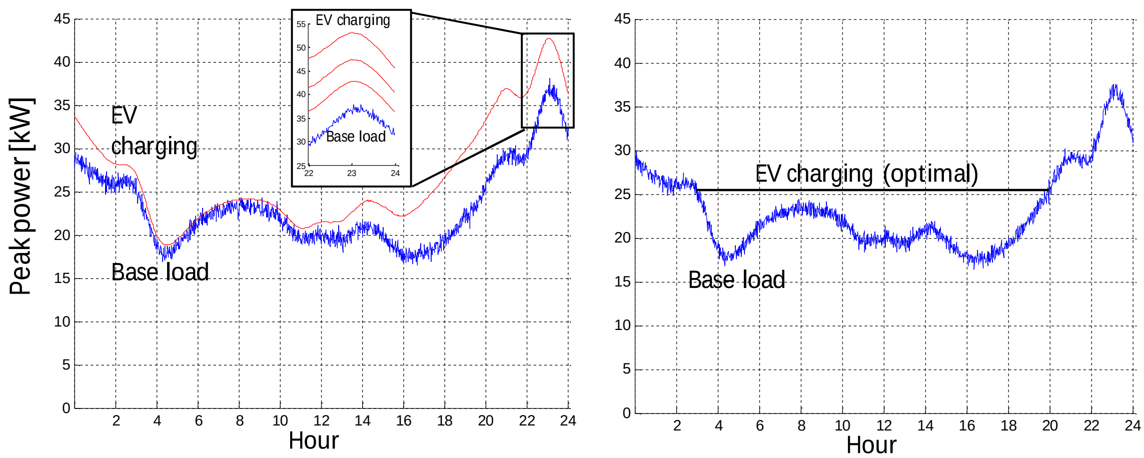
a) b)

Fig. 2. Annual (a) and daily (b) load curves of residential customers (electric heating with a water storage).

From the annual load curve we can see that the maximum load of the year is in wintertime. This is a typical situation in the Nordic countries. From the viewpoints of electricity distribution and transformer cooling, winter-time peak loads are easier to handle than summer-time peaks. Fig. 2b shows that the peaks are scheduled in the evening time. The highest peak occurs at 22–23 hrs, when electric heating is automatically switched on.

Methodological background

In this section, the methodology behind the feasibility study is discussed. The main focus in the paper is on the V2G perspective. Load curve analyses and the vehicle charging process (G2V) are in a minor role. The problems concerning the definition of charging curves are discussed in more detail in [5]-[7]. However, later in the paper the energy needed for driving is taken into account so that 1) vehicle charging is adjusted to low-load moments, and 2) the battery capacity available for V2G operation is reduced by the energy needed for driving. In Fig. 3, the effects of EV charging in the case network with and without control and intelligence is presented. The uncontrolled charging curve is based on national traffic statistics, where the use of (traditional) cars can be evaluated for the case area (driving distances, schedules). In the controlled (theoretical) alternative, charging is adjusted to low-load moments.



a) b)

Fig. 3. Load curve when (a) no intelligence and (b) intelligence is implemented into charging.

In Fig. 3b, the charging curve is more or less theoretical, but it shows that the daily energy for driving could be taken from the grid without increasing the present peak. In reality, a challenge is how to manage vehicle charging if cars are not available and connected to the grid during the low-load moments.

Economic principles

The economic effects of EVs will be significant on the electricity distribution business. The amount of required or delayed investments can be estimated by defining the transmission- or distribution- capacity-related average marginal cost of the network (€/kW). The principle has previously been discussed in [8]. The average marginal cost is based on the network replacement value and the maximum load of the year, and it describes how much the network capacity costs for the distribution company per each peak load kilowatt. For instance, if the network replacement value is 1 M€ and the distribution capacity of the network is 1 MW, the average marginal cost is 1 €/W or 1000 €/kW. Information to define the average costs can be achieved from network information systems (network component, unit costs) and load measurement databases (for instance SCADA).

$$\text{Reinforcement} = \text{Average marginal cost} \cdot \Delta P \tag{1}$$

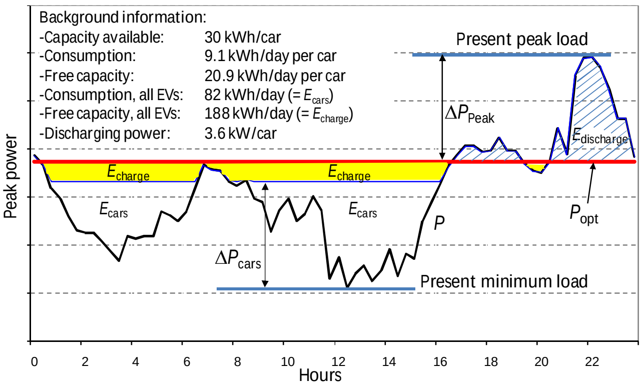
We have to remember that the use of average marginal costs supports network analyses in large-scale analyses; in other words, too target-specific cost analyses should be avoided. In this case, the focus is on the low-voltage network. Based on the replacement value and the present peak power of the network, the average marginal cost is 320 €/kW. A change in the network capacity has an effect on the distribution fee (cent/kWh). The additional network investments will eventually be paid by the end-customers. This can be determined when the annuity of reinforcement costs (€/a) is compared with the annual delivered energy in the network.

$$\text{Network value per delivered energy} = \frac{\text{Reinforcement}}{\text{Annual energy}} \tag{2}$$

For the case area, the delivered annual electricity consumption without EVs is 112 MWh. With (2), the network value per delivered energy (without EVs) can be defined in the present situation. The replacement value of the case low-voltage network is 19.4 k€ (a pole-mounted distribution transformer and aerial bundled cables), the annual value of which is 1120 €/a (40 a, 5 %). With (2), the network value per delivered energy is 1.0 cent/kWh in the present situation. It can be seen from (2) that if the amount of delivered energy can be increased in the present network without increasing the capacity, the network value per delivered energy decreases. This is actually the main target in the load control (shifting) in smart grids; to adjust (new) loads to the moments when the base load is low. This way, the capacity is better utilized and the overall efficiency of the distribution system is improved. In the case network, the estimated need for energy for EV driving is 29.9 MWh/a when the penetration level is 100%. If full penetration and charging of cars could be carried out without increasing the present peak load, the network value per delivered energy (2) would be 0.79 cent/kWh. This would mean that in theory, the distribution fees could be lowered if the growth in the energy use can be managed. In the opposite situation, charging is uncontrolled and without any intelligence as presented in Fig. 3a. In one scenario, peak power could almost double in the case network during the uncontrolled charging. By doubling the peak power and network capacity, network value per delivered energy would increase to 1.2 cent/kWh.

Methodology for V2G

In Fig. 4, the principle of V2G operation and peak cutting is presented. In the example, the free capacity of batteries is utilized by charging the batteries above the level that is needed just for driving. This additional energy (E_{charge}) is discharged ($E_{\text{discharge}}$) during the peak hours. The theoretical balance in charging and discharging can be found by taking into account the base load curve of the feeder, the energy needed for driving, and the capacity of batteries to store and discharge the additional energy.



$E = \int P(t)dt$	Energy distributed in a medium-voltage network, EVs not included	(3)
$E_{cars} = \int \Delta P_{cars} dt$	Energy required by EVs	(4)
$E_{discharge} = \int \Delta P_{Peak} dt$	Energy needed for a peak decrease	(5)
$E_{charge} = \frac{E_{discharge}}{\eta}$	Additional energy charged to batteries	(6)
$E_{cap} = \sum (E_{battery})$	Total capacity of batteries in EVs	(7)
P_{opt}	Load level when charging of EVs and the peak decrease have been taken into account	
ΔP_{cars}	Charging power, time dependent, optimized to base load	

Fig. 4. Additional energy (E_{charge}) needed to decrease the peak load and definitions included in the analysis.

At the moment, the price of batteries compared with their lifetime (number of charging and recharging cycles) is quite high. If the price of a battery is 300–700 €/kWh and the lifetime is 2000–4000 cycles, the investment price per discharged energy is 10–40 cent/kWh (Fig. 5). This is relatively high for instance compared with the typical electricity market spot price, 3–7 cent/kWh in the Nordic markets. When the number of cycles is increased by the battery technology improvement, the investment price per stored energy will be lower. The battery lifetime also depends strongly on the depth of discharging.

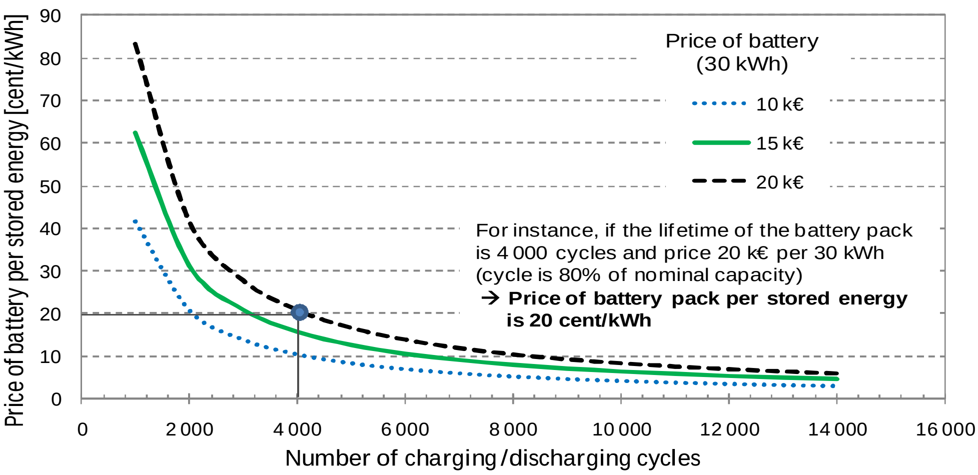


Fig. 5. Price of batteries (30 kWh) compared with their lifetime (number of charging and recharging cycles).

The principle of the battery cost definition presented in Fig. 5 is used in the following results. In this case, the price of battery pack per stored energy is 20 cent/kWh. This parameter as well as other parameters used in the study have to be updated depending on the case environment or by the overall battery technology improvement.

Results

In this chapter, the main results of the analyses have been presented. As discussed above, the original load curve (and the peak operating time) of the network strongly influences the feasibility of the peak cutting process. Based on the present load curve of the case network, it is shown in Fig. 6a how much energy is needed to cut a certain peak level in one year. We can see for instance that if the target is to cut the peak load by 10 kW over a whole year, about 0.3

MWh/a of energy has to be stored in the batteries and discharged back to the network during the peaks. We can also see that doubling the stored and discharged energy to 0.6 MWh/a, the peak cut is not doubled to 20 kW but it is now only 12.5 kW.

By (1), we can define an estimate for the saved reinforcement cost. The costs of batteries are based on the principle presented in Fig. 5. Fig.6b shows the presented economic limit for the peak cut in the case network. In the break-even point, the costs of the use of batteries and savings from the avoided or delayed network reinforcements are equal. In this case, the economic break-even point is reached if the charged and discharged energy from batteries for peak cutting is 1.75 MWh/a. By charging this energy in the batteries at low-load moments and discharging the energy back to the network at peak moments, about 19 kW cut from the present peak power can be reached (Fig. 6a). If the target for the peak cut is higher than this, the charged and discharged energy needed for the purpose will wear out the batteries (shorten their life-times), causing more costs than the benefit obtained from the network capacity savings.

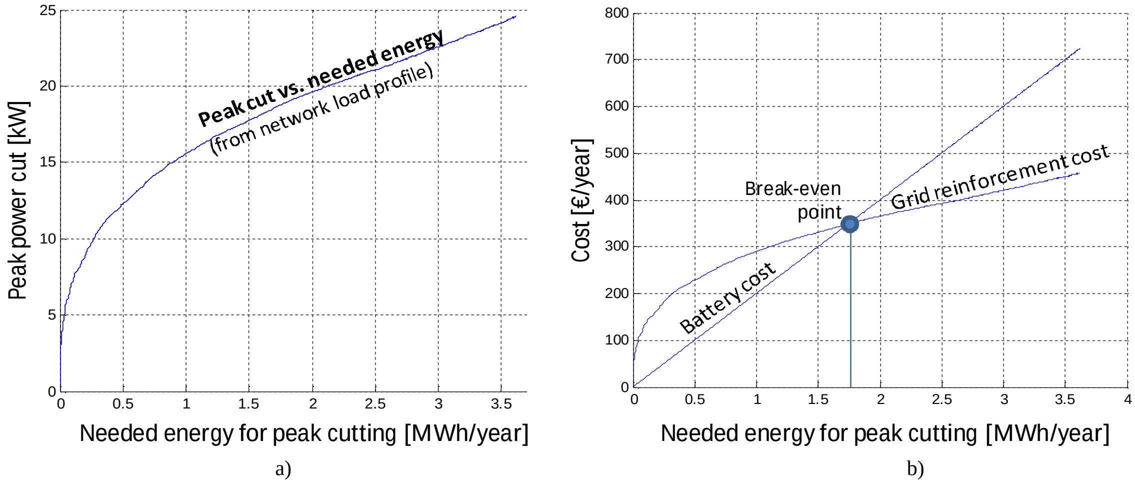


Fig. 6. a) Peak cut vs. needed energy (taken from the network load profile). b) Economic limit for peak cut.

Fig. 6b shows that a positive difference in the grid reinforcement costs and battery costs is highest with a low use of energy storages (batteries). In Fig. 7, savings related to the case are presented in more detail. The maximum savings for the case network (136 €/a) are reached when the peak cut is 10.9 kW. The energy required for the peak cut is 342 kWh/a.

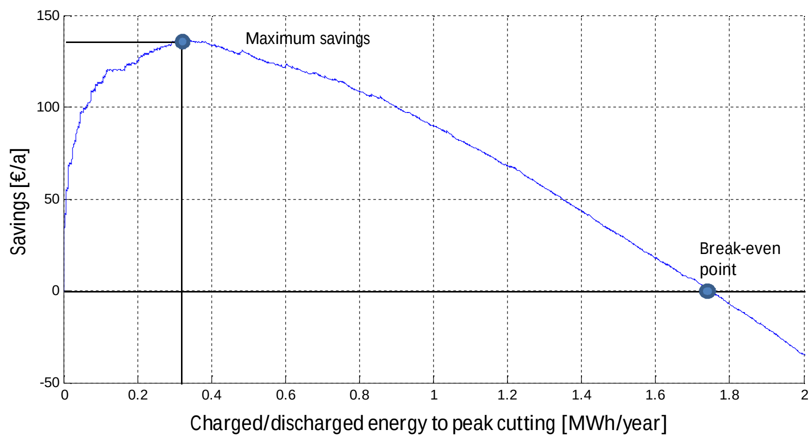


Fig. 7. Savings vs. needed battery capacity (charging/discharging).

Economic range for the use of car batteries for the peak cutting in the case network was shown in Fig. 6 and 7. By comparing the calculated economic cut limit (19 kW) to the actual load curves (Fig. 3) with and without EVs, it can be seen that the economic limit is in this case unobtainable. When the energy needed for driving is taken into account, overall load level is already that high, that the defined economic peak cut can't be reached with the full range. This technical restriction has to be taken into account when optimisation for V2G-operation is done. Other restriction comes from the maximum discharging power, in other words number of EVs available to supply electricity at the same time to the network. However, Fig. 7 shows that in the cost optimisation the best result can be achieved with the relatively low utilisation of energy storages. In theory, optimal peak cut presented in Fig. 7 would release the network capacity almost by 30%. This would decrease the network value per delivered energy to 0.65 cent/kWh which is 46% lower than in the scenario where EVs are charged without intelligence and V2G operation is not in use.

Conclusions

Energy storages will be part of the future Smart Grids. So far, the prices of battery systems have been so high that there has been no economic justification for energy storages in distribution networks. However, the prices are decreasing and the technological properties of batteries are improving. The role of energy storages will be significant in the peak shaving and in smoothing of the load curves. The first results show that the need for peak cut arises rather from the power than energy perspective. The economic feasibility is at best when the maximum peak cut can be achieved with the minimum energy stored in the battery.

It has to be borne in mind that the values presented in the paper are case specific. However, the study shows how important it is to understand the correlation between the network value, capacity, and energy storage systems. If the issue can be reasonably taken into account in the system planning, it will be possible to cut the distribution fees charged to the electricity end-users during the large-scale adoption of EVs. Correspondingly, if the system planning requirements are neglected, huge reinforcement investments will have to be made in the distribution infrastructure. This will significantly increase the distribution fees.

The main outcomes of this paper are:

1. Description of the overall energy storing methodology in distribution networks; what background information is required and how it is used to determine the need for EV charging and discharging energy and to analyze the associated economic effects.

2. The results verify the feasibility of the peak cutting function in a distribution system. There are economic incentives to use EVs as energy storages. Peak loads could be decreased significantly depending on the number and type of EVs, charging and discharging arrangements, their daily driving distances, and the shape of the base load curve. However, information used in the analyses has to be specified further.

3. It is possible to cut the distribution fees charged to the electricity end-users during the large-scale adoption of EVs, if the charging system is well planned and enough intelligence is included in it.

4. The major challenges will be faced in those low-voltage networks where load overlapping is more probable. However, there is a lot of experience of the transfer of loads (air condition, sauna ovens, electric space heating, water heaters, block heaters).

5. The values presented in the paper are case specific. Sensitivity analyses have to be done to recognize dependencies between the background information and the results.

The use of EVs as distributed energy resources makes it possible to decrease the above-presented peak loads. However, this kind of an arrangement is very complicated and will require significant technological development in EV control systems.

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