Final report – Development and integration of the Blue Battery for electrical energy storage within the built environment: Blue Battery System (BBS)

Project number: TEUE116250

Lead applicant: AquaBattery
Co-applicants: Compass, TU Delft, REDstack and Technolution
Project period: 01-11-2016 until 30-04-2019

Summary
This report provides an overview of the final results of the TKI Urban Energy for the development and upscaling of a Blue Battery System (BBS). A BBS stores electrical energy using water and table salt. The conversion is facilitated via membranes, which create or use the difference in concentration (osmosis) between freshwater and salt water, and thereby can store and subsequently generate electricity. This study, carried out from November 2017 to May 2019, examines four aspects: 1) upscaling, engineering and set-up of production of membrane stacks for 1 kW power and 10 kWh storage capacity, 2) automation and integration within the electricity grid, 3) operation of the scaled up system, and 4) study and validation of market characteristics and implementation of life-cycle (cost) analysis, and dissemination of knowledge.

Engineering of the stacks, reservoirs and process system has been finished, and results have been obtained through experimental research at REDstack in which several types of membranes were tested (Evoqua, FumaTech, FujiFilm). Experiments were conducted using stacks with membranes, electrodes and end plates were tested in a system for leakage, power and efficiency. The test site was set up in Delft, where pumps, tanks with salt water, sensors, power source/load sensor and battery management system were realised. For the design of the system, knowledge gained from TKI System integration studies was utilised, for example, the system was carried out using a 3-tank principle, whereby salt is circulated while the fresh water is circulated via the membrane stack back and forth between 2 reservoirs. The pilot facility was opened for operation at November 24, 2017. In the second phase of the project the battery was fully automated, and charges and discharges at the moment by means of smart algorithms. Results of the continuous operation of all 10 stacks have been obtained, and power has been delivered back to the grid. For this and next year, 2020, operation is continued within a follow-up TKI project.

The results were disseminated through networking events, news items following the Postcode Lottery Green Challenge, a scientific publication, and presentations on conferences.

From a financial point of view, AquaBattery has spent her entire budget, REDstack and Compass were too tight in terms of budgeting with expected expenditure defined at the beginning. Compass had to save costs for phase 2, REDstack had to make a deal for spacers and was too tight to make many adjustments to stack design. Technolution's role was much smaller than anticipated, due to the bottleneck of attracting proper manpower for programming the battery management system; the main programming was taken over by SeaState5 (as previously communicated, now known as Dot Robot). TU Delft has spent her entire budget.

Samenvatting
Dit rapport geeft een overzicht van de eindresultaten van het TKI Urban Energy voor de ontwikkeling en opschaling van een Blue Battery Systeem (BBS). Een BBS slaat elektrische energie op met behulp van water en tafelzout. De omzetting wordt gefaciliteerd via membranen, die het concentratieverschil (osmose) tussen zoet en zout water creëren of gebruiken en zo elektriciteit kunnen opslaan en vervolgens opwekken. Deze studie, uitgevoerd van november 2017 tot mei 2019, onderzoekt vier aspecten: 1) opschaling, engineering en opzet van de productie van membraanstacks voor 1 kW vermogen en 10 kWh opslagcapaciteit, 2) automatisering en integratie binnen het elektriciteitsnet, 3) exploitatie van het opgeschaalde systeem, en 4) studie en validatie van marktkarakteristieken en implementatie van levenscyclus (kosten)analyse, en verspreiding van kennis.

De engineering van de stacks, reservoirs en het processysteem is afgerond en de resultaten zijn verkregen door experimenteel onderzoek bij REDstack waarin verschillende soorten membranen zijn getest (Evoqua, FumaTech, FujiFilm). Met behulp van stacks met membranen, elektroden en eindplaten zijn in een systeem experimenten uitgevoerd op lekkage, vermogen en efficiëntie. De testlocatie is opgezet in Delft, waar pompen, tanks met zout water, sensoren, load/supply en accumanagementsysteem (BMS) zijn gerealiseerd. Voor het ontwerp van het systeem is gebruik gemaakt van de kennis die is opgedaan bij TKI Systeemintegratiestudies. Zo is het systeem uitgevoerd volgens het 3-tankprincipe, waarbij zout wordt gecirculeerd terwijl het zoete water via de membraanstapel heen en weer wordt gecirculeerd tussen 2 reservoirs. De pilotfaciliteit is op 24 november 2017 in gebruik genomen. In de tweede fase van het project werd de batterij volledig geautomatiseerd en laadt en ontlaadt op dit moment door middel van slimme algoritmes. De resultaten van de continue werking van alle 10 stacks zijn verkregen en er is weer stroom geleverd aan het net. Voor dit en volgend jaar, 2020, wordt de exploitatie voortgezet binnen een vervolgproject van TKI.

De resultaten werden verspreid door middel van netwerkevenementen, nieuwsberichten naar aanleiding van de Postcode Loterij Green Challenge, een wetenschappelijke publicatie en presentaties over conferenties.

Vanuit financieel oogpunt heeft AquaBattery haar hele budget besteed, REDstack en Compass waren te krap in termen van budgettering, waarbij de verwachte uitgaven in het begin zijn gedefinieerd. Compass moest kosten besparen voor fase 2, REDstack moest een deal maken voor afstandhouders en was te krap om veel aanpassingen te doen aan het stackontwerp. De rol van Technolution was veel kleiner dan verwacht, vanwege het knelpunt van het aantrekken van de juiste mankracht voor het programmeren van het accumanagementsysteem; de hoofdprogrammering werd overgenomen door SeaState5 (zoals eerder gecommuniceerd, nu bekend onder de naam Dot Robot). De TU Delft heeft haar hele budget besteed.

0. Introduction

Project number:TEUE116250
Project title: Ontwikkeling en integratie van de Blue Battery voor elektrische energieopslag binnen gebouwde omgeving: Blue Battery System (BBS)
Partners: AquaBattery (manager), Compass, REDstack, Technolution, TU Delft.
Period: 01-11-2016 up to 30-04-2019

In this document we will elaborate on the mid-term reports handed in earlier. In the first section we will go into the description of the project, with goals, strategy, methods, results, discussion and conclusion. In the final section we will elaborate on the realisation of the project including encountered hurdles and will provide an overview of realised costs, promotional activities and knowledge dissemination.

1. Vision, goals and strategy

1.1. Vision on role of TKI

The transition towards a sustainable energy economy has already started and gaining more and more momentum, especially in the residential sector, where most of the newly built houses and small buildings are designed to have ~50% of the energy production from renewable sources (mainly solar panels and heat pumps). As a result of this transformation, batteries are becoming “trendy”, as they enable the dwellers to auto-consume very high shares of energy from their solar installations. With rising energy prices, because of generation, transmission and distribution costs, the incentive for households to generate (and use) their own energy becomes increasingly bigger.

Renewable energy production has a daily pattern (solar) and a seasonal pattern (solar and wind). In addition, periods of high solar influx or high winds have a typical timescale of several days. The consumption has also a daily and seasonal pattern. Different applications require different time scales of storage (minutes, hour, day, week, year), and in this residential storage project these different time scales (with exception of storage on longest time scale) will be investigated. To do so, together with The Green Village, data of consumption and production is gathered.

In the European market which we are focussing on, the following brands/batteries are currently taking lead: Tesla, Sonnen, Kostal, Enphase, Fronius, Leclanché, Solarwatt, Varta, Victron Energy, ABB, Siemens and Schneider Electric. The majority of these brands propose two types of batteries to satisfy different customer's needs: lead-acid batteries and lithium-ion batteries, with a stronger and stronger prevalence of the second one due to the high safety standards, low maintenance needs and long(er) life span. Most of these batteries allow storage only on smaller time scales (up to several hours), due to the inherent characteristics of the technology (coupled power/storage ratio).

1.2. Goals of TKI

Main goals during the project have not changed and remained to develop and scale the Blue Battery System (BBS) from a lab-scale product (TRL 4) to a practical and scalable solution for energy storage and the delivery of electricity in times of low supply of solar and/or wind power, and to test how it functions within an operational scale by means of a pilot project of 1 kW power- and 10 kWh storage capacity (TRL 6).

To achieve this, the project was subdivided in 4 work packages:

1) Scaling, engineering and setting up production of membrane stacks (AquaBattery + REDstack)
Involves development of production mechanisms for manufacturing of Blue Battery installations, on a scale smaller than envisioned product size, but big enough to validate technical functionality and economic costs. This part takes place in two different stages, with stage 1 the manufacturing and operation of two membrane stacks, and stage 2 the additional eight stacks, to reduce the risk of unexpected setbacks and to obtain a maximum learning curve.
2) Automation and integration within electricity grid (AquaBattery + Compass + Technolution)
Integration within grid by means of in- and converters, and automatic operation in a maintenance-free setting. For this purpose, also a fully functional battery management system is designed.
3) Operation of scaled-up system (AquaBattery + REDstack)
Analysis of the use of the BBS, investigating charging- and discharging profiles, depth of discharge, rate of discharge (C-rate), energy efficiency, charge-discharge cycles per day and the ramp rate (time to start the system).
4) Life cycle analysis and life cycle cost analysis (AquaBattery + TU Delft)
Validation of costs for economic viability and energy costs for the production of materials (life cycle analysis, LCA).

1.3. Method, strategy and realisation

After granting the TKI subsidy, AquaBattery met up with each partner individually in January 2017, to discuss action items, planning and finance. On February 1st 2017, the project kick-off meeting took place in Delft, on The Green Village site. In the first year the first two stacks were built, that were soon after integrated with all piping, tanks and sensors at the pilot location. Obtaining a building permit, selecting and receiving all components and actual building of a battery management system were the main delaying factors. In 2018 scaling took place of the system, with a fivefold increase in the number of membrane stacks as well as a fivefold increase in energy storage capacity (by means of connecting more water reservoirs and increasing the pump flow rate by means of new pumps), with intense testing of stacks for charging specifically.

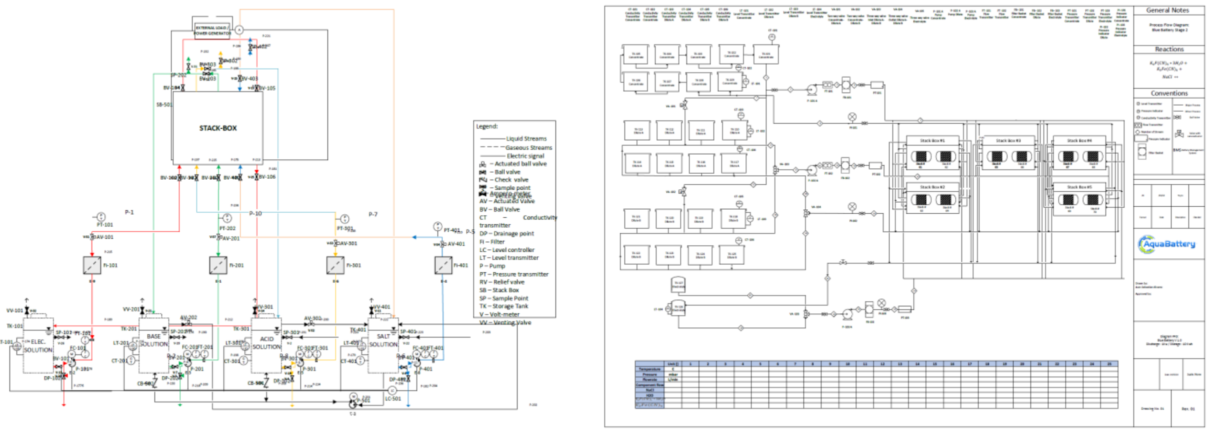


Fig. 1: PFD & PID of stage 2 of BBS pilot

Fig. 2: 3D-drawings were made for designing entire second phase of pilot development, which allowed us to specifically determine the number of components also.

Stacks

Just before the kick-off meeting a new supplier of membranes was identified, a manufacturer of cheap membranes with comparable quality to a membrane that we wanted to use as reference stack. To deal with delivery problems of spacer material, we had to choose for poorer performing material, leading to lower performance than expected for stage 1. A problem identified as well in the first stage was the temperature effect. For multiple weeks in the winter of ’17-’18 it was freezing in The Netherlands, with water temperature dropping to 1.2 degrees Celsius. Although this did not physically break anything, it led to observed shrinking behaviour of polymer gaskets, and hence water started to leak from the stacks. Changes had to be made to the design of the stacks. For stage 2 we faced problems with the one of the membrane types from this new supplier, that led again to a partial redesigning and building of the stacks, but most of all to long waiting times as an entire new batch of membranes had to be produced by the manufacturer. One batch of membranes, for just one of the types of the membranes showed curly behaviour along the edges of the membranes, making it nearly impossible to assemble properly. This led to the fact that the last 4 stacks only arrived at the pilot location by half of March in Delft.

Reservoirs, sensors and additional equipment

Reservoir installation proved difficult too, extra steps had to be taken, like ordering additional pallets to lift the metal frame from the floor (salt!) and supporting these pallets with wood because of collapsing under the heavy weight. Main learning point related to reservoir selection is that larger reservoirs are more economical, because of a) reduced manpower for interconnecting reservoirs, b) fewer points of failure (leakage), and c) significantly lower costs because of reduced number of pipe-connecting elements. As indicated earlier, because of performance reasons, it was decided to go from a 2-reservoir Blue Battery System to a 3-reservoir system (salt water is circulating, fresh water flows A-B-A). To allow such a configuration, 2- and 3-way valves had to be added to the piping. Furthermore, to obtain similar flow rates in all stacks the in- and outlet of each stack had to be designed on equal length. Both aspects complicated the piping work significantly, adding up to more than 400 components, components that all needed to be glued or wrapped in Teflon-tape to make it watertight. That was just for the first stage, the second stage proved to be much easier, as experience was there to construct everything leakage-free. The system did have to be expanded significantly in terms of number of piping work connectors, as 20 new tanks had to be connected to the storage part.

Selecting proper sensors with a high number of criteria they had to meet was a cumbersome process, especially to obtain the right measurement range in combination with the data protocol. Furthermore, several conductivity sensors broke down due to a low quality of the power supply to the sensors. Different pumps for stage 1 and stage 2 were selected to match the required flow rates for the membrane stacks. Heavier pumps had to be selected due to significant pressure drop, to make sure water was equally distributed across flow channels in the stacks. A variety of pumps was tested in our workshop for efficiency and pressure drop.

Battery management system

The Battery management system (BMS) controls the automatic operation of charging and discharging, including a user-friendly interface. In the original plan, execution of this part of the project would be fulfilled by employees and interns of Technolution and AquaBattery. Attraction of skilled interns and employees in the field of programming and electrical engineering was proven very difficult for both partners, and the existing manpower to execute this by Technolution employees was not sufficient in time and budget. As a result, SeaState5 (now DotRobot) was hired to develop the software system (paid from budget of AquaBattery and Technolution), while the electronics were developed by employees of AquaBattery. SeaState5 was known to both partners, having experience in power and sensor component integration in among others the Nuna solar car. End of July 2017 SeaState5 started the design and implementation phase, a first alpha-version was finished end of 2017, a beta-version ran by March 2018, and afterwards AquaBattery focused on acquiring programming skills themselves as well, and the final phase (with integration of new power converters, sensors and control of 3-way valves) is now completed, which means in practice that the battery charges and discharges autonomously. Some last modifications are done with respect to GUI and data extraction, and for the follow-up project this will be expanded with an energy management system (EMS) for the entire Green Village site. A difficulty proved to be the reliability of sensor data, as quite a few sensors had large fluctuations in their reading output. As our charging and discharging profiles were based on this data, we had to integrate a lot of smart algorithms to circumvent this issue. Hence, more time had to be spend on programming in 2018 than anticipated earlier. Nowadays this all works well, and charging and discharging proceeds with much more stability.

Housing

The Green Village offered to facilitate housing for the battery pilot. Initially, it was arranged to do this free of charge. When the project actually started, The Green Village could not cover the budget for offering location free of charge, so needed to charge us for using their facilities and for making use of the exposure the site has on national and regional level. Compass has paid for the preparing the site, construct housing and installing electrical facilities, which made them tight in their budget. AquaBattery has agreed with The Green Village to pay for using the general facilities.

After agreement was reached, safety and building documentation was prepared, and the permit for the pilot location could be sent out to the municipality. Hence, the building could only be completed half of July. After realization, we still had to work on electric connection to the rest of The Green Village, on building a wall to separate control from power plant room, and on the grounding and insulation of the shed (realized in Q3 of 2017). A full connection, initially scheduled for mid-2018, to the DC-grid, which allows more efficient energy regeneration, has still not been completed.

The current status is of the pilot plant is illustrated in section 1.4.

1.3.2 Project management

The project was coordinated by AquaBattery. AquaBattery had a role in each work package, and also had the goal to market the product after a successful pilot. Within AquaBattery David Vermaas, Emil Goosen, Jan Post and Jiajun Cen dedicated their efforts on execution of the project. During the project AquaBattery hired multiple employees, a product developer (Maurits Maks, after July 2018 replaced by Gerard van Laar), a pilot engineer (Juan-Sebastian Alvarez) and an electrical engineer (Jelle Zeilstra). The daily operation is mostly performed by the pilot engineer Juan-Sebastian Alvarez. Emil Goosen and David Vermaas kept close contact with all project partners, to make sure work was executed in time.

The financial situation of all partners was discussed continuously throughout the project, and it was found that in particular Compass and REDstack got tight in their budget. For Compass opportunities arose to save costs for phase 2, by combining multiple membrane stacks with a single power optimizer (power conversion hardware). REDstack was very dependent on the delivery price of spacers, and they made a deal with their supplier. AquaBattery investigated the option to make cheaper spacers in addition to the existing supplier, but was not able to scale production of this product (nowadays sold as AquaSeal) fast enough to allow integration in membrane stacks of REDstack (in all membrane stacks together there are >10.000 spacers!). REDstack managed to get a good discount on the spacers, yet still got tight in hours because of amendments to stacks and problems with membrane stack building (curly membrane behaviour). Technolution's role got smaller than anticipated, due to the bottleneck of attracting proper manpower for programming the battery management system; the main programming has been taken over by SeaState5 (as previously communicated), which is covered by budget of Technolution and AquaBattery. The final financial overview is presented in chapter 3.

1.4 Results

1.4.1 Results of Blue Battery demonstration project at The Green Village, Delft

We have engineered and built a pilot facility of the Blue Battery. Operation of stage 1 has been opened at November 24, 2017. Since then we scaled the power capacity by a factor to 1000W, and the energy storage capacity by a factor 5 as well (providing 10 kWh energy storage). In order to do so, we selected new pumps with a higher flow rate, as we needed to pump more water to more stacks. This required installing new wiring (230V instead of 24V) and integration of a frequency controller, as the way to specifically control larger pumps proceeds differently compared to small pumps (frequency-regulated compared to voltage-regulated).

All IBC-reservoirs (25 in total) were connected in this phase as well, to accommodate the larger required storage capacity. Our pilot engineer Juan-Sebastián Alvaréz did the main engineering work for this (including drawing and designing, calculating, ordering and installing of new piping work), with support of an intern for installation. The physical extension of this part took in total 3 work days, a huge reduction of time investment compared to the first part.

A difficulty in 2018 proved to be the stability of sensors. Multiple sensors broke down, causing other components to malfunction as well, hence quite a few replacements had to be made from an electrical engineering point of view. Furthermore, the stability of the sensors proved to be a difficulty. As the output showed highly fluctuating values, and as our charging and discharging algorithms were based on this data, we needed to focus significant attention on this aspect. That is why charging and discharging data was primarily produced from 2019 onwards.

The Blue Battery stacks have, in addition to charging and discharging based on supply and demand, also been subjected to endurance tests. Once, for a consecutive period of five days the stacks were operated over several charge-discharge cycles without problems and need for manual operation, steering or maintenance. Expectations initially were that membrane stacks would be able to achieve a maximum power output per stack of 100 Watt, to obtain a maximum power output of 1000 Watt-peak. It was found that internal leakages of membrane stacks were much higher than anticipated, leading so significant losses of power. Whilst with 30 g/L and 1 g/L directly after assembly power outputs were obtained of 51.8W per stack, it did not manage to obtain later in time (under ambient temperature conditions) power outputs with similar concentrations above 30W. With concentrations of 60 and 1 g/L we managed to obtain a maximum power output of 77.2W per stack (see Figure 7 for example, bottom left in Cycle 5). Under the condition of stable performance of stacks in time we believe it would be possible to do obtain values of 100W per stack. The exact reason for the diminished performance is uncertain hitherto, but likely can be explained by a few factors: a) influence of temperature on stack materials (causing internal leakages), b) poor chemical stability of electrolyte, c) impact of ionic short-circuit currents.

Below are pictures of the pilot facility at the first stage (Fig. 1 up to 5) and second phase (Fig. 6-7). Furthermore few results are provided of charging and discharging individual stacks.

Fig. 1: Pump and filter system (at the wall panel) and two stack boxes. Per blue box two membrane stacks are present, together being able to generate 200 Watt power. Above the box three cables (grounding, phase and switch wire, combined in black wrapping for safety purposes) go into the cable tray, from both stacks. Piping work in the background supplies water to the two stacks, with two big pipes on top directing it back towards the reservoirs. Piping work will be extended to the right side in stage 2. The large piping work construction mounted on the concrete plex houses two big filters for fresh and salty water streams (to remove larger particles such as glue, saw dust, etc.), 3-way valves (red-yellow boxes), pressure meters (white clocks), and pumps (in-between the yellow tubing blue pumps are visible for fresh and salt water).

Fig. 2: *Water reservoirs visible for salt and fresh water streams (salt on top). Piping work installed on the sides, going to the rear panel of figure 1. Furthermore, level sensor (blue) and conductivity sensors (small grey pipe) are installed double in each reservoir (fresh and salt).*

Fig 3: Close-up of the sensors. In the background the cable tray coming from IBCs is visible, installed for guiding the cables from sensors towards the electrical cabinet. Furthermore the control room is visible, below the big yellow blocks of insulation material. Installed in a separate room to have a 100% dry room for electrics and electronics, but also be able to heat up the place a bit for comfortable working on the BMS programming.

Fig 4: Opening of the pilot for partners. In the background on the wall the state-of-charge indicator, making visible to visitors how full the battery is. The pilot engineer, product developer and COO Goosen pushing the button, with CTO Vermaas giving a speech.

Fig 5: Goosen and Vermaas during construction of the building.

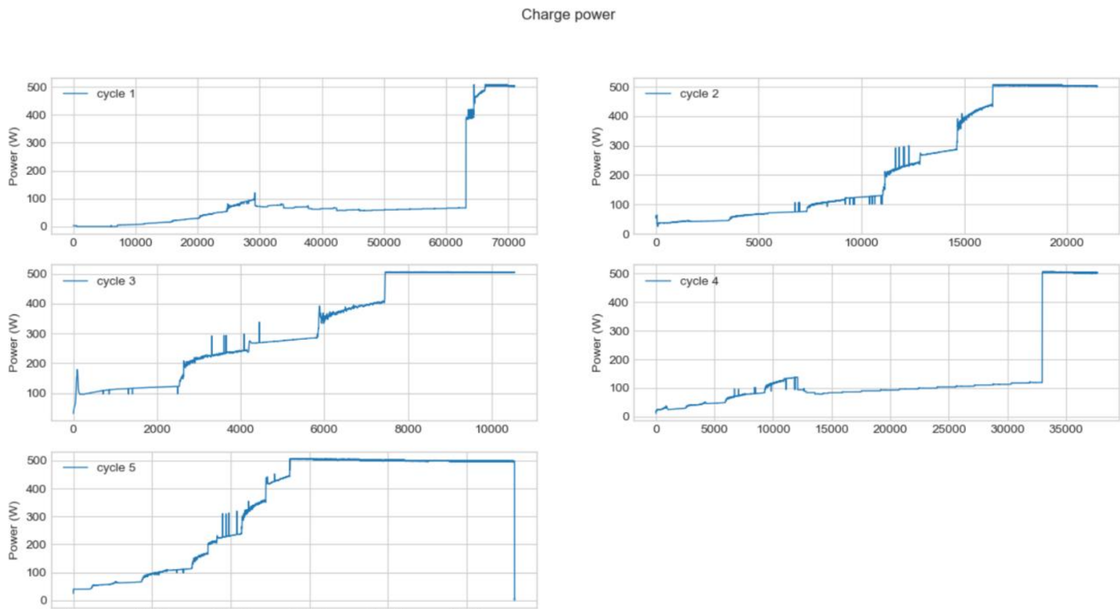


Fig. 6: First results of charging stack with Evoqua membranes. Stacks were tested for performance with different power inputs, to determine specific membrane characteristics, but also to determine optimal charging regimes. Hence, stacks were sometimes also charged up to 5C.

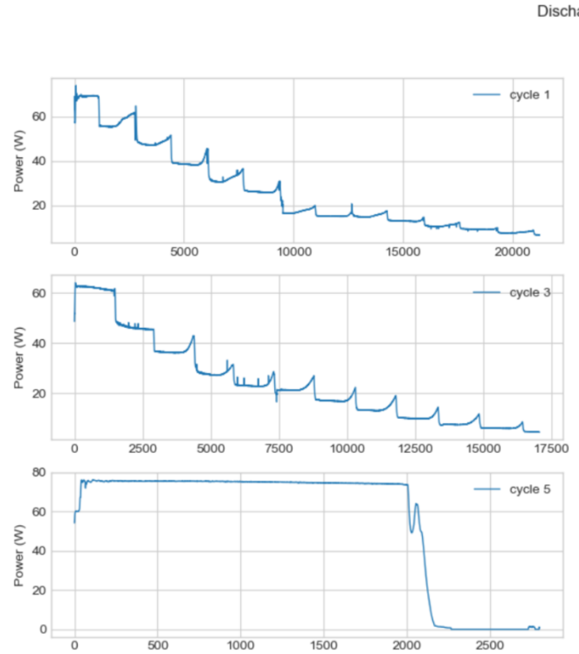


Fig. 7: First results of discharging stack with Evoqua membranes. Large membrane stacks were hitherto never tested for discharging power up to such high concentration differences. The power diminishes in time because of reduced concentration difference in time between the reservoirs, and based on concentrations the amps were modified. Unfortunately it seemed impossible to obtain results above 0.8C. It became clear that several membrane stacks had much higher internal leakage than expected, and that as a result of that sometimes obtained power was much lower than anticipated. During cycle 5 an unexpected error appeared in the BMS, hence the much shorter duration of the cycle.

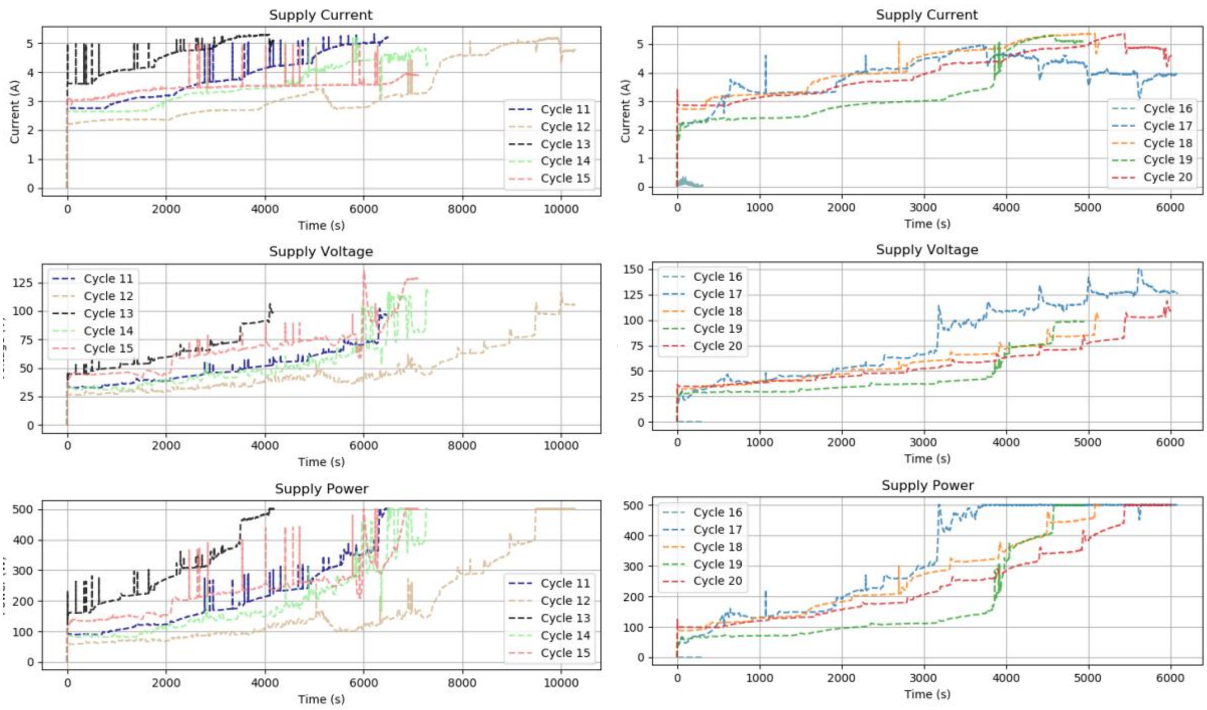


Fig. 8: Charging cycles 11 to 20 for stack #63 and #64 . It refers to the power [W], the voltage [V] and the current [A] during the charging phase. The supply refers to charging process of the Blue Battery.

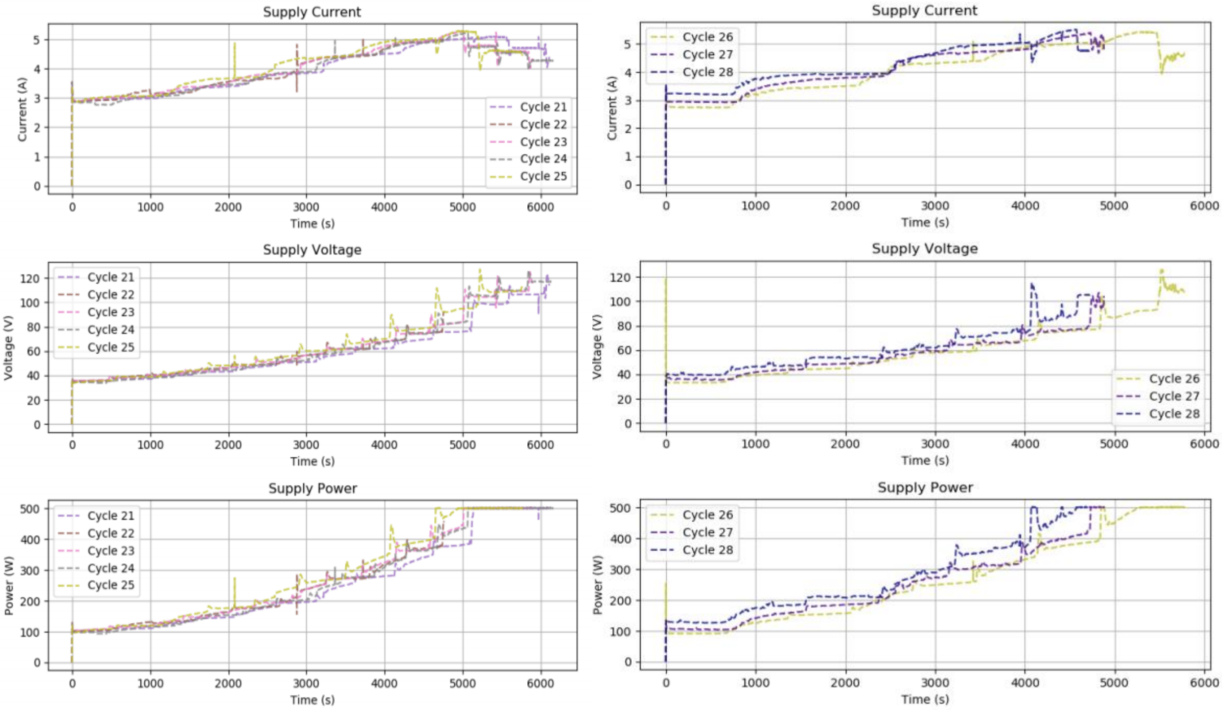
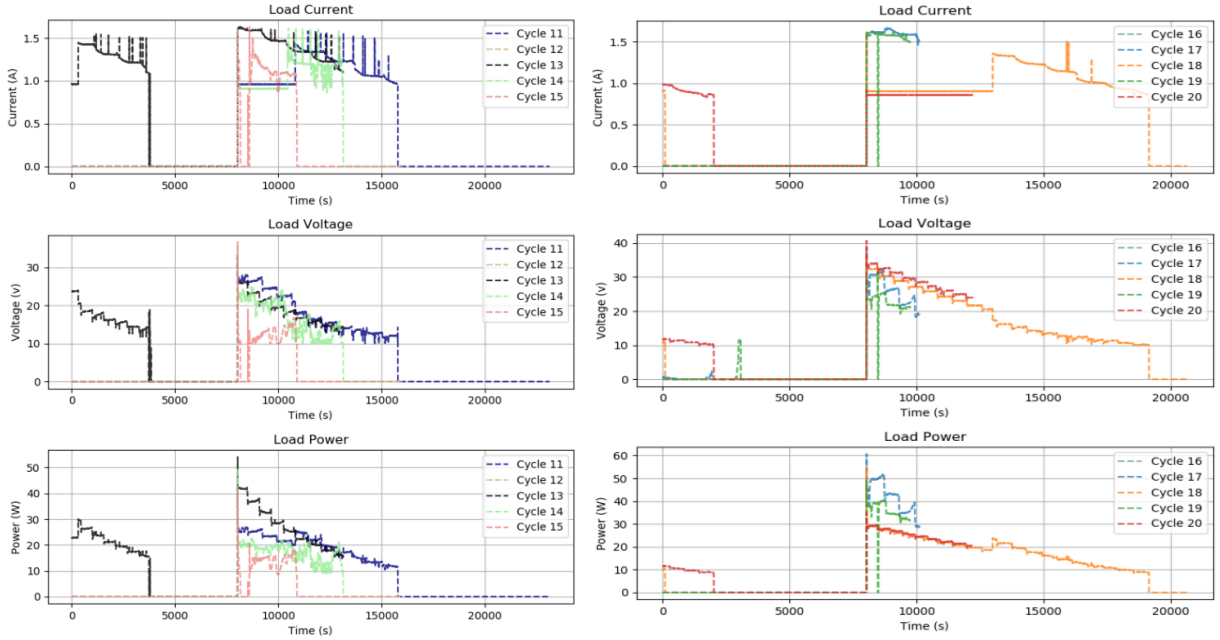


Fig. 9: Charging cycles from 11 to 28 for stack #63 and #64 . It refers to the power [W], the voltage [V] and the current [A] during the charging phase .



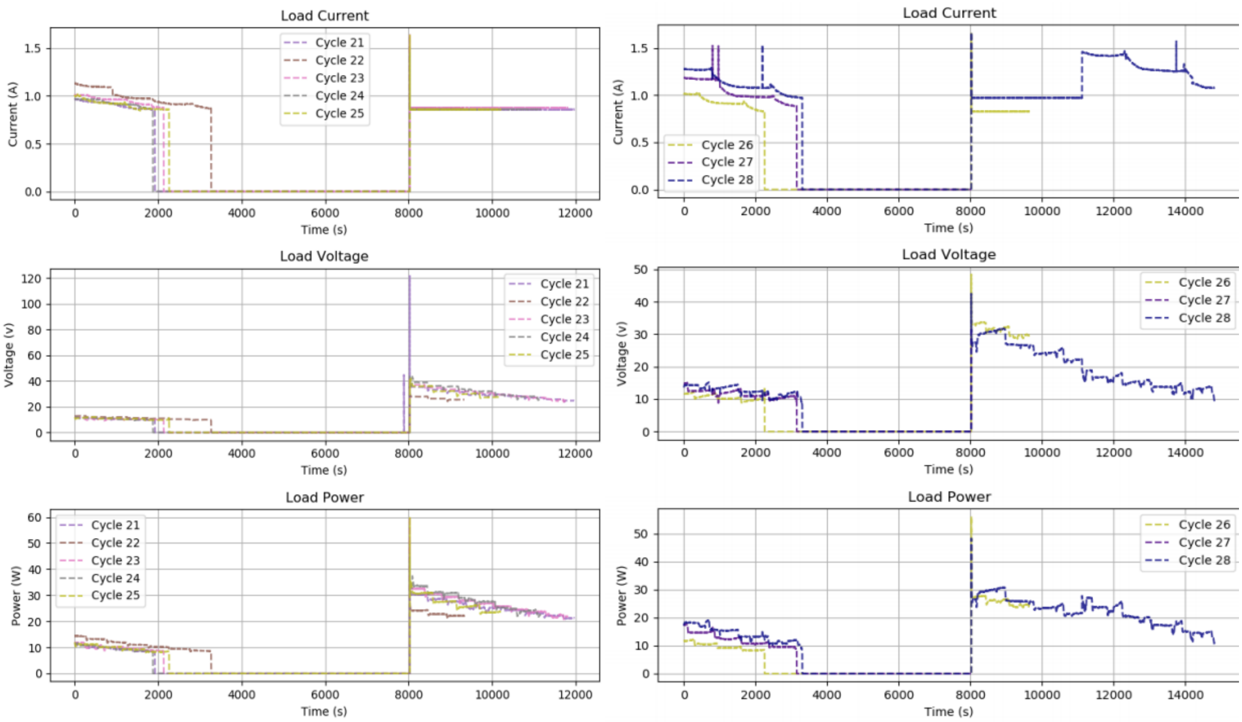


Figure 12 Discharging cycles 11-28 for stack #63 and #64. It refers to the power [W], the voltage [V] and the current [A] during the discharging phase . The load refers to discharging process of the Blue Battery.

Table 1: Performance of membrane stacks #63 and #64.

Cycle number	*µRTE*	*µCE*	*µVE*	*Power Density (W/m^2)*	*Energy Density [kWh/m^3]*
11	0.115	0.345	0.33	0.131	0.014
12	0	0	0	0	0
13	0.177	0.632	0.28	0.328	0.018
14	0.061	0.206	0.294	0.108	0.005
15	0.02	0.11	0.182	0.042	0.002
16	0	0	0	0	0
17	0.044	0.143	0.307	0.172	0.002
18	0.163	0.535	0.305	0.201	0.015
19	0.075	0.168	0.449	0.125	0.001
20	0.084	0.225	0.372	0.201	0.007
21	0.077	0.21	0.364	0.198	0.006
22	0.067	0.24	0.278	0.142	0.006
23	0.078	0.225	0.339	0.207	0.007
24	0.065	0.182	0.358	0.19	0.005
25	0.051	0.166	0.309	0.158	0.004
26	0.042	0.144	0.292	0.132	0.004
27	0.033	0.163	0.199	0.95	0.006
28	0.156	0.574	0.272	0.266	0.014

Results of Life Cycle Analysis and Life Cycle Cost Analysis

In the fourth work package the Blue Battery was compared from a life cycle point of view with several storage technologies:

- Compressed Air Energy Storage (CAES)
- Lead Acid (LA)
- Lithium Ion (Li-ion)
- Pumped Hydro Electricity Storage (PHES)

Several sustainability indicators were assessed: environmental, exergetic and economic. This multi-dimensional sustainability assessment did not lead to one preferred system. All systems were normalised for 10 kWh of storage capacity with a lifetime of 20 years and 300 charge-discharge cycles per year. Looking at the sustainability indicators, it was found that the Blue Battery System (BBS) scores second best, right after PHES, for the indicators human health, ecosystems, global warming potential and resources.

From an economical sustainability perspective BBS scored best on NPV and PWR, with PHES following as a close-second. From exergetic perspective BBS performed worse, primarily caused by efficiencies hitherto.

The most interesting part of the research was the sensitivity analysis however, and the learning points obtained from that. The impact of the touch screen in the BBS was found to play a major role, and omission of it would reduce the normalised environmental impact by nearly 40%. Another large impact was caused by the assumption of replacing our water tanks by means of water bags. What we learn from that is that we need to carefully consider the material of our bags, as chloride within a plastic has a high environmental impact.

The primary lesson learnt from the LCC and LCA is that the larger the system, the lower the environmental impact. A PHES is often in a scale from MWh to GWh, and scaling all components down to 10 kWh, it makes the environmental impact small, despite having to make use of huge quantities of concrete and steel (both with large environmental impacts per kilogram). Scaling BBS by a factor 100 does not lead to 100x as much piping work, wires, cable trays and cabinets, and even not 100x as much material needed for membrane stacks, as stack sizes will become bigger on such a scale.

Table 2: Normalised environmental assessment results.

	BBS	CAES	Lead acid	Li-ion	PHES
Human health	411	4895	7852	1580	100
Ecosystems	839	3435	9366	4034	100
Resources	429	3192	2113	501	100
Total[a]	586	3970	7310	2346	100

[a] 40% human health, 40% ecosystems and 20% resources.

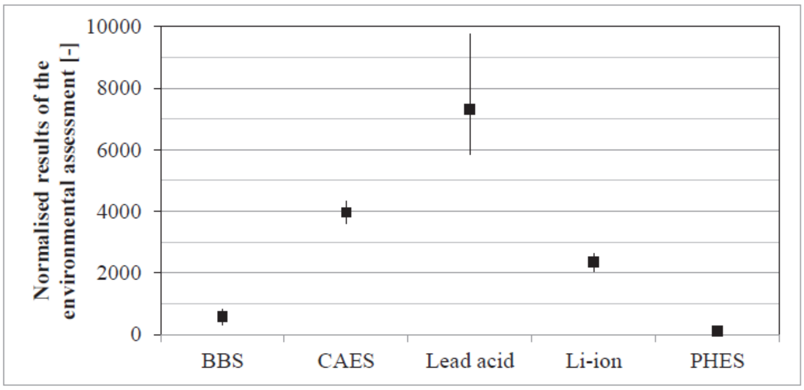


Fig. 13: Sensitivity analysis of the normalised environmental assessment results.

1.4.2. Discussion, Conclusion, Follow-up and Learning points

The last 24 months have allowed us to grow our company and product substantially, from technical perspective especially due to the realisation of the Blue Battery System within the TKI Urban Energy. Simultaneously with the granting of the TKI subsidy end of 2016, an additional Horizon2020 call was granted to a consortium in which AquaBattery is also playing for realisation of a battery on the island of Pantelleria, Italy. Also the obtained funding from grid operators Enexis and Alliander, allows us to focus broader than purely project realisation of the TKI Urban Energy. AquaBattery is since October 2018 focusing on building a second pilot project in Gorinchem, in time in-between Delft and Pantelleria. Here we will store energy for a solar park of 2700 solar PV panels; the project, a 3-stage project with GO/NO-GO moments between the phases after having met specific technical and economical criteria, was initiated to allow scaling of technology and increase the learning curve. The first phase will constitute a battery with 1 kW/35 kWh capacity, and in every following phase will be scaled by a factor 9.

Product development and pilot realisation are the two roads we as AquaBattery are focusing on for the upcoming three years in order to develop our product to allow storage in a economically competitive manner. Pilot realisation allows to apply our battery in a range of different applications, to scale our product to MW-scale and with that reduce membrane prices together with FujiFilm, while product development allows to determine customer demand and desired specs by them, and integrate components such as pumps, reservoirs, piping, stacks and battery management system in an efficient manner.

Another important learning point is that we have gained solid experience in budget estimation for a scaled-up battery system. This first kW-scale battery is very expensive compared to mature battery technologies. The large number of uncertainties in terms of technology, time and price make it necessary to focus in detail on each component, and to have back-ups in place for many. For that reason, we have tested several options for membranes, pumps, sensors, etc., which had a large impact on the costs of the pilot, but gain very valuable information for the future cost estimation and battery performance. The same holds for estimating the man hours; due to the early stage of development, the engineering took a lot of time. In total, we underestimated how much effort it would take to acquire the right people for developing the battery management system, to get membrane stacks in time, to get the system leakage free, and underestimated the level of difficulty for obtaining proper piping by testing all components. Underestimation took place by all partners, and many aspects that led to delays were (to a major extent) unforeseen. The learning point here is to be as flexible as possible, to adapt easily to a new strategy, and continue with the goals.

Specific learning points relate to reservoirs, membrane stacks and automation. For the Blue Battery it is important to scale reservoirs not by interconnecting many small reservoirs, but by installing large reservoirs for the fresh and salty water. One option is to install pillow bag tanks, that can attain volumes up to 5000 m3, which reduces the price per m3 of storage by a factor 7 approximately. Another very interesting option is to excavate soil and use that for constructing a dike, and by using foil to construct a reservoir. Both options we are considering for follow-up projects.

Related to the membrane stacks, AquaBattery is in discussion with REDstack to intensify the collaboration, and fasten the product development of membrane stacks. REDstack right now has a new type of membrane stack under development that goes up to 1 kW per stack with much lower power losses and reduced internal leakage. Furthermore, AquaBattery herself is developing membrane stacks as well to allow faster and cheaper construction by means of industrial production techniques.

The last major learning point relates to industrialization of the battery management system (BMS) of the battery. The instability of the BMS is still a major hurdle hitherto, sometimes crashing for unknown reasons, requiring restarts and modifications once a while. Internally we are now switching to PLC systems for control, and are focusing on full remote control to minimize the need to physically visit sites to check and modify code.

To conclude, the project itself was a project much bigger and more difficult than expected. Participants learnt a lot from this specific project however. REDstack has professionalized membrane stack development and is doing first tests with a leak-free membrane stack, one that is also having minimal internal short-circuit currents (an aspect that is minimizing the performance of the stacks in Delft significantly right now). AquaBattery started development of her own membrane stacks as well to allow faster development of the technology, has started production of her own spacers, and is right now investigating to market a scaled-version of the battery used for the pumps, to gain more insights in the added value for a variety of customers. All these developments have led that at the moment multiple projects are in the pipeline to be developed (2) and to be constructed (2), with significant interest that would allow to develop more.

2.1 Bottlenecks encountered during project

Availability of spacers

Availability of spacers was a big problem in the beginning of the project. We had to deal with the fact that a large, unknown party bought a batch of spacer material that we wanted to utilise in our stacks. We had to find an alternative, but to obtain still high power densities from our stacks, we had to choose between lower performance and 6 weeks delivery time or high performance and 20 weeks delivery time. To not further delay any process, we chose for the poorer performing membranes for stage 1. For the second stage the manufacturer of spacers indicated that delivery will be problematic because of larger demand. REDstack has held close contact with the producer and managed to get a proper netting and quality for the second stage, without having to spend more money on them than expected.

Programming of BMS

In the original plan, execution of this part of the project would be fulfilled by employees and interns of Technolution and AquaBattery. Attraction of skilled interns and employees in the field of programming and electrical engineering was proven very difficult for both partners, and the existing manpower to execute this by Technolution employees was not sufficient in time and budget. As a result, SeaState5 was hired to develop the software system (paid from budget of AquaBattery and Technolution), while the electronics were developed by employees of AquaBattery. SeaState5 was known to both partners, having experience in power and sensor component integration in among others the Nuna solar car. SeaState5, together with EXE Zown is now working on further scaling the BMS to an EMS.

Integration of components

Initially the project encountered many problems with integration of different components from an electrical and data point of view. SeaState5 (now DotRobot) was approached to solve in collaboration with Compass & AquaBattery these problems. This led to substantial delay in testing of the pilot, as the battery could not be operated from a distance, nor could experiments be done without an employee being physically on-site (to operate 2-way valves, that make sure the fresh water can go from Fresh1 to Fresh2. In the second stage the volatility of sensors also posed a problem, this problem was solved finally by means of BMS-code written by AquaBattery.

Quality of membranes

In the initial project plan it was the plan that FumaTech membranes would be used as benchmark and to compare FujiFilm membranes to FumaTech, to investigate what cheaper FujiFilm membranes would do to the business case. At the start a new supplier was found: Evoqua. Whilst the membranes were of comparable quality to FumaTech in the first phase, and the membranes were much cheaper, it was decided to assemble more stacks with Evoqua membranes for phase 2. The quality of membranes in the second phase however proved to be a big problem. The batch of membranes that came in showed curly behaviour for one of the two types of membranes, making assembly almost impossible (and time consuming). The third batch in this second phase was finally good, and hence the last four stacks were operating much later than anticipated.

2.2 Changes compared to original plan

As all changes have been discussed in detail elsewhere in this document, hereby a brief overview:

- SeaState (now DotRobot) primarily executed BMS development;
- Instead of one fresh and one salt reservoir, the fresh reservoir was split up in two, pumping water from A via stack to B, and when A is empty and B is full, the water flows from B via stack to A, and so on;
- Evoqua membranes were primarily used for the stacks.

2.3 Finances

2.3.1. AquaBattery

Salaries

Phase	*Budgetted hours*	*Budgetted costs*	*Hours realised*	*Remaining*
WP1	820	€ 49.200,00	838	-18
WP2	700	€ 42.000,00	735	-35
WP3	1680	€ 100.800,00	1770	-90
WP4	272	€ 16.320,00	320	-48
Total	**3472**	**€ 208.333,00**	**3663**	**-191**

A larger number of hours has been dedicated to all aspects of the pilot, from the engineering of the pilot plant (WP1+WP2), but also for operation, maintenance and problem solving many more hours were spent than budgeted. Also on the fourth work package more hours were spent, especially in getting all components with all their details fully clear (it required investigation of type of materials, production processes, country of production, but also for a final product it had to be investigated which components could be simplified or even left out).

Original budget – consumed resources and materials & costs payable to third parties

Phase	Description costs	Total costs (excl VAT)
WP2	Hardware (other)	€ 45.000,00
WP3	Membranes	€ 85.000,00
WP2-4	Third party costs	€ 10.000,00
	Total	**€ 140.000,00**

Consumed resources and materials up to 30-04-2019

Phase	Description costs	Total costs (excl VAT)
WP3	Membranes	€ 44.853,95
WP2	Piping work	€ 10.271,17
WP2	Electronics	€ 16.477,43
WP2	Pumps	€ 9.994,98
WP2	General/other	€ 40.117,66
	Total	**€ 121.715,19**

Costs payable to third parties up to 30-04-2019

Phase	Description costs	Total costs (excl VAT)
WP2	Design and building of electrical cabinets	€ 2.000,00
WP2	Software development SeaState5 (total € 23.400, covered by Technolution (€ 9.900) and AquaBattery (€ 13.500))	€ 13.500,00
WP3	Location rent + installation facilities The Green Village	€ 7.078,07
	Total	**€ 22.578,07**

2.3.2. Compass

Original budget – salaries

Phase	Budgetted hours	Budgetted costs	Hours realised	Remaining
WP2	950	€ 57.900,00	350	600
Total	**950**	**€ 57.900,00**	**350**	**600**

Original budget – consumed resources and materials

Phase	Description costs	Total costs (excl VAT)
WP2	Sensors, converters, preparation site, hardware (other)	€ 49.000,00
	Total	**€ 49.000,00**

Consumed resources and materials up to 30-04-2019

Phase	Description costs	Total costs (excl VAT)
WP2	Hardware, sensors, converters, site	€ 45.806,76
	Total	**€ 45.806,76**

The man hours of Compass were smaller than anticipated within the budget, and also the material costs were slightly lower than budgeted, mainly because of unexpected expenses at the construction site, and because converters were harder to find than expected. Budgeted costs for stage 2 of the project were diminished by installing one load and one supply for two stacks, instead of per one stack. In previous report it was indicated that it was expected to finish it for the set budget, and that was done. Compass realised everything in much less hours than anticipated, and also communicated earlier, which was because it was only late in the project that it became clear that Compass had previously summed up all hours spent on the Blue Battery System project, including hours of a previous subsidy project, not making a distinction between projects.

2.3.3. REDstack

Phase	Budgetted hours	Budgetted costs	Hours realised	Remaining
WP1	1370	€ 82.200,00	679,5	690,5
WP3	960	€ 57.600,00	2263,2	-1303,2
Total	**2330**	**€ 139.800,00**	**2942,7**	**-612,7**

Original budget – consumed resources and materials & costs payable to third parties

Phase	Description costs	Total costs (excl VAT)
WP1	Material assembly line + test bank	€ 40.000,00
WP3	Stack casings for pilot	€ 125.000,00
WP3	Third party costs (e.g. transportation)	€ 1.000,00
	Total	**€ 166.000,00**

Consumed resources and materials up to 30-04-2019

Phase	Description costs	Total costs (excl VAT)
WP1	Material assembly line + test bank	€ 10.082,00
WP3	Stack casings for pilot	€ 137.079,00
	Total	**€ 147,161,00**

Costs payable to third parties up to 30-04-2019

Phase	Description costs	Total costs (excl VAT)
WP3	Third party costs	€ 1.653,00
	Total	**€ 1.653,00**

The man hours of REDstack were much higher than anticipated and expected prior to stage 2. This primarily related to the fact that the curly membrane behaviour led to significant testing and renewed stack building. The material costs seemed to be on track at first sight (slightly more material costs than estimated), but in the second phase substantial costs were saved on the construction of an assembly line and test bank, as REDstack managed to design this more efficiently. The savings were used to cover the burden of having to spend many more man hours than anticipated.

2.3.4. TU Delft

Phase	Budgetted hours	Budgetted costs	Hours realised	Remaining
WP4	490	€ 30.346,00	490	0
Total	**490**	**€ 30.346,00**	**490**	**0**

Original budget – consumed resources and materials

Phase	Description costs	Total costs (excl VAT)
WP4	50% increment	€ 14.654,00
	Total	**€ 14.654,00**

Consumed resources and materials Realised

Phase	Description costs	Total costs (excl VAT)
WP4	Other	€ 14,654
	Total	**€ 14,654**

TU Delft remained within planned budget.

2.3.5. Technolution

Phase	Budgetted hours	Budgetted costs	Hours Realised	Remaining
WP2	292	€ 17.500,00	30	262
Total	**292**	**€ 17.500,00**	**30**	**262**

Original budget – consumed resources and materials

Phase	Description costs	Total costs (excl VAT)
WP2	Software platform	€ 2.000,00
	Total	**€ 2.000,00**

Consumed resources and materials Realised

Phase	Description costs	Total costs (excl VAT)
WP2	Software platform	€ 0,00
	Total	**€ 0,00**

Third parties Realised

Phase	Description costs	Total costs (excl VAT)
WP2	Contribution for software development at SeaState5	€ 9.900
	Total	**€ 9.900**

As the role for software development has been mainly performed by SeaState5, the majority of the remaining budget of Technolution was dedicated to the costs of SeaState5. Technolution made extra hours in 2018 for the software communication between the BBS and the other consumers (student houses + office) at The Green Village.

3.4 Knowledge dissemination

The Green Village is a demonstration area of new sustainable technologies, and is often visited by industry leaders, policy makers (among other members of the parliament) and local people. For example, at the 24th of August 2017 a visitation of policy makers took place. This day a dedicated safety event was organized at The Green Village, where several parties who showcase their technology at The Green Village were asked to present cases, and investigate points of attention together with a delegation from the Ministry of Infrastructure and the Environment. The workshop was about identifying potential barriers. In general our Blue Battery system can be considered a highly safe system, with the main safety issue related to potential leakages of reservoirs, what would infer that multiple thousands of litres of salty water end up in the sewage system. A follow-up assessment took place end of 2018 by water authorities in The Netherlands, and the salty water is considered a non-soil-threatening substance on small-scale. On large-scale compartmentalizing might be required, but that assessment requires further research.

Similar events are continuously organized at The Green Village, and almost daily groups of different people following a tour visit our pilot location. Municipalities of Breda and Amersfoort did a visit, and with the latter one a workshop (facilitated by TGV) created a lot of interest in having one of our batteries in their new “sustainable neighbourhood”. In general, during these tours we provide the people with a brief introduction to our technology, product and company. During another tour, a visit of energy industry leaders from the USA and the Middle-East, a lot of interest was shown in our product. Furthermore, several companies paid a visit to our pilot and we identified new potential partnerships for technology and business development.

A visualization of the concept is located large on the outside of the BBS pilot building, and a window our pilot allows to see the operation 24/7.

Furthermore, dissemination took place by scientific publications (**Van Egmond** *et al.,* 2017*, Energy efficiency of a concentration gradient flow battery at elevated temperatures*, J. of Power Sources), by publication papers about the lifecycle (cost) analysis of the Blue Battery compared to other storage technologies (**Stougie** *et al.,* 2019, *Multi-dimensional life cycle assessment of decentralised energy storage systems,* Energy*)* by presentation at a 2-day seminar for water technology scientists and industries, presentation at a 2-day conference at the TU Delft, by winning the Accenture Innovation Awards in the category of Circular Economy, and by becoming finalist at Postcode Lottery Green Challenge competition (with significant publications in national newspapers, a.o. Trouw, NRC, etc).