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Report

The benefit of batteries in a flexible distribution grid

Results from the FlexNett project

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ABSTRACT
This report is developed within the FlexNett project (2015-2018) and summaries the results from the demonstration sites focusing on batteries, located both at BKK Nett, NTE Nett and the municipality of Hvaler.

The FlexNett project aimed to contribute to increased flexibility in the future smart distribution grid by demonstration and verification of technical and market based solutions for flexibility, on different grid levels and for different stakeholders.

This report focuses on stationary batteries. A stationary storage is typically a lithium battery (Li-ion) and often consists of modules that can be assembled into larger units depending on the specification. A battery can be installed anywhere in the mains; at the customer (behind the meter), in a neighbourhood, in a network station / transformer station or at a production unit.

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1 Introduction

This report has been developed within the Norwegian research project "Flexibility in the future smart distribution grid – FlexNett" (2015-2018) and summaries the results from the demonstration sites focusing on batteries – located both at BKK Nett (Bergen), NTE Nett (Steinkjer) and the municipality of Hvaler.

The FlexNett project aimed to contribute to increased flexibility in the future smart distribution grid by demonstration and verification of technical and market based solutions for flexibility, on different grid levels and for different stakeholders.

The project results presented in this report are focusing on the benefit of batteries in a flexible distribution grid – located both at the customer side (behind the meter), in a community/neighbourhood or at the MV/LV substation (in the distribution grid).

The following topics related to the utilization of energy storages (batteries) in the grid are further elaborated:

- Batteries as a grid component (Chapter 4.1)
    - *Postponement of grid investments* and reduced *costs for energy not supplied* (CENS) when installing a battery in the distribution grid.
    - *Voltage support* when using the battery inverter to reduce imbalances between the voltage on the different phases (for a prosumer located in a weak distribution grid).
- Customer location (Behind the meter) (Chapter 4.2)
    - *Increased self-consumption* (prosumer) using the battery to store surplus energy for use at other times of the day when the consumption is higher than production from the solar panel.
    - *Load levelling* (household customers) using the battery to store energy in periods when the customer has low consumption (low load periods), to cover portions of the consumption during periods of high power consumption (peak load periods).
    - Market based optimization of consumption (*Energy arbitrage*) using the battery to store energy in low-price periods, so that the customer can use energy from the battery in high price periods.
- *Energy community with battery* to be used for peak load reduction (reducing grid costs for the area), providing flexibility to balance responsible parties and local producers, and to benefit from energy arbitrage (Chapter 4.3).

The report is based on contributions from:

- Per Erik Nordbø (BKK Nett)
- Merkebu Zenebe Degefa (SINTEF Energi) (Chapter 3.1, 4.2.1, 4.2.2) [1], [2]
- Eirik Thorshaug (NTE Nett) (Chapter 4.1.2) [3]
- Geir Mathisen (SINTEF Digital) (Chapter 4.1.2) [4]
- Bernt A. Bremdal (Smart Innovation Norway) (Chapter 4.3) [5]

2 The FlexNett project

The Norwegian research project "Flexibility in the future smart distribution grid – FlexNett" (2015-2018)[1] aims to contribute to **increased flexibility in the future smart distribution grid** by **demonstration and verification** of technical and market-based solutions for flexibility, on different grid levels and for different stakeholders.

The project will promote increased flexibility…

- at *active customers*, in the interplay between consumption, generation and energy storage, contributing to a more efficient use of energy, reduced costs and new services.
- in the *distribution grid* by locating energy storages in substations to reduce peak loads, improve the utilization of existing grid capacity, reduce coincident peak load and postponing the grid investments.
- in *smarter operation of the distribution grid*, for example through energy storage, remote control in the grid and voltage control, contributing to reduced grid losses, improved security of supply and voltage quality.

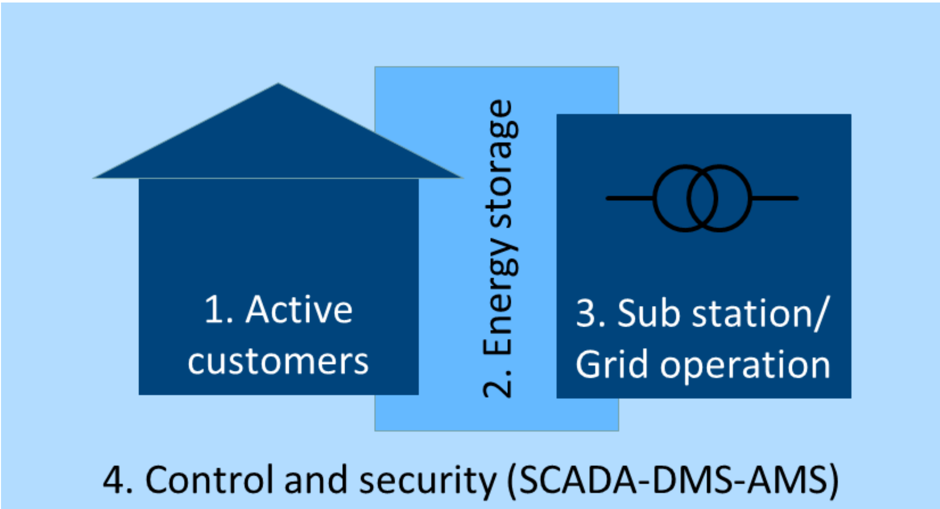

Figure 2.1 Realization of flexibility

The project owner is BKK Nett, and the research partners are SINTEF Energi, Smart Innovation Norway and SNTEF Digital. The research project received funding from the Research Council of Norway, in addition to funding from the 20 partners in the project.

The total budget was approximately 21 million NOK (Approx. 2.1 million Euro), including both funding of research activities and in-kind from the participating partners.

Project structure

The project structure is presented in Figure 2.2. In total the project consisted of five work packages (WPs).

[1] https://www.forskningsradet.no/prosjektbanken/#/project/NFR/245412

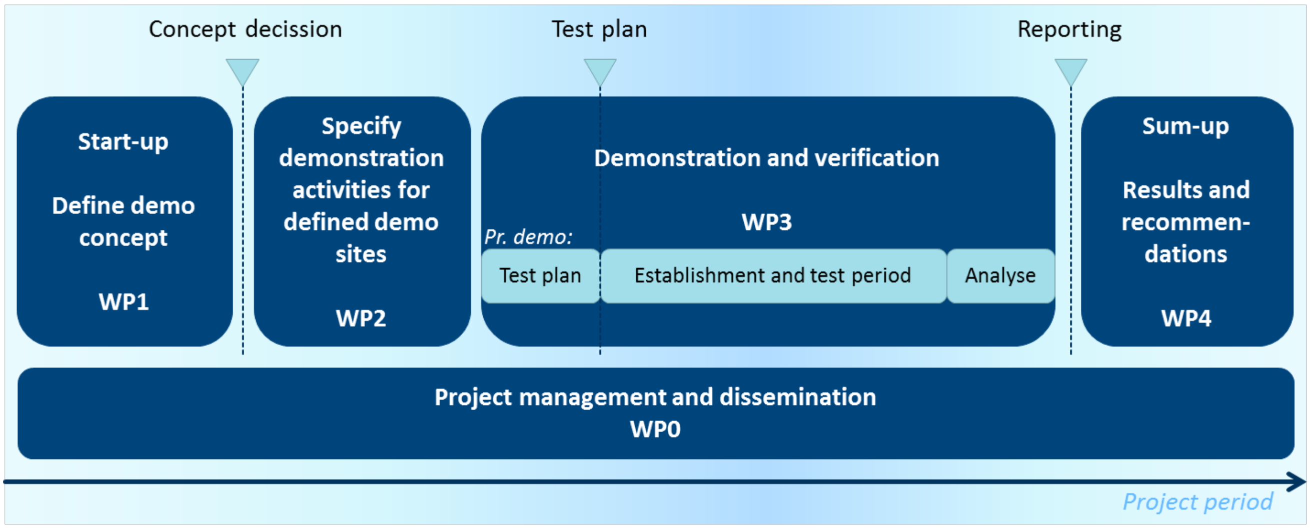

Figure 2.2 Structure of the FlexNett project

The project started with WP1 and arranged workshops with the objective to define the demo concept for the project, focusing on the future distribution grid and demand response. WP2 continued this work, and specified the demonstration activities for the three defined demonstration sites. The largest work package was WP3 – the actual demonstration and verification. The final work package (WP4) summarised the results from the different demo activities in WP3 and developed recommendations based on these. WP0 was project management and dissemination during the whole project period.

Research activities

Three demonstration sites were included in the FlexNett project. The work had a broad focus, spanning from focus only on the customer, to customer and grid topics and with focus only on the distribution grid. The topic at the different demonstration sites are illustrated in Figure 2.3.

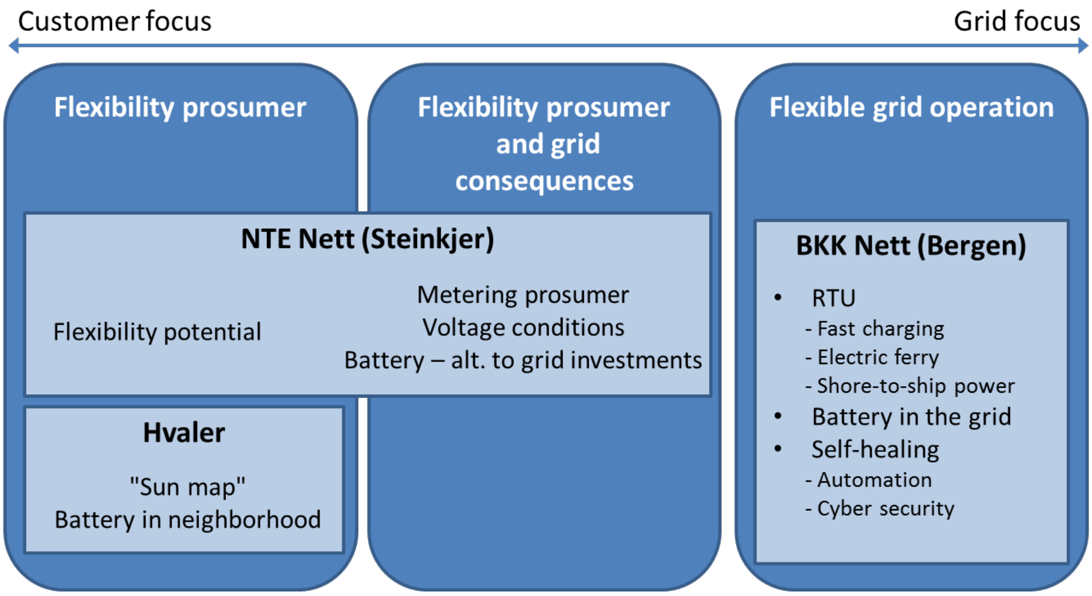

Figure 2.3 Demonstration sites within the FlexNett project

The geographical locations of the demonstration sites are presented in Figure 2.4.

Figure 2.4 Geographical locations of demonstration sites within the FlexNett project (Source: www.zeemaps.com)

The structuring of stakeholders (Distribution System Operators – DSOs, Aggregator, industry, household), systems (SCADA, DMS, Smart meters, RTU, …), technologies (consumption, production and energy storage) and functionalities (control, measurement, security, …) involved in the different demonstration activities, are presented in Figure 2.5.

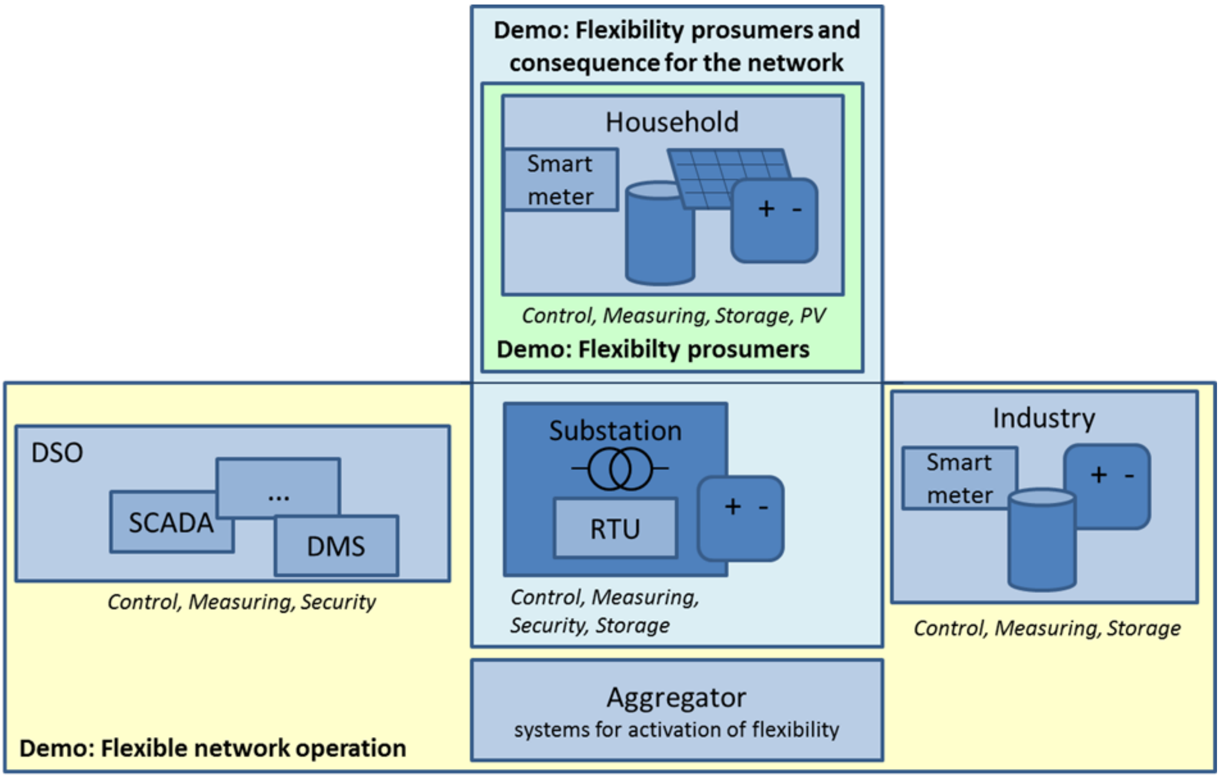

Figure 2.5 Structure of stakeholders, systems, technologies and functionalities [6]

This report summaries results from the demonstration sites focusing on batteries– located both at BKK Nett (Bergen), NTE Nett (Steinkjer) and the municipality of Hvaler.

3 Types of energy storage

3.1 Battery (Electric storage)

A battery is a device that converts chemical energy directly into electrical energy. It consists of one or more galvanic elements or cells with a specific cell tension.

Each cell consists of a positive electrode (with excess protons), a negative electrode (with excess electrons), and an electrolytic solution with electrode separators placed in a suitable vessel. When the cell emits electrical current, it takes place by means of a chemical reaction; in the form of oxidation at the negative electrode and a corresponding reduction at the positive electrode. A battery can store a certain amount of energy based on how much active electrode material it has.

The battery capacity is measured in amperage hours (Ah), where 1 Ah is defined as 1 ampere current for one hour. The product of battery's voltage, discharge current and discharge time indicate the electrical energy stored in the battery. This is expressed in watthours (Wh). The specified capacity is specified for optimal conditions and can be reduced by overload, low / high temperature or mechanical loads [7].

Mobile applications
The main sale of electric cars in Norway started in 2011, as Nissan Leaf was introduced [8]. In 2011, the so-called "triplets" were also launched in Norway (the same car model sold as Mitsubishi i-MiEV, Citroën C-Zero and Peugeot iOn), and in August 2013 the sale of Tesla Model S. started. By the end of 2017 it was more than 140.000 EVs in Norway, representing approximately 4% of a total of 2.5 mill. private cars. Figure 3.2 shows the development of the number of cars using electricity in Norway – both electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs).

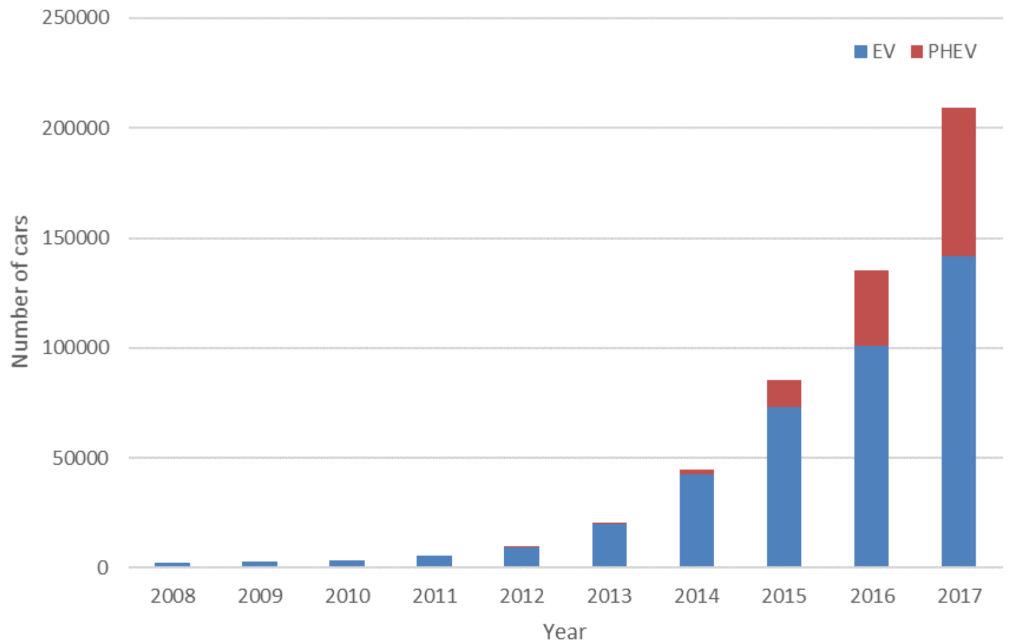

Figure 3.1 Number of registered electric vehicles in Norway (Source: www.elbil.no)

The battery capacity specified by the manufacturer for electric cars available in Norway today varies between 7 kWh to 90 kWh. Driving range is a parameter that the owners of electric cars are most concerned with and the maximum range varies between 100 and 480 km, depending on, inter alia, outdoor temperature. The battery technology in the cars is dominated by lithium batteries (Li-ion). The battery lifetime is stated by each manufacturer and, for example, the Mitsubishi i-MiEV indicates that 70 - 90% of the battery capacity is available after 10 years or 150,000 kilometres of drive. The battery in a car is of course mobile and available when the car is connected for charging.

Stationary applications

A stationary storage is typically a lithium battery (Li-ion) and often consists of modules that can be assembled into larger units depending on the specification.

With the increasing price of electricity and the falling battery cost, the installation of electric battery storage systems is increasing. Battery storage systems are also getting more compact in design and are coming with better efficiency.

A battery can be installed anywhere in the mains; at the customer (behind the electric meter), in a neighbourhood, in a network station / transformer station or at a production unit. What varies is battery capacity and operating procedures (charging and discharging). Another thing that also varies is the motivation for installing the battery. The application will of course also determine which parameters are chosen for the battery. Household level batteries are also sometimes referred to as "behind the meter systems".

An example of *prosumer/ household level battery storage systems* is the Tesla Powerwall batteries (Figure 3.2). The Powerwall 2 battery has 13.5 kWh capacity and supports applications such as solar self-consumption, time of use (ToU) load shifting, backup and off grid.

Figure 3.2 Installed Powerwall 2 battery storage system on a residential household (Source: www.electrek.co)

An example of a *community energy storage system* is the 250kWh/500kW unit installed in North York, ON, Canada, which is tied to a community centre's 75 kW solar panel and is connected to the grid (see Figure 3.3).

Figure 3.3 This unit will provide 250 kWh/500kW of storage and is very compact; it only requires a small pad mount, a bit larger than a normal Toronto Hydro transformer. (Source: http://www.ecamion.com/)

An example of a battery installed in the distribution grid is presented below. In Germany, close to Wettringen (100 km north of Essen) 400 V grid was utilized above its designed load capacity due to strong PV feed-in. A planned 110 kV-grid extension would solve this overload issue in several years. Nevertheless, temporary grid congestions can be eliminated cost-competitively with a battery storage due to its reusability. From welfare point of view, a DSO-owned and operated storage asset (1MWh/250kW) has been selected over 10-kV cable reinforcement to be used as a temporary solution (see Figure 3.4).

Figure 3.4 The utility scale 250kW/1MWh battery system (left) and the location in Wettringen, Germany with grid assets, farms, and PV-generators (right). (Source: [9])

3.2 Thermal storage

The definition "thermal storage" means electrical appliances that have possibility to store energy in a medium for a shorter or longer period, for example a tap water heater (household), electric boiler (larger customers) and heating cables (for example in floors). Such appliances can be equipped with a thermostat.

Appliance with possibility for thermal storage of energy with thermostat can keep the temperature in the storage medium at a defined level [10]. Due to losses of energy in periods of disconnection such appliances will be reconnected with a predefined power setpoint for a period, to increase the temperature again. Thermally slow appliances without thermostat are either on or off.

Dependent on thermal storage capacity and availability of alternative energy sources, the disconnection of the appliances could be done for a shorter or longer period.

Electric water heater (WH)

In the "Market-Based Consumption Adjustment" project (2005-2008), water heaters were defined as low-priority consumption. Low-priority consumption means loads that a customer can disconnect for a limited period (preferably on an hourly basis) as these are loads that have the potential to store energy during this period. For household customers, the water heater is an example of an energy storage with storage capacity lasting few hours, while larger customers have larger electric boilers with an additional storage capacity (unprecedented consumption).

Hot water heaters (residential boilers) in Norwegian households use a heating element located at the bottom of the tank. The cold water flows into the tank and gets warmed up, then rises to the top, where it is passed on when a tap valve opens somewhere in the home. The heating element warms the water to a temperature given by the thermostat's setpoint, typically 60-90 °C. The thermostat has to be set above 60 °C (often recommended 75 °C) to prevent legionella bacteria from developing[2]. For a 200 litre electric boiler with a heating element of 2 kW it takes more than eight hours to heat the water from 5 to 75 °C. During normal use, the tank is never completely empty for hot water.

In the project "Consumer Flexibility in Effective Use of ICT" (2001-2004) a systematic test was conducted where electric water heaters were disconnected for different time of the day at approx. 1200 customers to analyse the changes of the potential demand response (DR) from the WHs. In that project, the water heaters at most customers had an installed capacity of 2 kW and a volume of approx. 200 litres. The result shows average demand response per household of 330 W in hour 8 (07:00-08:00), 600 W in hour 9 (08:00-09:00), 300 W in hour 10 (09:00-10:00) and 50 W in hour 11 (10:00-11:00), see Figure 3.5.

[2] http://www.dinside.no/bolig/hvor-varmt-skal-varmtvannet-vaere/61310529

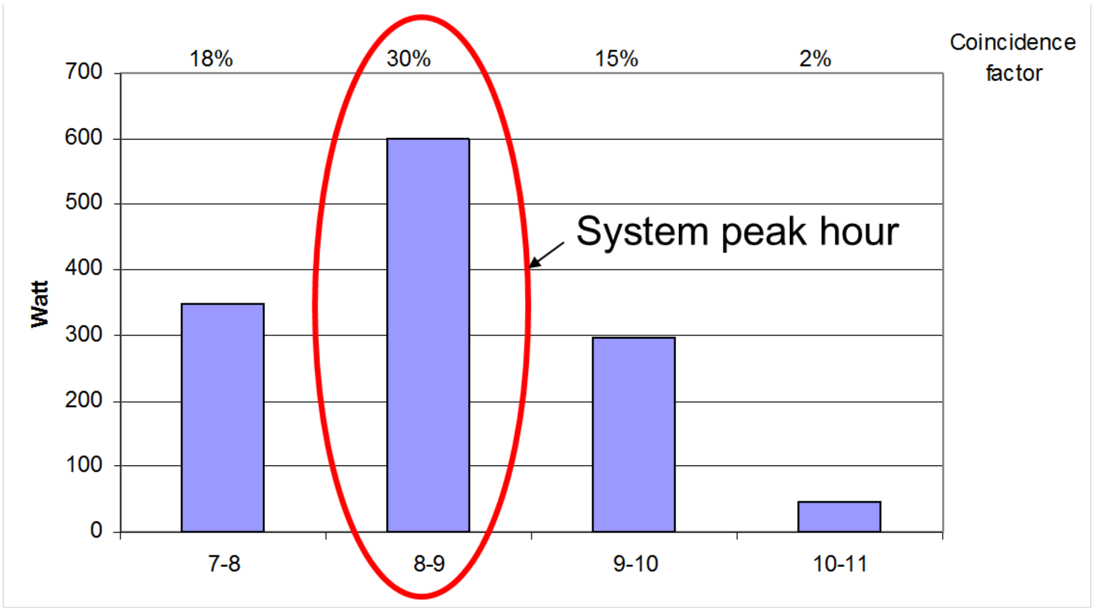

Figure 3.5 Result from remote load control of water heater between 7 and 11o'clock (hours 8-11) on working days [11]

Heating cables
Heating cables are electrical appliances that can store thermal energy in another medium with sufficient thermal inertia, such as heating cables in floors that store energy in concrete. Energy is stored when heating cables are turned on, which allows the heating cables to be switched off for a limited period (depending on thermal storage capacity). Heating cables in the floor can be installed with and without thermostat.

4 Utilization of energy storages (electric batteries) in the grid

An energy storage (electric battery) can in theory be installed anywhere in the grid to meet different needs, and these needs will vary with who is considering using and owning the energy storage.

For a *Distribution System Operator (DSO)* it is required to have a cost-efficient operation of the distribution grid, and ensure that all customers connected to the grid have a supply of electricity with a quality as defined in the legislation, for example *Regulations about quality of supply in the power system* (FoL) [12]. If a DSO has inefficient operation and, for example, many long outages, the revenue cap will be reduced accordingly. At the same time, a DSO, as a natural monopoly, should not perform activities that affect the competitive situation in the energy market, for example, it is mandatory to connect all customers to the grid, and give them access to the market so they can buy / sell electricity.

A *customer* may have different needs. A customer producing own electricity (prosumer) can be interested in investing in an energy storage, either to ensure increased level of self-consumption or to adapt to the electricity prices in the market to get the highest possible price for the power fed into the grid. This can be a single customer or an association of customers (neighbourhood), an owner of a larger production unit or a third party (a stakeholder operating on behalf of one or several other customers).

A summary of reasons for different stakeholders to invest in and use energy storages or create incentives for others to use energy storages is presented below and in Figure 4.1, based on relevant experiences from the demonstration cases within the FlexNett project.

Distribution System Operators/Transmission System Operator (TSO):

- Postpone reinforcements in the grid (Chapter 4.1.1).
- Reduced costs for Energy not supplied, for example to secure electricity to be delivered in areas with a lot of long outages. (Chapter 4.1.1).
- Voltage support (Chapter 4.1.2). Voltage support may be required due to loads or generation in the grid causing voltage problems, for example to reduce harmonic disturbances and eliminate imbalances between the voltage on the different phases.
- Black start[3] (not demonstrated in FlexNett project, but illustrated in [13]).

Customers:

- Customers with own generation (solar panels - PVs) may be interesting in investing in their own electricity storage for increased self-consumption of the electricity they have produced (Chapter 4.2.1).
- Reduced peak load and levelling out consumption to get reduced costs from a capacity based grid tariff (Chapter 4.2.2).
- Optimizing the sale of electricity by feeding electricity in to the grid when the market prices are high and store electricity in periods with low prices (Chapter 4.2.3).
- Back-up power (not demonstrated in FlexNett project, but illustrated in [13]).
- Reduced curtailment periods, which can be potentially caused by local congestions and/or voltage violations.

[3] A black start is the process of restoring an electric power station or a part of an electric grid to operation without relying on the external electric power transmission network to recover from a total or partial shutdown. https://en.wikipedia.org/wiki/Black_start

Power retailers / Third Party: (Not demonstrated in FlexNett project)

- Power retailers can benefit by storing electricity at low prices and sell at high prices (Energy Arbitrage), especially for renewable energy sources such as wind and water, or
- Power retailers / Third party can offer balancing services for different stakeholders (DSO/TSO) in the power system based on aggregation of storage/flexibility capacity.

Authorities:

- Can give incentives for investing in storages, such as electric cars (for environmental reasons)

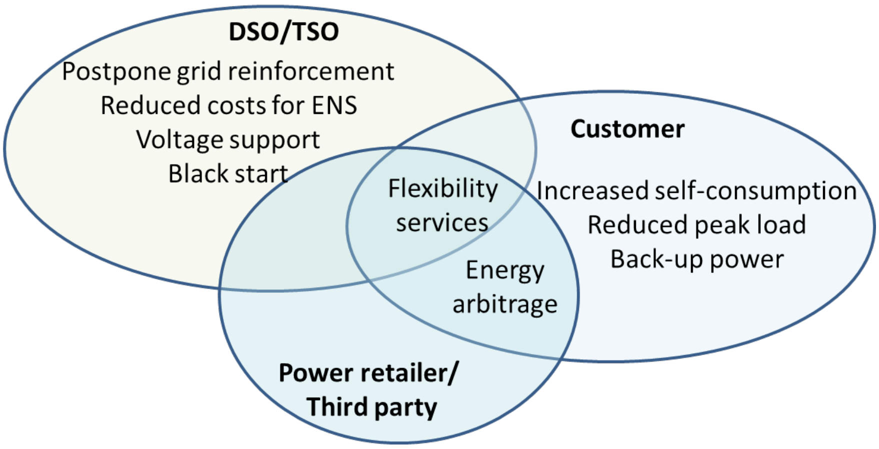

Figure 4.1 Summary of services from a battery and involved stakeholders

4.1 Electric batteries as a grid component

The technical development of batteries and reduced prices of this technology have made batteries to become a promising alternative to traditional grid investments, but there is an ongoing discussion about how this should be organised and performed.

In 2018 NVE published a report discussing the use of batteries in the distribution grid [14]. In this report batteries are evaluated as a cost-efficient alternative to traditional grid investments, but in a long term it should not be the DSOs owning the batteries, but in certain cases exemptions from this rule could be made. In short term the report points out that both DSOs, other stakeholders and the Regulator have little experiences with what the batteries can do and how this should be organised. Pilot projects and testing are therefore important to gain experiences with use of batteries and technical, economical and commerce topics.

Within the FlexNett project there has been several demonstration cases focusing on batteries as a grid component, and these cases are summarized in this chapter.

4.1.1 Postponement of grid investments and reduction of costs for "energy not supplied"

A battery can be a viable alternative to reinforcement of the grid in some cases, and thereby also contribute to reduced costs for energy supplied (especially if several long outages are the reason why grid investments are necessary). Within the FlexNett project there have been several cases where this topic has been relevant.

Case: Electric ferry in a weak distribution grid

In areas where the load is close to the capacity limit, but only in a limited number of hours per year, a battery can be an alternative to reinforcement in the grid. A battery can be located in the grid close to the problem area and be used in peak load periods. If the DSO is the owner of the storage system, it may occur challenges related to market interference (also discussed in [14]).

In 2015, "Ampere" the first electric ferry, was put into operation between Lavik and Oppedal [15]. The ferry has two electric motors, each of 450 kW, and two 500 kWh batteries. The ferry makes 17 trips every day, and the 10 minutes long stops at the ferry quays (on each side of the fjord) are used for charging from the high voltage distribution grid via a dedicated substation. Figure 4.2 shows the ferry quays and the route for the electric ferry "Ampere".

Figure 4.2 Route for the first full-electric ferry in Norway – "Ampere"

Often ferry quays are located in areas with a weak distribution grid, which is also the case for this ferry. On each side there is therefore installed a 350 kWh Li-ion battery as an intermediate storage. These storages are continuously charged from the grid when the ferry is not alongside the quay. These intermediate storages are rapidly discharged when the ferries are connected, as a complementary charging in addition to the charging from the distribution grid. With this solution the charging of the ferry from the grid's point of view can be seen as a continuous load of approx. 200 – 250 kW.

With the extra storages located at the quays on each side of the route, the charging of the electric ferry can be done without any extra investments in the distribution grid.

Case: Customer located in a weak distribution grid experiencing long outages and voltage quality issues

Another case is grid areas with long, often weather-related outages (hard-to-reach areas) and voltage quality issues, where an electric battery can be used both to ensure supply to the area in periods of probable outages in the grid and solve voltage quality issues. The battery should always be charged and start de-charging when the outage occurs. The size of the battery depends on how long the battery will maintain the power supply during an outage - the longer the period is, the bigger and more expensive battery is needed. A storage for these purposes may be owned by a DSO. The customer will then pay to the power supplier for the power used, irrespectively whether it is from the grid or the battery, at the price at the actual time of use. The DSO will cover all other costs related to the battery (investment, maintenance, etc.).

Brushytten is a tourist cabin and a popular hiking destination located in the city mountains of Bergen [16] [17]. It is supplied by a 3 km long low voltage line with small cross section area. Several measures have been performed to improve the local voltage quality: A 230/1000 V transformer at each end of the line has been installed, together with a voltage booster at the far end, but still there are remaining issues i.e. flickering, that have not been solved. In addition to the voltage quality issues, the line has weather related faults causing outages at the cabin. The faults are undetected until the weekend, when the cabin is opened, and maintenance actions are expensive and impractical for the DSO. Outages are also unpopular, as hikers must continue their trip without waffles, what causes bad reputation for the local DSO.

One possible solution is to build a new HV line all the way to Brushytten, but at a very high cost. This would solve the voltage quality issues and some non-weather-related failures as well. Another possibility is to install a battery system, both to smooth the load (increasing voltage quality) and to provide a backup during all types of interruptions (increasing the operational uptime).

The selected solution is a 12kW/130kWh battery pack, which will be sufficient to cover at least 24 hours with an open cabin and much longer outages outside of the cabin's opening hours. The investment cost of this solution is less than building HV-distribution network to the café. In addition, Compensation for Energy Not Supplied (CENS) would be reduced and public reputation would be improved.

4.1.2 Voltage support

In one of the demonstration cases in the FlexNett project a battery with inverters (per phase) delivered by Eltek, was installed, at a prosumer located in a weak distribution grid (Steinkjer). The chosen battery was 12 kW power from 6 bi-directional inverters and a battery storage consisting of 2 parts, each with 4 x 170 Ah 12V batteries. This equals approximately 16 kWh.

This prosumer has a waterborne heating system for space heating and heating of tap water, with energy delivered from an electric boiler. The electric boiler has four heating elements (1,5 kW, 2,3 kW, 2,9 kW and 4,5 kW. In total: 11,2 kW), each with an individual thermostat set to 60 °C. The prosumer also has an electric vehicle, using 2,2 kW when charging. The PV panel is 3,06 kWp, 12 panels each of 255 W. The solar panel is located on the roof with an incline of approx. 15 °C, oriented towards south [4].

The battery and inverters were installed to demonstration the benefit of a storage located in a weak distribution grid, specially related to problems with voltages and short circuit values.

The following metering equipments have been installed (Figure 4.3):

- A – Meters for voltage and current on all the three phases at the connection point to the grid (ElitePro) (1-minute resolution).
- B – Meters for voltage and current on three phases at the electric boiler (ElitePro) (1-minute resolution).
- C – Meters for the outdoor temperature (1-minute resolution).
- D – Computer, collecting the metered data.
- E – 2G modem transferring the metered data.
- F – Smart Meter. Hourly metering of the electricity bought from and fed into the grid.
- G – Meter for the electricity produced by the PV panel (Elspec) (1 minute resolution).

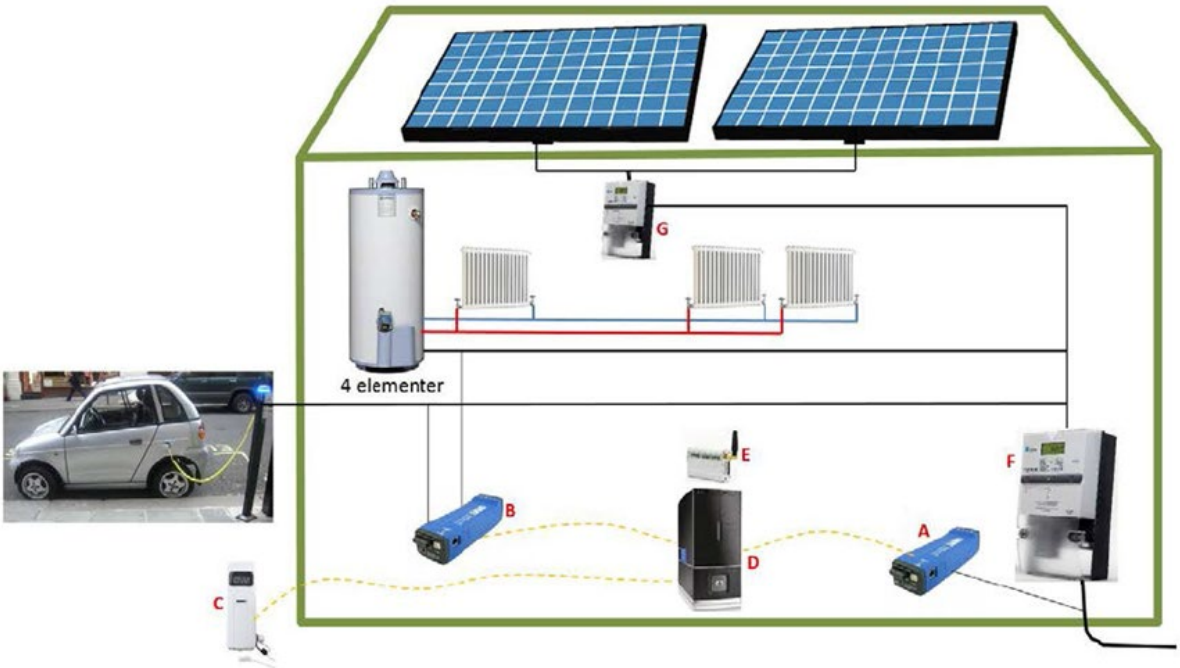

Figure 4.3 Measurement technologies installed at the prosumers, related to the FlexNett project [4]

An additional Elspec Power Quality meter[4] was installed at the point where the customer is connected to the distribution grid, to meter the response from the battery system. The first test with this battery and inverter was to level out the imbalances between the voltage on the different phases. The result was an improvement in the voltage quality for the customer. The data from the Elspec meter are presented in Figure 4.4 and Figure 4.5.

[4] https://elspec-ltd.com/

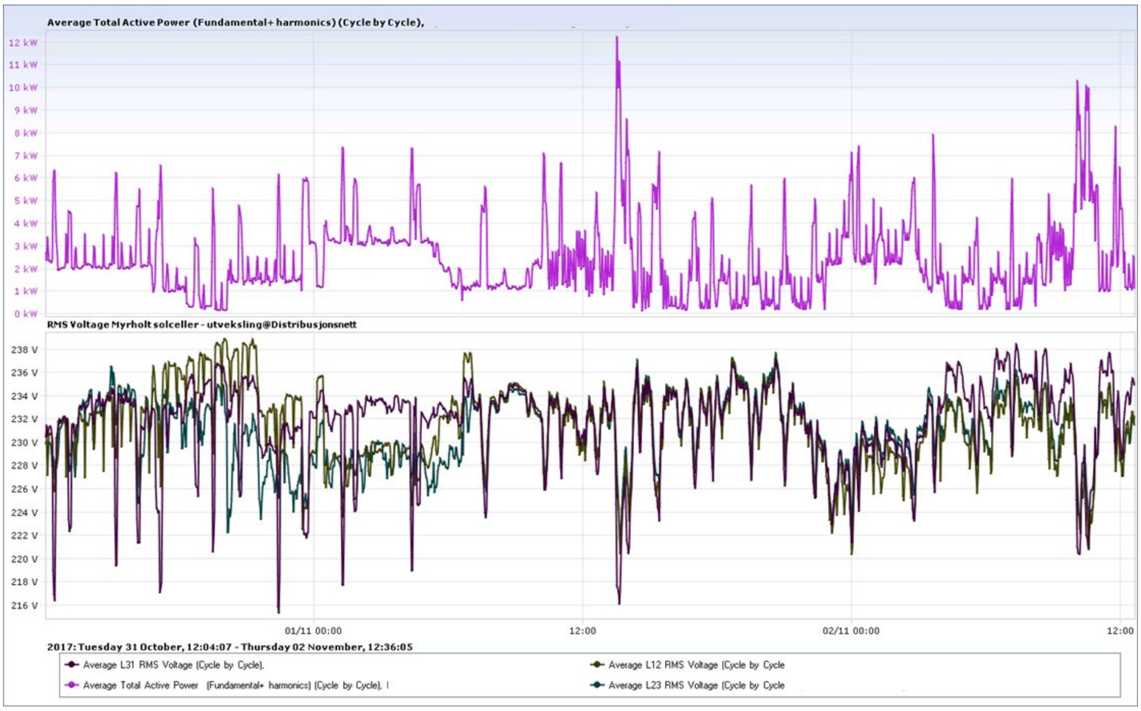

Figure 4.4 Meter data for two days, at the prosumer (Source: NTE)

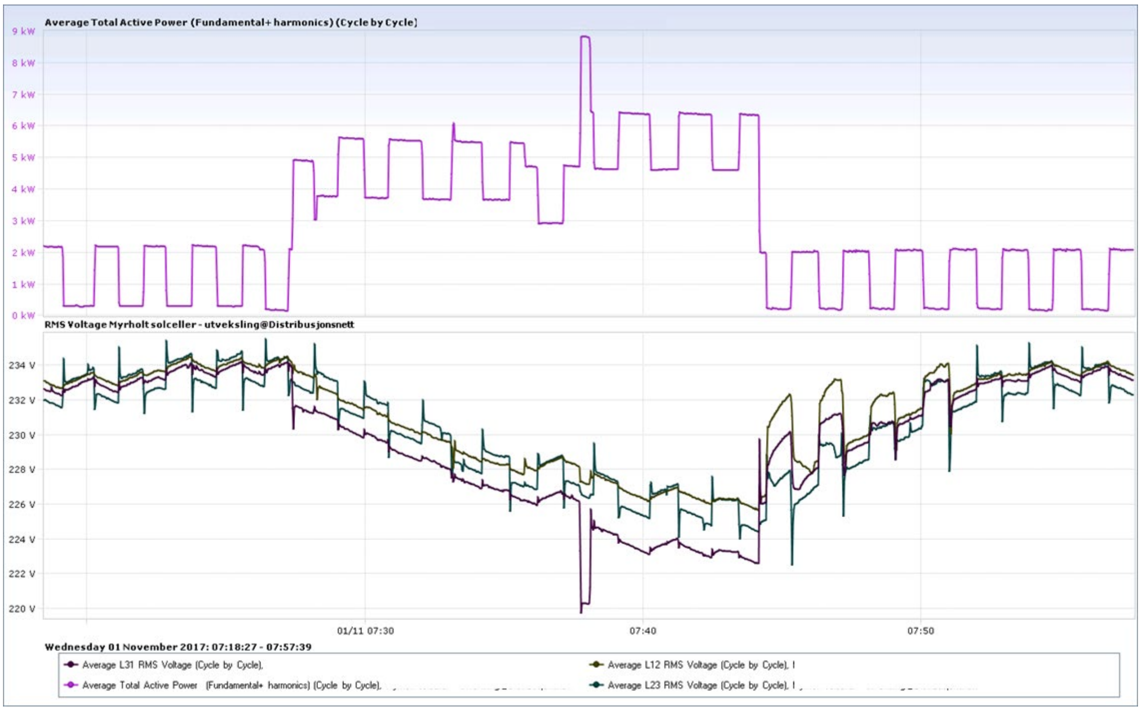

Figure 4.5 Meter data for 30 minutes, at the prosumer (Source: NTE)

However, the inverter connected to the phase with the largest heating element of the electric boiler went into a saturation mode (Figure 4.6), probably due to limited capacity to completely balance this phase. Three additional inverters, each of 2 kW were therefore installed, and then each phase had each an inverter capacity of 6 kW.

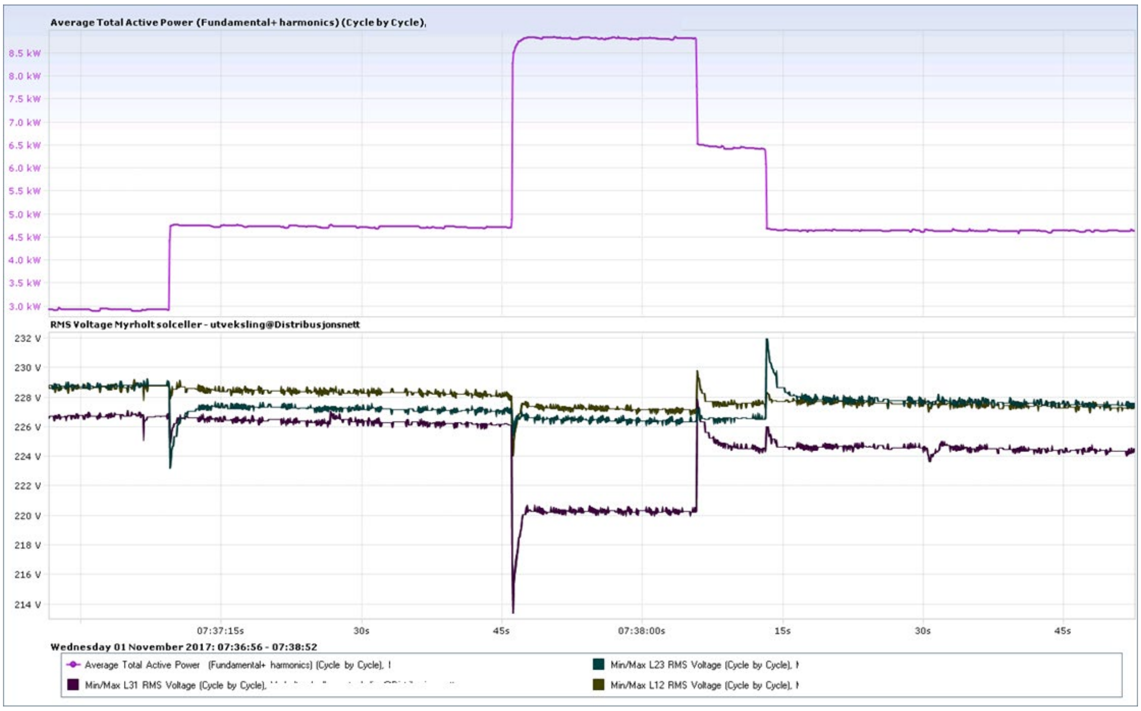

Figure 4.6 Meter data for 2 minutes, at the prosumer. Saturation (Source: NTE)

After upgrading the capacity of the inverters, the system manages to resolve the imbalances between the voltages on the different phases. This has been confirmed by electricity quality reports from the Elspec meter. In these reports the number of events with rapid voltage changes was reduced with 68 % in a week when the functionality for voltage balancing was active, compared to a week were this functionality was stopped.

4.2 Customer location (Behind the meter)

Within the FlexNett project there was no demonstration case with a battery installed behind the meter, at a customer, but simulations related to how the battery could be used for increased self-consumption for a prosumer and load levelling for household customers were presented in [1]. These are summarized in this chapter, in addition to an evaluation of the use of a battery for energy arbitrage presented in [18].

4.2.1 Increased self-consumption (prosumer)

A customer-owned energy storage can help prosumers to increase their self-consumption. For example, a typical household customer will have reduced consumption during the daytime, as there are no people present, but this is also the same period as a solar panel has the greatest output. By installing an energy storage system, this can be used to store energy during the day. This enables storage of surplus energy for use at other times of the day when the consumption is higher than production from the solar panel.

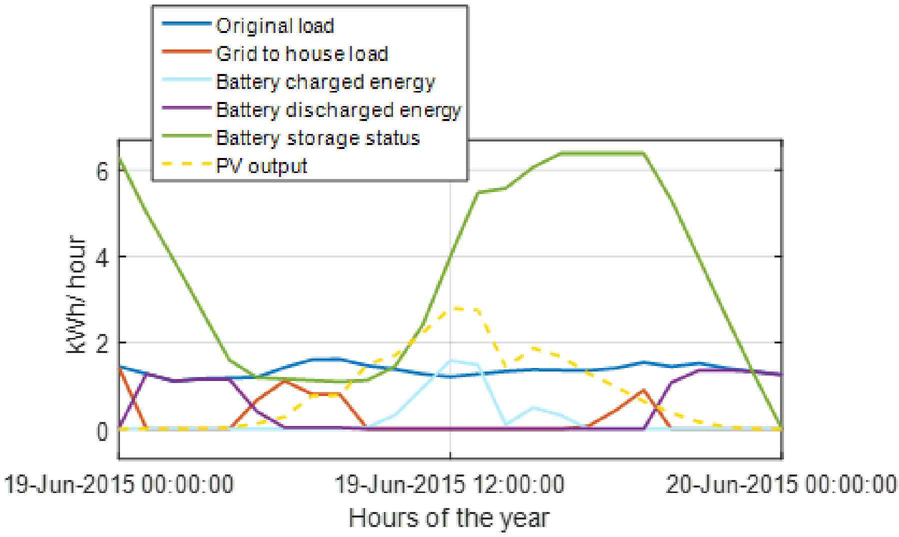

Figure 4.7 Load profiles with PV-battery system on weekday summer (3.06 kWp PV and 6.4kWh/3.3kW battery system) [1]

Installed capacity of a storage system located at the customer side should be optimized according to the production capacity of the solar panel.

4.2.2 Load levelling (household customers)

A customer-owned energy storage can help reducing the peak load and levelling out the consumption. Energy can be stored in periods when the customer has low consumption (low load periods), while portions of the consumption can be covered from storage during periods of high power consumption (peak load periods). This will increase the consumption during low-load periods (valley filling) and decrease the peak load with peak shaving. The total energy consumption during the day will mainly remain unchanged.

Load levelling is illustrated in Figure 4.8 [1], where the blue curve is the original load (before energy storage) and the red curve show how the load is levelled out and the same amount of energy is delivered from the grid for each hour. The green curve shows the status of the stored energy in the battery.

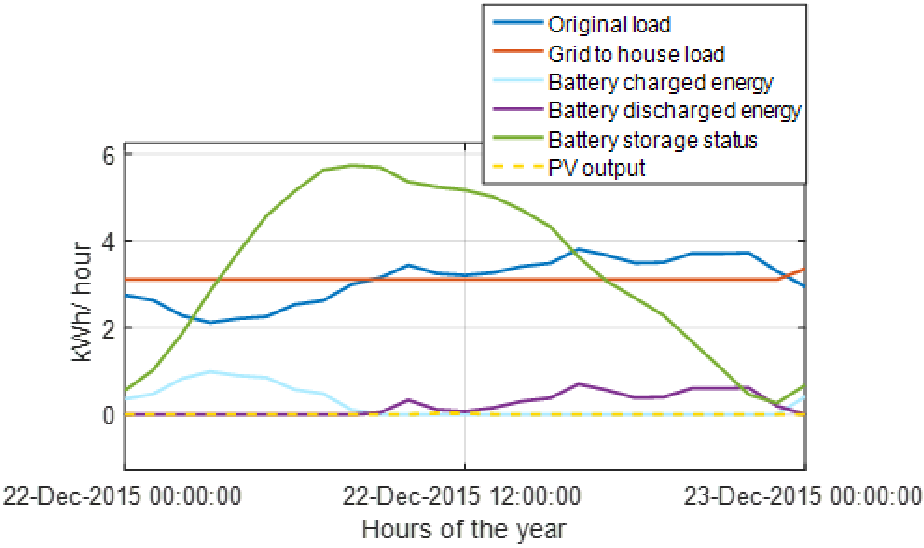

Figure 4.8 Load profile with PV-battery system on weekday winter (3.06 kWp PV and 6.4kWh/3.3kW battery system, PV generation = 0) [1]

If the customer has an energy-based grid tariff, constant consumption patterns will not contribute to a cost reduction for the customer, but by introducing a capacity-based grid tariff, an energy storage used in this way will provide a financial gain to the customer (investment costs for energy storage are not included here.).

4.2.3 Market based optimization of consumption (Energy arbitrage)

A customer-owned storage can also contribute to economical optimized power consumption for the customer, referring to the price the customer pays for electricity. The customer can get a retail price based on the hourly spot market (Elspot), which are known the day before the day of operation. Energy can be stored in the low-price periods, so that the customer can use energy from the battery in high price periods. In order to benefit from this, it is a prerequisite that the customer has a power contract with at least hourly rate and hourly settlement.

There are two main factors that are important for making this beneficial. The first one is the efficiency of the battery and the second is the price differences between low and high price periods [18]. Therefore, the crucial point is the relations between the price in off peak and peak periods, compared with the efficiency factor[5] of the battery. The benefit from the use of the battery will increase with increasing price difference.

Total energy consumption over the day is unchanged for the customer, but the energy storage makes it possible for the customer to access the most affordable power - either directly from the energy storage or from the power market. For example, spot prices will typically be highest in the morning and afternoon, and during these hours, parts of the customer's consumption can be covered by an energy storage.

The necessary price differences between peak and off peak periods are calculated in [18], based on an assumption of an efficiency at η=0,9 of the battery. The results are presented in Figure 4.9.

[5] The efficiency of a battery can be calculated as the amount of power discharged by the battery divided by the amount of power delivered to the battery. This takes into account the loss of energy to heat, which warms up the battery. http://large.stanford.edu/courses/2010/ph240/sun1/

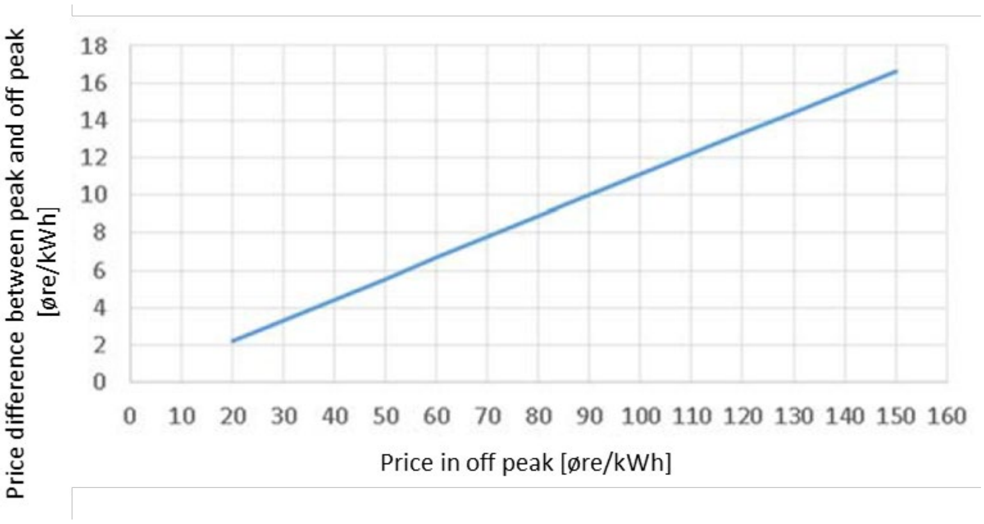

Figure 4.9 Necessary price differences to achieve an economical benefit from the use of battery [18]

4.3 Energy community with battery

A neighbourhood at Hvaler with PV panels installed was selected as demonstration site, and in cooperation with the H2020 project EMPOWER[6] a local energy market was established to further study the commercial potential related to local sales of renewable energy and flexibility for different purposes [5].

The residents in this area live in single-family wooden houses built during the 1970-ies and with a typical Nordic architecture. Electricity consumption varies between 20.000-40.000 kWh per year. All of the households are equipped with smart meters with hourly metering of the electricity consumption, and a small number of them has PV panels installed already. In relation to the FlexNett project a community battery was installed in the neighbourhood of the houses. The local DSO invested in the battery system.

The battery was installed in December 2016, with a capacity of 18 kWh. The battery system is presented in Figure 4.10. The battery system was provided by Eltek and purchased by the local DSO.

From the beginning, the local Energy Management System (EMS)/Battery Management System (BMS) was programmed to be autonomous to a high degree, with a communication to the Aggregator system developed by eSmart Systems. With this solution the local battery system could operate locally (charging/discharging), or remote control could be performed.

The display of the Aggregator system is presented in Figure 4.11.

Figure 4.10 Battery system (battery, inverters and local EMS/BMS display) [5]

[6] http://empowerh2020.eu/

Figure 4.11 Interface showing State-of-Charge (SOC) for the battery (SOC curve - blue, discharging curve – light blue, charging profile – red, generation curve - green and consumption (not activated)) [5]

As a first step of the technical and economic analysis of the energy community, a market analysis for batteries was performed, with main focus on the Lithium-Ion battery technology. The long-term trend in price of Lithium-Ion batteries shows that from 2020 prices below 3000 NOK/kWh could be achieved, and in certain occasions even lower (down to 50% of this) [5].

The price of 3000 NOK/kWh towards 2020 and an estimated lifetime of the battery of 5 years was used in a technical-economic analysis for the neighbourhood. Based on today's grid tariff with a peak price of 6 Euros/kWh/h, the analysis shows that today it will only be beneficial with a small battery reducing peak loads with 200 W, but already in the next 1-2 years it will be feasible to use batteries reducing the peak load with up to 1 kWh/h. To make it beneficial with even larger reductions in peak load, the costs of batteries should be lower than the assumptions used in this analysis.

Figure 4.11 show the technical solution of the demonstration of the battery installed in the household area at Hvaler. In a scenario where this will be an energy community, several stakeholders will be involved, and the battery can be used for several purposes [5]. A Multi-service battery (independent on today's regulations) will improve the economy, scalability and be basis for new business cases.

Potential benefits with such an energy community with a common battery are:

- Peak load reduction – reducing grid costs for the area
- Providing flexibility to balance responsible parties and local producers
- Benefit from energy arbitrage

5 Benefits of different locations of a battery

Several of the pilot cases within the FlexNett project have evaluated alternative use of a battery – both located at the customer site (behind the meter), in a community /neighbourhood and in the distribution grid. The different cases are all presented in chapter 4.

All the different uses of a battery are summarized in this chapter (Table 5.1) to give an overview of benefits a battery can contribute to, dependent on the different locations.

Table 5.1 Quality evaluations of different benefits from batteries at different locations

Battery		Stakeholders			
Location of battery	**Battery service**	**Customer**	**DSO**	**Aggregator**	**Market**
Customer (Behind the meter)	Load levelling	(+) Reduced grid costs	(+) Reduced peak load. (+) Reduced grid investments	(-) Reduced potential for flexibility	
	Increased self-consumption	(+) Reduced amount of electricity bought from the grid	(+) Reduced feed in of electricity in distribution grid.		(-) Reduced sale of electricity in the retail market
	Energy arbitrage	(+) Reduced costs for electricity	N/A	(+) Include this as a new service	(+) Increased flexibility in the market?
In weak distribution grid	Postponement of grid investments	(+) Reduced length of outages	(+) Reduced grid investments	(-) Limited availability of flexibility due to local grid constraints(?)	(+) Solving congestion issues (-) Limited availability of flexibility due to local grid constraints(?)
	Voltage support	(+) Improved voltage quality	(+) Improved voltage quality	N/A	N/A
Energy community	Increased self-consumption	(+) Reduced grid costs	(+) Reduced peak load in the specific area	(+) Increased potential for flexibility (aggregated)	(+) Increased utilizing of flexibility
	Energy arbitrage	(+) Reduced costs for electricity	(+) Reduced peak load in the specific area	(+) Include this as a new service	(+) Level out prices

Today, there is an ongoing discussion related to ownership, locations and the use of batteries. Table 5.1 presents experiences from both simulations and actual use of batteries from a pilot project.

6 Summary

This report has been developed within the Norwegian research project "Flexibility in the future smart distribution grid – FlexNett" (2015-2018) and summaries the results from the demonstration sites focusing on batteries – located both at BKK Nett (Bergen), NTE Nett (Steinkjer) and the municipality of Hvaler.

The FlexNett project aimed to contribute to increased flexibility in the future smart distribution grid by demonstration and verification of technical and market based solutions for flexibility, on different grid levels and for different stakeholders.

This report focuses on stationary batteries. A stationary storage is typically a lithium battery (Li-ion) and often consists of modules that can be assembled into larger units depending on the specification. A battery can be installed anywhere in the mains; at the customer (behind the meter), in a neighbourhood, in a network station / transformer station or at a production unit.

Batteries as a grid component
The technical development of batteries and reduced prices of this technology have made batteries as a promising alternative to traditional grid investments, but there is an ongoing discussion about how this should be organised and managed.

The FlexNett project has had the following demonstration cases focusing on batteries as a grid component:

- Postponement of grid investments and reduced costs for energy not supplied (CENS).
    - A battery can be an alternative to reinforcement in the grid in different cases, and thereby also contribute to reduced costs for energy supplied (especially if several long outages are the reason why grid investments are necessary). A battery in the grid can also solve voltage quality issues.
    - *Electric ferry in a weak distribution grid*
      The electric ferry is charged from the (weak) high voltage distribution grid during the 10 minutes long stops at the ferry quays (on each side of the fjord). The storages located at the ferry quays are continuously charged from the grid when the ferry is not alongside the quay. These intermediate storages are rapidly discharged when the ferries are connected, as a complementary charging in addition to the charging fed by the distribution grid. With this solution the charging of the ferry is from the grid seen as a continuously load on approx. 200 – 250 kW. With the extra storages located at the quays on each side of the route, the charging of the electric ferry can be performed without any extra investments in the distribution grid.
    - *Customer located in a rural area*
      Brushytten is a tourist cabin and a popular hiking destination located in the city mountains of Bergen, supplied by a 3 km low voltage line with small cross section area. For this customer there is problems related to power quality and weather related faults causing outages at the cabin. The faults are undetected until the weekend when the cabin is opened, at a time when maintenance actions are expensive and impractical for the DSO. A battery is evaluated as an alternative solution to build a new HV line all the way to Brushytten. This battery will both smooth the load (increasing voltage quality) and provide a backup during all types of interruptions (increasing uptime). The battery system has the capacity to cover at least 24 hours with an open cabin and much longer outages outside of the cabin's opening hours. The investment cost of this solution is less than building HV-distribution network to the café. In addition, CENS would be reduced and public reputation would be improved.

- Voltage support
  - The inverter connected to a battery can be used to reduce imbalances between the voltage on the different phases (for a prosumer located in a weak distribution grid). This was confirmed during tests and measurements. This means that such inverters can be a solution for voltage quality problems at prosumers located in weak distribution grids – either as a permanent measure or temporary solutions until grid investments are performed.

Customer location (Behind the meter)

In the FlexNett project the following simulations related to a battery installed behind the meter have been performed, evaluating how this could be beneficial for the customer:

- Increased self-consumption (prosumer)
  - The battery can be used to store surplus energy (when the production from the PV panel is higher than the consumption) for use at other times of the day when the consumption is higher than production from the solar panel.
- Load levelling (household customers)
  - The battery can be used to store energy in periods when the customer has low consumption (low load periods), to cover portions of the consumption during periods of high power consumption (peak load periods).
  - This will increase the consumption during low-load periods (valley filling) and decrease the peak load with peak clipping. The total energy consumption during the day will mainly remain unchanged.
- Market based optimization of consumption (Energy arbitrage)
  - The battery can be used to store energy in low-price periods, so that the customer can use energy from the battery in high price periods. Total energy consumption over the day is unchanged for the customer, but the energy storage makes is possible for the customer access the most affordable power - either directly from the energy storage or from the power market.
  - Two important factors for making this beneficial is the efficiency of the battery and the price differences between low and high price period. The benefit from the use of the battery will increase with increasing price difference.

Energy community with battery

A demonstration case with an energy community equipped with a battery was performed within FlexNett project. A battery installed in a neighbourhood can be used for peak load reduction (reducing grid costs for the area), providing flexibility to balance responsible parties and local producers and benefit from energy arbitrage. The trade of energy can be performed in a local energy market for renewable energy and flexibility.

Several stakeholders will be involved in a scenario with an energy community, and the battery can be used for several purposes. A Multi-service battery (independent on today's regulations) will improve the economy and the scaling effect in the case and be basis for new business cases.

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8 List of abbreviations

CENS	-	Costs for energy not supplied
DMS	-	Distribution Management System
DR	-	Demand Response
DSO	-	Distribution System Operator
EV	-	Electric vehicles
LV	-	Low voltage
MV	-	Medium voltage
NVE	-	Norges Vassdrags- og Energidirektorat (Norwegian Regulator)
PHEV	-	Plug-in hybrid electric vehicles
PV	-	Photovoltaic
RTU	-	Remote Terminal Unit
SCADA	-	Supervisory Control and Data Acquisition
ToU	-	Time of Use
WH	-	Water heater

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