# Final report

## 1.1 Project details

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| **Project title** | 12518-Grid Connected Flow Batteries |
| **Project identification (program abbrev. and file)** | GCFB |
| **Name of the programme which has funded the project** | EUDP17-1 |
| **Project managing company/institution (name and address)** | Eniig Holding A/S (Eniig Forsyning A/S)<br>Tietgensvej 4<br>8600 Silkeborg |
| **Project partners** | VisBlue A/S<br>Aarhus University |
| **CVR** (central business register) | 39072793 |
| **Date for submission** | September 6th 2016 |

## 1.2 Short description of project objective and results

## 1.3 Executive summary

## 1.4 Project objectives

## 1.5 Project results and dissemination of results

## 1.6 Utilization of project results

## 1.7 Project conclusion and perspective

**Annex**

Relevant links

## 1.2 Short description of project objective and results

### Danish

Formålet med Grid Connected Flow Batteries (GCFB) projektet var at undersøge mulighederne for at installere et redox flowbatteri i det offentlig elnet til at rebalancere spændingsfrekvensubalancer forårsaget af ubalancer i belastningen på elnettets tre faser.
Projektets første fase gik ud på at definere systemkrav baseret på analyser af et typisk elnet med synlige ubalancer. Herefter startede systemudviklingen, hvor en egnet testlokation i Eniigs (nu Norlys) forsyningsområde blev valgt.
I projektet blev forskellige analyser af elnetkarakteristika og typiske elforbrugskomponenter ved en række elforbrugere udført. Undervejs blev batteriet udviklet og bygget, herunder inklusiv de specielle komponenter og batteristyring, der skulle til for at styre batteriet individuelt på elnettets tre faser.
Efterhånden viste det sig, at den planlagte installation på testlokationen ikke var mulig, fordi batteriets invertere ikke nåede at blive godkendt til brug på det danske elnet i tide. Derfor blev batteriet testet på VisBlues testlaboratorie med en forbindelse til det offentlige elnet. Testresultatet viste sig at være tilfredsstillende, da batteriet beviste, at det kan individuelt udkompensere en del af den ubalance, der blev simuleret på de tre faser.
I et opstillet scenarie, hvor en opgradering af elnettet vha. kabler og transformerstationer eller en installation af et batteri i elnettet sammenlignes økonomisk, blev det i projektet også bevist, at batteriløsningen er konkurrencedygtig, samt har den fordel, at den er fleksibel mht. muligheder indenfor effekt, placering og styring.

### English

The objective for the Grid Connected Flow Batteries (GCFB) project has been to investigate the possibility of installing a redox flow battery in the public grid to rebalance voltage and frequency imbalances caused by unbalanced load on the grid's three phases.
In the initial phase of the project, the system was defined based on analyses of a typical scenario with an unbalanced grid. Subsequently, development of the system started, and a suitable test site in Eniig's (now Norlys) distribution area was selected.
During the project, analyses of grid characteristics and load types of various consumer electrical appliances were completed at the selected test site. Underway, the battery system was developed and built, including its special components and battery control, which enabled individual control of the battery on each of the grid's three phases.
Gradually, it came to light that installation at the test site was not possible, because the battery inverters were not approved for use on the Danish grid. Instead, the battery was tested at VisBlue's test facility with a connection to the public grid. The test results were good, as the battery proved its ability to compensate imbalances caused by simulated unbalanced loads on the grid's three phases.
In the project it was proved in a scenario, where an upgrade of the grid via cables and transformer stations or an installation of a battery solution in the grid are compared in regards to economic feasibility, the battery solution is competitive and has the advantage of flexibility within possibilities of power output, placement, and control.

## 1.3 Executive summary

The project has ended based on laboratory tests at VisBlue's facilities. As a proof of concept, the results are promising in the sense that it was proven that the battery could be controlled independently on each of the three phases. Additionally, the battery was capable of automatically reacting to voltage changes and the compensation of these changes. Since the test was performed in a laboratory (VisBlue's test facilities) during a shorter period of time, further tests in the field with genuine imbalances must be completed, in order to tune the battery control. The results, however, prove a potential to utilise this configuration of the flow battery, as it can be configured and altered to fit the requirements of the particular site with an unbalanced grid. Another advantage of the flow battery is the fact that you can scale power output and capacity independently. Project results show that this characteristic is useful, when you have different objectives to solve in the grid, e.g. transformer overload, voltage fluctuations, or cable overload in the low voltage grid close to the consumer. Moreover, the flow battery can easily be moved to another site, which in comparison to upgrading cables and transformer stations provides a more flexible solution.

## 1.4 Project objectives

The project has evolved as planned, according to the project plan, and there has been a rewarding cooperation between the project participants. One of the risks in the project proved to be the battery inverter used in VisBlue's battery system. The inverter is a key component, as it must support the required functionalities in order to fulfil the individual grid phase compensation. Additionally, the inverter must be approved for installation on the Danish public distribution grid. The first requirement was obtained during the process of the final tests, but the last requirement was not obtained until after the project's end.

In milestones 2.3 and 2.5 cost analyses of different solutions for the improvement of a grid with unbalancing issues were performed. In milestones 3.1 and 3.2 the overall conclusion proved that flow batteries can compete with other battery technologies, such as lithium-ion (Li-ion), within scenarios of grid reinforcement using cables. Compared with lithium ion, redox flow batteries have advantages in the following categories: lifetime, safety, and recyclability. However, flow batteries cannot compete with Li-ion on the subject of energy density.

## 1.5 Project results and dissemination of results

Throughout the project, the main activities have been to characterise an unbalanced grid, in-order to set up requirements and, subsequently, design and produce a redox flow battery that can solve/compensate the imbalances that are experienced in today's grid. These main activity steps are part of the original scope of the project, which is reflected in work packages and deliverables that have been completed as planned during the project.

In the report "Flowbatterier i distributionsnettet" by Dansk Energi (DE), the impact of batteries installed in the grid has been simulated and evaluated. Different installation locations of the battery have been simulated with two different goals: i) to prevent the selling of photovoltaic (PV) energy to the grid and ii) to assist the existing 10 kV/0.4 kV transformer stations during peak load situations. In both scenarios, the simulations show that batteries can help and alleviate possible complications in the grid. However, it is important to first define the purpose of the battery and then to install it, according to the purpose, in the right location in the grid.

**Notes concerning the battery power:**

If the purpose of the battery is to stabilise the voltage in the grid, decentral batteries will have a larger impact within the grid compared with central batteries. A decentral battery will be able to compensate the power flow in the cables and, hereby, reduce voltage fluctuations. To exemplify, these situations could occur when PV panels produce a large amount of energy during the day-time, where a lot of power is injected into the grid with the result of the grid voltage increasing. An opposite situation could occur when electrical vehicles charge during the night, where a large amount of power is drawn from the grid and the grid voltage drops. Here, the battery can help in two ways: i) if the drawn/injected power is well-balanced over the three grid phases and the battery can absorb the PV energy by charging during the day, or ii) if the drawn/injected power is not well-balanced over the three grid phases, where the battery can both absorb and inject energy at the same time by charging on one phase and discharging on another phase(s).

If the goal is to assist the transformer stations in peak load situations, the battery should be larger and placed in a central location, close to the transformer station and the middle voltage distribution grid. This centrally located battery will be easier to control and maintain. For more details see the report from DE.

**Notes concerning the battery capacity:**

The completed investigations regarding battery capacity size documented in the report from DE, it is proven that the first kWh will give the most value and that the value falls gradually to a point, where a larger capacity does not provide any added value.

For a household battery, the capacity of 10 kWh (equal to 0.8 hour of the household peak load) is sufficient to collect adequate energy, in order to prevent the selling of energy to the grid in 50% of the cases.

To reduce the peak load situations for centrally placed batteries and the prevention of overload of the transformer stations, the battery power, not the capacity, is a factor of limitation. Half of the transformer stations will not have any advantage of battery capacities larger than 1.3 hours of the transformer stations' peak loads. A battery capacity of that size will be able to reduce the peak load situations with approx. 35-45% on a typical transformer station. In such scenarios, the nature of the flow battery is well-suited because of the battery's ability to individually scale power and capacity.

As a part of the project, investigations to find a suitable site with issues of imbalance was completed, and a suitable site was found in a city in Jutland. The grid in this city was facing imbalance issues due to the closing of the local central water heat plant and a rise of heat pumps in the city's grid. A large amount of the citizens has bought heat pumps and, in general, the energy that was previously bought from the central water heat plant is now bought from the local electricity company, project partner Norlys (N1). The additional disturbances of PV panels and electrical vehicles made the site optimal for the project to install the battery and perform real life tests.

It was the expectation of the project to test the designed battery at the city in Jutland (in the N1 distribution area). This goal was not succeeded due to the lack of approval of the battery inverter for the Danish grid. Therefore, the tests of the designed battery were executed in a simulated setup that matched that of the city in Jutland, where the battery design concept was proven to work. The battery inverters were approved for operation on the Danish grid close to the project's end.

The test results from final tests in a simulated setup were evaluated and discussed as a part of deliverables D5.1, D5.2, and D5.3. Here, the conclusions proved that the designed battery is still in need of required improvements in the battery control when going to a real site, but that is has passed "proof of concept".

The project has been disseminated by two main reports from DE "Flowbatterier i distributionsnettet" and "Experiments with flow battery for phase imbalance compensation" (deliverable D5.3).

## 1.6 Utilisation of project results

Based on the promising results of the project, the project partners can see the perspective and have already discussed how to roll out a real test site and test the battery. During the project, DE has gained a better understanding of the flow battery, where the organisation will use this in their work and counselling of Distribution System Operators (DSO's) and other stakeholders.

VisBlue expects to utilise the results of the project as a battery configuration in the company's product portfolio.

## 1.7 Project conclusion and perspective

The project results can be used as a "proof of concept" of VisBlue's flow battery solution and to prove that it can compete with other solutions and an upgrade of the electrical distribution network on site.

Simulations, done by DE, of the low voltage grid show that the installation of batteries has a significantly positive influence on the grid voltage and grid components. On the one hand, if the battery is placed close to the transformer station, only the transformer station and the middle voltage grid will be relieved. In this case, the grid voltage and degradation of other components in the low voltage grid will not be changed.

On the other hand, if the battery is installed in different places in the low voltage grid, the battery will be able to change the power flow in such way that the grid voltage will be more stable and the degradation of the grid components is reduced.

VisBlue has attained a large amount of knowledge about this type of grid issues and exactly how to solve this with the company's battery solution. Using the battery configuration with independent control of each phase, VisBlue expects to be able to adapt to other real life applications of the battery solution.

The project partners expect to be able to use the knowledge and battery design in their future businesses. The project missed results from the field test site, but based on the project results, there is a good basis to go out and perform a real life test. A real life test is also needed to convince the DSO's and the energy/grid industry that a flow battery can be a genuine and sometimes better alternative to transmission upgrading and other battery systems.