= iSTORMY =

EUROPEAN COMMISSION

HORIZON 2020 PROGRAMME – TOPIC: Hybridisation of battery systems for stationary energy storage

Interoperable, modular and Smart hybrid energy STORage systeM for stationarY applications

GRANT AGREEMENT No. 963527

Deliverable Report

D2.4 – Report on performance and testing of the BP prototype

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 963527

Deliverable No.	iSTORMY D2.4	
Related WP	WP2	
Deliverable Title	Hybrid battery pack development and validation	
Deliverable Date	31-05-2023	
Deliverable Type	REPORT	
Dissemination level	Public (PU)	
Written By	Miguel Encabo (CEG) Igor Cantero (CEG) Mário Paroha (GW) Wlodzimierz Walkusz (GW) Erik Hoedemaekers (TNO)	25-05-2023
Checked by	Erik Hoedemaekers (TNO)	26-05-2023
Reviewed by	Antoine LAURIN (CEA)	26-05-2023
Approved by	Project Coordinator (VUB)	30-05-2023
Status	Final	31-05-2023

Disclaimer/ Acknowledgment

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 963527. The information and views set out in this publication does not necessarily reflect the official opinion of the European Commission. Neither the European Union institutions and bodies nor any person acting on their behalf, may be held responsible for the use which may be made of the information contained therein.

Publishable summary

Based on the specifications defined in the project (WP1) and the design optimization of the system (WP3), the batteries that make up the hybrid storage system have been developed and manufactured.

This hybrid system consists of two types of batteries, one for energy and one for power:
The energy battery is composed of 7 modules of 7.7 kWh of energy and the power battery is composed of 20 modules of 2.5 kWh, so that the demonstrator is formed by approximately 50% of each battery in terms of capacity. Each group of batteries is controlled by a control and protection system and both are connected to the power electronics for optimized management.

This deliverable shows the development of the prototypes as well as the tests to which they are subjected to confirm their correct operation, before being sent for integration with the power electronics.

The Total Cost of Ownership (TCO) is also analysed for the realised system and compared against standard energy storage systems (without any hybridisation and updated technology like advanced SoX algorithms and inclusion of Phase Change Material (PCM)). This analysis is done for the use-cases in iSTORMY and shows a potential TCO reduction of >17% for one of the use-cases while showing smaller, but still positive, difference for the other use-cases.

Contents

List of figures 5
List of tables 5
1 Introduction 6
2 High Energy battery 7
  2.1. General characteristics 8
  2.2. Electrical characteristics 8
  2.3. Physical characteristics 8
  2.4. Protection and Communication Cabinet (PCC). 9
3. Validation test of high-energy battery 10
  3.1. System: PCC & 7 eBick Pro Serie 160Ah 10
  3.2. Validation Tests 11
    3.2.1. Communication Testing 11
    3.2.2. Charge/Discharge Testing 12
    3.2.3. Protection Testing 12
4. High-Power Battery 14
  4.1. First power module prototype 15
    4.1.1. Electrical characteristics 15
    4.1.2. Physical characteristics 16
  4.2. Preliminary thermal test 16
  4.3. Welding process 19
  4.4. Module assembly 19
5. Validation test of high-power battery 24
  5.1. System: PCC & 20 NMC Battery 50.4V 50Ah modules 24
  5.2. Validation Tests 25
    5.2.1. Communication Testing 25
30 in 25
    5.2.2. Charge/Discharge Testing 26
    5.2.3. Protection Testing 27
6. iSTORMY Hybrid Battery Pack Total Cost of Ownership 29
  6.1. iSTORMY solution 29
  6.2. Scope of the TCO analysis 29
  6.3. TCO analysis assumptions 30
  6.4. TCO analysis results 32
7. Discussion and Conclusions 33
8. Risk Register 33
Acknowledgement 34

List of figures

Figure 1. Drawing of the hybrid battery 6
Figure 2. Energy module 7
Figure 3. Inside of PCC for high-energy battery 9
Figure 4. Validation of the high-energy battery pack 10
Figure 5. Power module drawing 14
Figure 6. Power module 3D representation 14
Figure 7. Power module prototype 15
Figure 8. Thermocouples position for thermal testing 16
Figure 9. Thermal and SoC evolution during first cycle 17
Figure 10. Thermal and SOC evolution during second cycling process 18
Figure 11. High power module rack 3D drawing 19
Figure 12. High-power module rack prototypes 19
Figure 13. High power battery design 20
Figure 14. High-power battery cabinets 21
Figure 15. High-power battery string 22
Figure 16. Inside of PCC of power battery 23
Figure 17. Complete high-power battery system 24
Figure 18. Battery Management System control interface 26

List of tables

Table 1. High energy battery configuration update 7
Table 2. Electrical characteristics of the high-energy modules 8
Table 3. Physical characteristics of the high-energy modules 8
Table 4. Test of communications with the BMS 11
Table 5. Test of communications between the inverters and the batteries 11
Table 6. Charge/Discharge test for high-energy battery 12
Table 7. Protection test for high-energy battery 12
Table 8. Electrical characteristics of the high-power modules. 15
Table 9. Physical characteristics of the high-power modules. 16
Table 10. Test of communication with the BMS. 25
Table 11. Test of communication between the inversters and the batteries 25
Table 12. Results of balancing tests for the high-power modules 26
Table 13. Charge/Discharge for high-power battery 27
Table 14. Protection test for high-power battery. 27
Table 15. Technical parameters of the 3 considered energy storage solutions 29
Table 16. Yearly number of cycles for 3 alternative energy storage solutions and 3 Use cases 30
Table 17. Cycle life analyses results 30
Table 18. CAPEX estimation 31
Table 19. Discount factor with discount rate 3.2% 32
Table 20. TCO estimation for the Use cases 32

1 Introduction

The main work carried out in this task is to develop and manufacture a prototype of the hybrid battery system. This battery has two parts, one optimised in energy and the second one optimised in power. The preliminary proposal was a configuration as depicted in the drawing in Figure 1.

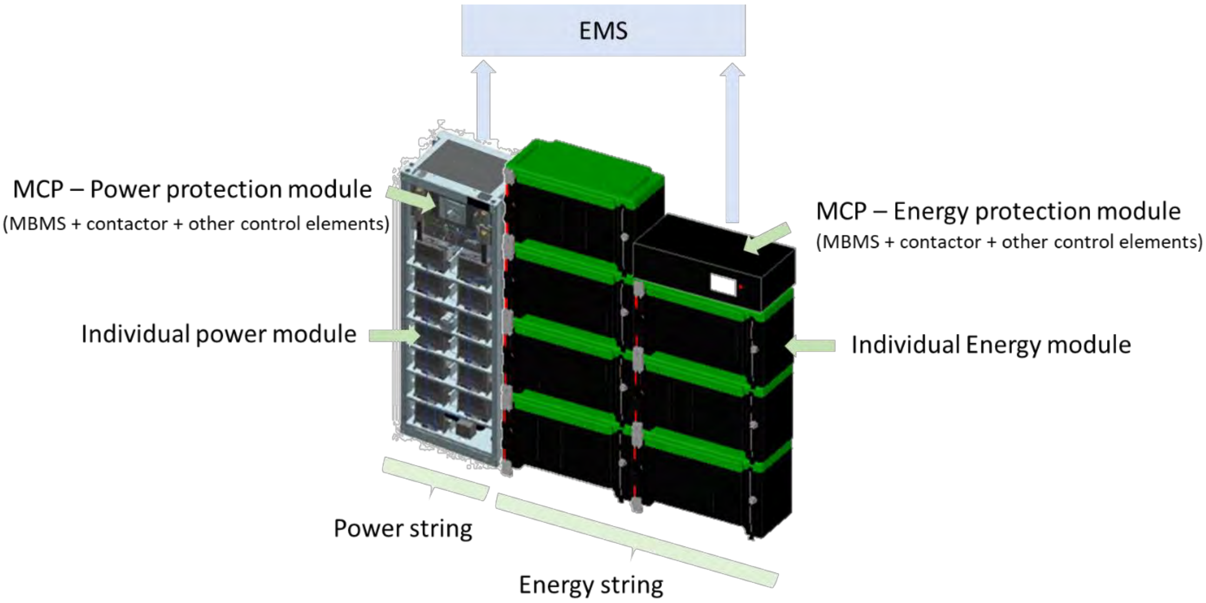


Figure 1. Drawing of the hybrid battery

During the course of the project update on the above shown initial idea has been incorporated to create the overall battery system. This now consists of two types of batteries (as proposed), one optimized for energy content (using LFP cells) and the other for power delivery (using NMC cells). The energy battery is composed of 7 modules with 7.7 kWh of energy and the power battery is composed of 20 modules of 2.5 kWh, so that the demonstrator is formed by approximately 50% of each battery type. Each group of batteries is controlled by a control and protection system and both will be connected to the power electronics for optimized management. The high-energy battery is constructed from modules that CEGASA produces as standard, while the high-power battery system is completely designed from scratch.

Initially the objective was to use CEGASA's standard 48 V, 280 Ah module for the energy battery and develop a completely new module for the power battery. However, due to the voltage and power requirements, the energy module was too large for this demonstrator. Therefore, even though it was not included in the project and without a budget increase, CEGASA agreed to develop a variant of the original module using a smaller cell size (160 Ah vs 280 Ah) and increasing the number of cells per module (18 vs 15). The power module remained unchanged.

2 High Energy battery

The energy battery is based on eBick modules developed by CEGASA, as shown in Figure 2.

Figure 2. Energy module

Externally, the module is similar to the current module in the CEGASA catalogue. It uses the same enclosure and connectors to facilitate the assembly of the prototype. However, inside it is a new product. The cells used are prismatic LFP cells of 3.2V and 160 Ah, with aluminium housing and dimensions of 154 mm high, 174 mm long and 54 mm wide.

As indicated in the previous paragraph, this module was a variant of the original module and a higher voltage configuration (18s) was proposed to provide 58V instead of the original 48V. Due to manufacturability problems of the BMS adapted to the new voltage, finally the original idea of 58V (18 cells) was replaced by the original 48V (15 cells) and one more module was added in series. The final result is a bit more expensive (one more BMS, one more box, etc.) but the electrical configuration is practically the same, Table 1 details the similarity of the different configurations.

Table 1. High energy battery configuration update

	Original plan	**Final version**
Cell capacity	160Ah	160Ah
Module configuration	18s1p	15s1p
Battery configuration	6s1p	7s1p
Battery voltage	3,2 * 18 * 6 = 346V	3,2 * 15 * 7 = 336V
Battery energy	346 * 160 = 55,3kWh	336 * 160 = 53,8kWh

The final internal configuration of the prototype modules is fifteen cells in series using laser welding connections with aluminium bus-bars. The slave BMS inside the module is responsible for monitoring the cells in voltage and temperature. It also includes the balancing circuit and a communications port that transmits all this information by ISO-SPI to the master BMS.

2.1. General characteristics

- Cell working temperatures from -20ºC to 55ºC
- Stackable on itself up to 4 heights.
- Pre-wired. Less installation time.
- Finished in fast connectors. No need for insulated tool for installation
- Does not require additional facilities such as spill pans or ventilation systems
- With internal electronics (BMS) offering internal battery data
- Without maintenance
- Autonomous equalization, without the need for intervention by the end user

2.2. Electrical characteristics

The electrical characteristics of the high-energy modules are shown in Table 2 below.

Table 2. Electrical characteristics of the high-energy modules

Nominal voltage	48 Vdc
Maximum voltage	53 Vdc
Minimum voltage	43 Vdc
Rated capacity	160 Ah
Stored energy	7,68 kWh
Nominal discharge current	100 A
Overload current	300 A / 1 minute
Rated charge current	100 A

2.3. Physical characteristics

The physical characteristics of the high-energy modules are shown in the table below.

Table 3. Physical characteristics of the high-energy modules

Weight	70 kg
Width	390 mm
Long	762 mm
High	470 mm

2.4. Protection and Communication Cabinet (PCC).

The eBick modular system includes a Protection and Communication Cabinet (PCC), which is shown in Figure 3.

Figure 3. Inside of PCC for high-energy battery

The PCC includes current measurement, DC cut-off control and a 7” touchscreen HMI to display voltage, temperature, “SOC”, “SOH”, etc.) in addition to the CAN and Modbus communications module for connection to the inverter. The master BMS is also included in the PCC.

The PCC uses a user-friendly software that enables in-situ display of all the parameters provided by the BMS on a 7-inch touchscreen:

- Charge status
- Life-cycle status
- System current measurement
- String voltage measurement
- Temperature and voltage maximum and minimum measurements at both string and module levels
- Battery status (charge, discharge, balance, stand-by, etc.)
- It is also possible to connect and disconnect the contactor and to order equalization of the battery.

The main components of the PCC are:

- Cegasa master BMS (control system and string management)
- Up to 500 A Contactor
- Current measurement (LEM)
- HMI (7” touchscreen)
- Master busbar
- Fuses for each intake or string module
- 1 intake or module string
- IP55

3. Validation test of high-energy battery

This section shows the validation test for the high-energy battery pack. This system has a capacity of 53.76 kWh with a configuration of 7 eBick Pro 160Ah and a PCC 800V 300A. With the objective of validate both configurations, the current document details the different tests that have been carried out in the factory as part of the FAT protocols with a maximum power of 9kW.

3.1. System: PCC & 7 eBick Pro Serie 160Ah

The eBick storage system is formed by 7 eBick Pro modules of 48V connected in series to a CEGASA's PCC busbar cabinet through 1 power extension (7 in total) for each battery string. The PCC includes the busbar and the required protection components. The PCC input cables from the batteries are connected in the right side and the output cables to inverter clusters are connected in the left side. The diagram below shows the system set up, see Figure 4.

Figure 4. Validation of the high-energy battery pack

The proposed validation test for the eBick Pro storage system is divided in the following sections:

- Communication Testing
- Charge/Discharge Testing
- Protection Testing

3.2. Validation Tests

3.2.1. Communication Testing

Once communication and one power cables between the batteries and the PCC are connected, the battery system is switched on using the master switch in the PCC and its screen should turn on. Once the BMS configuration is fully loaded after one minute, the communication test between the battery modules and the PCC is carried out, see results in Table 4. This verification is made in each configuration prior to sending the equipment.

Table 4. Test of communications with the BMS

Test	Description of the test	Duration	Result
Communications with the BMS	1. Communication between the battery BMS and the PCC BMS.	30 min	
	1.1. Voltage and temperature values of the battery packs appear in the PCC screen.		OK
	1.2. There is no alarm in the screen. The main screen LED is on (green).		OK
	1.3. The PCC contactor is closed at the moment of switching on. The battery appears in connect state.		OK

The next step is the validation of the communications between the inverters and the batteries. For this test, the ethernet cable between the inverter and the PCC should be connected. In order to validate these communications, the next test should be done, see results in Table 5.

Table 5. Test of communications between the inverters and the batteries

Test	Description of the test	Duration	Result
Battery/inverter communications	2. Communication between the PCC BMS and the inverter	30 min	
	2.1. Inverter reads the state of the battery		OK
	2.2. Inverter reads the SoC of the batteries		OK
	2.3. Inverter reads the SoF of the batteries		OK

3.2.2. Charge/Discharge Testing

For the charge/discharge test, the power and communication cables among the batteries, the PCC cabinet and the inverter should be connected. Once communications are validated, and the battery contactor is closed, the inverter should charge and discharge the batteries following the power setting reference from the SCADA. The charge and discharge is validated through the inverter AC output, see results in Table 6.

Table 6. Charge/Discharge test for high-energy battery

Test	Description of the test	Duration	Result
Charge	3. Charge of the battery tests	1h	
	3.1. Charge of the battery through the inverter connected to the grid. Charge current is the same as SoF and the setting in the SCADA.		OK
	3.2. SoF is adjusted automatically with the SoC and the cell temperature.		OK
	3.3. Charge of the battery until 100% of SoC. The value of SoC is refreshed correctly.		OK
Discharge	4. Discharge of the battery test	1h	OK
	4.1. Discharge of the batteries through the inverter connected to the grid. Discharge current is limited by the SoF and power set in SCADA.		OK
	4.2. While discharging the batteries, check that SoC correctly updates when voltage lowers.		OK
	4.3. Inverter stops the discharge when the SoC lower limit is reached.		OK

3.2.3. Protection Testing

In order to validate the protection, different tests that cause programmed protection alarms are carried out in this section. The correct behaviour of the inverter and the batteries against these alarms is validated, see results in Table 7.

Table 7. Protection test for high-energy battery

Test	Description of the test	Duration	Result
Protection tests	5. Different errors are provoked to the batteries and the correct behaviour is checked	1h	
	5.1. A communication error is caused disconnecting the ethernet cable between the batteries. A warning appears at 30 seconds of communication lost. After 60 seconds, an error appears, and the contactor opens.		OK
	5.2. A communication error is caused disconnecting the ethernet cable between the PCC and the inverter. An		OK

	error in the inverter arises and the current flow stops.		
	5.3. An overvoltage warning is provoked by communicating it from the battery to the inverter. The inverter stops charging the battery.		OK
	5.4. An undervoltage warning is provoked by communicating it from the battery to the inverter. The inverter stops discharging the battery.		OK
	5.5. An overcurrent warning is provoked by communicating it from the battery to the inverter. The inverter stops charging the battery.		OK
	5.6. An overcurrent error is provoked by communicating it from the battery to the inverter. The contactor of the battery opens.		OK
	5.7. An overtemperature warning is provoked by communicating it from the battery to the inverter. The inverter stops charging the battery.		OK
	5.8. An overtemperature error provoked by communicating it from the battery to the inverter. The contactor of the battery opens.		OK

4. High-Power Battery

The high-power module of CEGASA is a completely new design. New cells were selected with better thermal behaviour. The cells used are prismatic NMC cells of 3.2V and 50 Ah, with aluminium housing and dimensions of 100 mm high, 148 mm long and 27 mm wide.

The cell that was initially selected was the LISHEN cell. Samples were requested and these are the ones that were used for preliminary characterization. However, when more cells were requested from Lishen, it was impossible to get them due to a peak of demand from automotive manufacturers (the supplier chose to give preference to this type of customers over CEGASA). Faced with this problem, a solution was requested to CEGASA's distributor in China and a second manufacturer was recommended: Gotion. This new supplier is also of first level and produces cells with very similar characteristics. The performance and ageing test data of both cells were analysed to evaluate the difference in electrical properties between the Gotion and the Lishen cells. Using the data of the new cells, a good estimation result for the precision (around 1% error) of the SoC estimation algorithm based on the performance model of the Lishen is obtained. Then, it is fair to consider that the cells are close enough to neglect the difference in electrical properties. For this reason, the cells for the prototypes were ordered from this second manufacturer. Figure 5 and Figure 6 display the power module design.

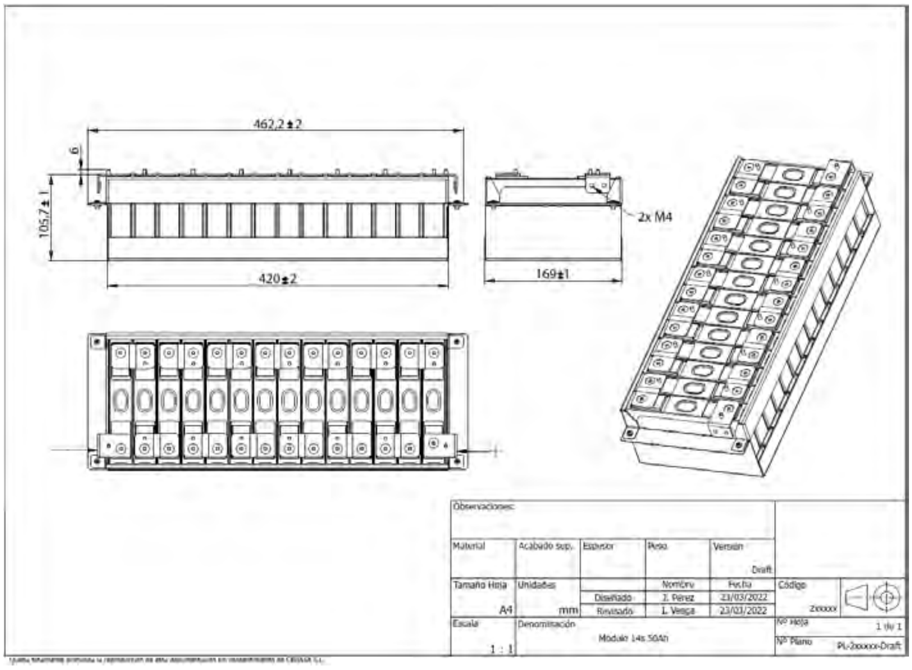


Figure 5. Power module drawing

Figure 6. Power module 3D representation

4.1. First power module prototype

Using the first batch of cells a preliminary prototype was manufactured, see Figure 7.

Figure 7. Power module prototype

As was shown in the figure, 14 cells in line are used. All the cells are connected in series obtaining the following characteristics.

4.1.1. Electrical characteristics

The electrical characteristics of the high-power module are shown in Table 8.

Table 8. Electrical characteristics of the high-power modules.

Nominal voltage	51 Vdc
Maximum voltage	58 Vdc
Minimum voltage	39 Vdc
Rated capacity	50 Ah
Stored power	2,55 kWh
Nominal discharge current	150 A
Overload current	150 A / 10 s
Rated charge current	100 A

4.1.2. Physical characteristics

The physical characteristics of the high-power module are shown in Table 9.

Table 9. Physical characteristics of the high-power modules.

Weight	15 kg
Width	164 mm
Long	420 mm
High	106 mm

4.2. Preliminary thermal test

The approach in the iSTORMY project is to use a novel system for power battery cooling based on phase change materials (PCM). With this objective, CEA was responsible of the research at laboratory scale, obtaining interesting results, although not definitive. Following CEA's recommendations, CEGASA tried to transfer the use of these materials to the constructed prototype. Unfortunately, working with a complete battery is much more complex than working with a few cells and the conclusion of the experiment was that it is extremely difficult to insert the PCM inside the modules without specific industrial tooling. The development of such tooling would be very time consuming and well beyond the budgetary capabilities of the project. On the other hand, trying to do it manually implied, in addition to a lot of work, a high risk of damaging some of the modules, so the whole demonstration could be compromised. In order to check whether the modules without PCM are able to withstand the conditions of the intended use of the demonstrator, a thermal study was carried out with the available prototype (without PCM).

The module was placed inside a plastic box for a safe cycling. It is important to note that this enclosure penalizes thermal dissipation, being the worst-case scenario in terms of thermal performance. The battery will thereby be cycled with minimal heat exchange with the environment, leading to an even more significant increase in internal temperature. Within the project, this module will be installed in a 2mm thick galvanized steel box in direct contact with the battery, which will aid cooling by both natural convection and conduction. The cell temperatures have been monitored with a datalogger with 4 thermocouples, as shown in Figure 8.

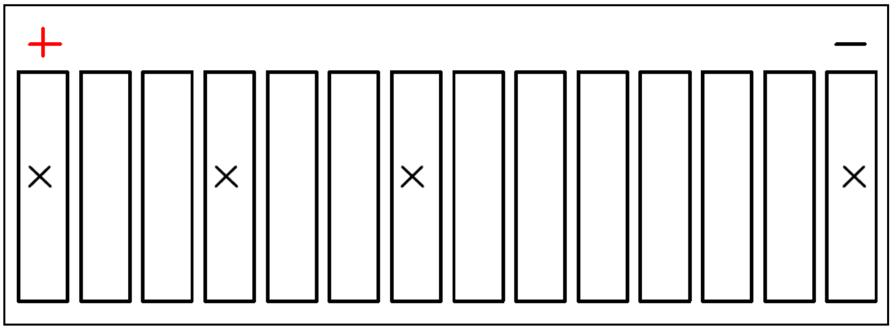


Figure 8. Thermocouples position for thermal testing

- CH1: thermocouple in cell 14
- CH2: thermocouple in cell 8
- CH3: thermocouple in cell 1
- CH4: thermocouple in cell 11

The first cycling follows these steps:

1. Discharge at 0.5C
2. Thermal conditioning of the battery up to 25ºC

3. Charge at 1C
4. Rest 1h
5. Discharge at 1C

The results are shown in Figure 9.

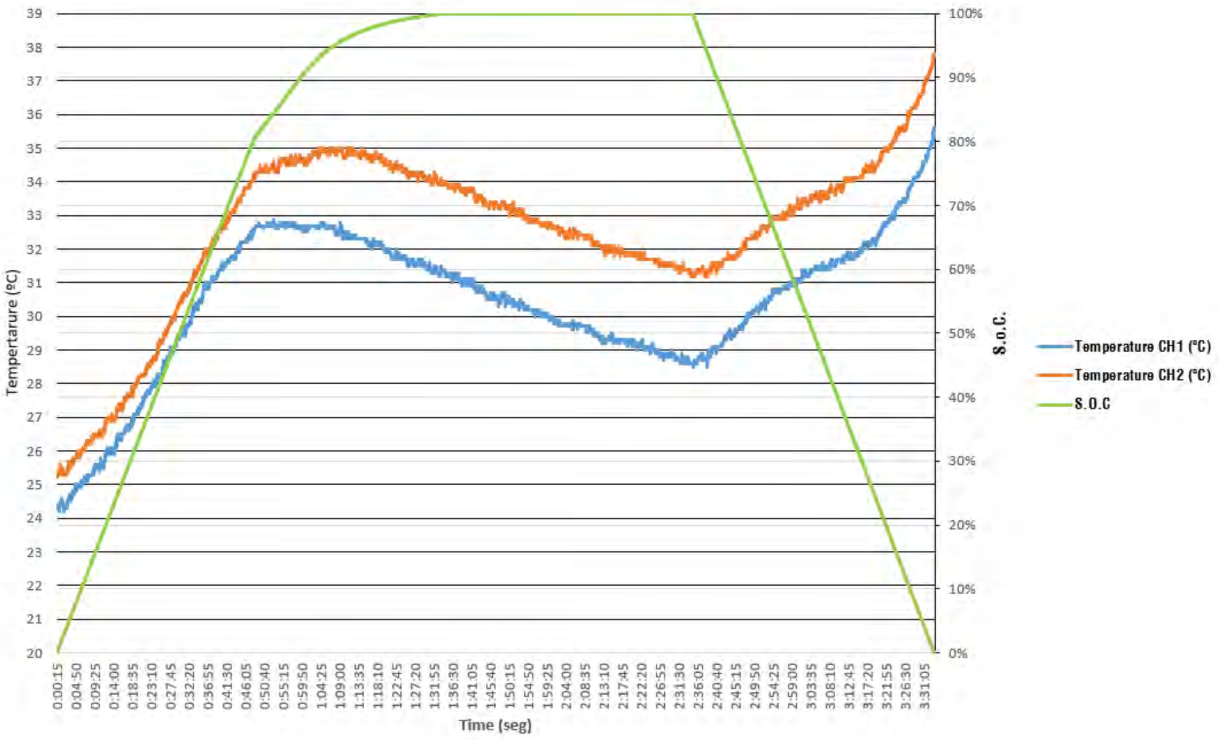


Figure 9. Thermal and SoC evolution during first cycle

Thermocouples CH1 (positive cell) and CH2 (Cell 8) are represented in the graph to evaluate the temperature gradient between the most favourable an the most unfavourable cell in terms of thermal dissipation:

- The module has been charged at 1C, being equivalent to 2.5kW continuous power for 1 hour.
- The initial temperature of the module was 24ºC in CH1 and 25ºC in CH2.
- At the end of the load, the temperatures obtained were, 33ºC in CH1 and 35ºC in CH2.

One hour of rest to start the discharge.

- The module is discharged at 2.5kW of constant power for 1 hour.
- The initial temperature of the module was below 29ºC in CH1 and 32ºC in CH2.
- At the end of the discharge the temperatures rose almost 36ºC in CH1 and 38ºC in CH2.

It is observed that the temperature curve corresponding to the discharge is linear, but from a DoD of 80% the temperature increases drastically.

The conclusions drawn from this first cycling are as follows:

- In spite of a cycling performed in a closed plastic box, with low heat exchange, the temperature in the resting time decreased by 0.05ºC/min.
- During charging, the temperature curve is linear, being 0.15ºC/min.
- Excluding the last 30% SoC of the discharge the curve is 0.07ºC/min.

The results of a second cycling with a much more constant temperature are shown in Figure 10.

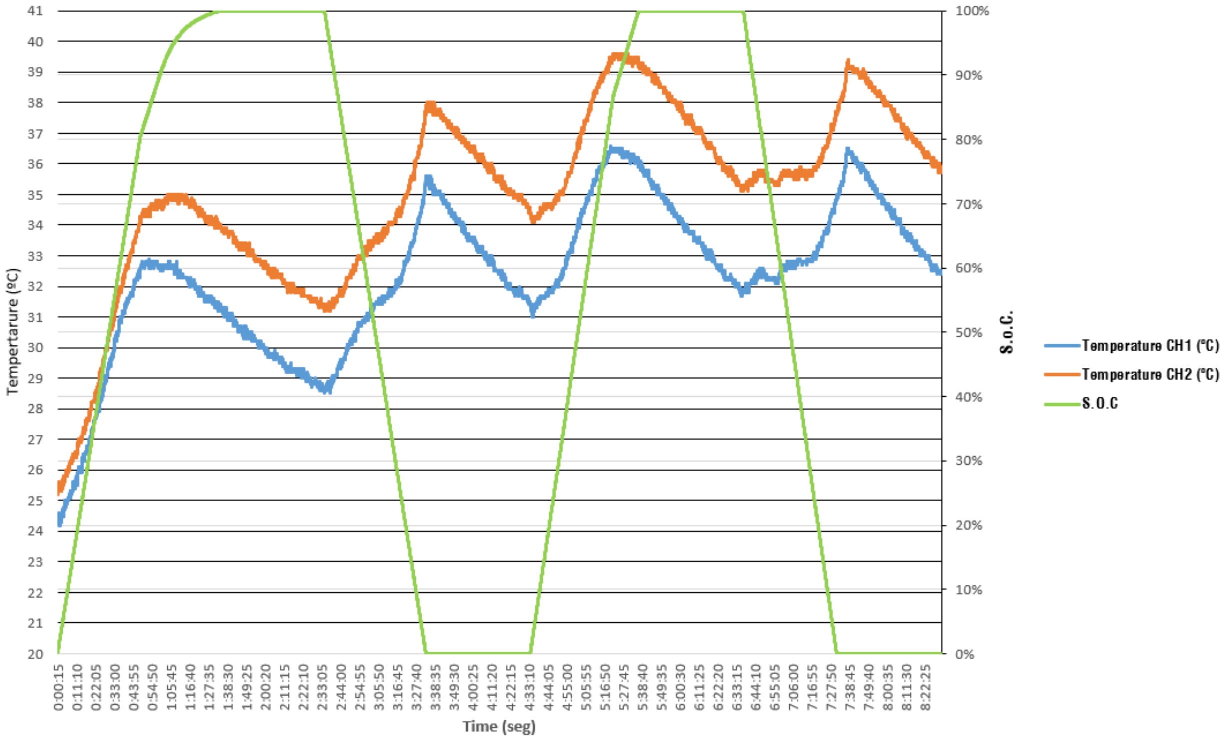


Figure 10. Thermal and SOC evolution during second cycling process

The conclusions for the second cycling process are:

- The maximum temperature never reaches 40ºC.
- The temperature range in CH1 (with higher dissipation power) is 32ºC to 37ºC, then the battery increases by approximately 0.08ºC/min of cycling.
- Based on this data, the dissipation of the battery is 0.05ºC, which means that the battery generates 0.13ºC/min.

Due to delays in the delivery of cells and therefore the manufacturing of the high-power batteries it was decided to not include the PCM in the demonstrator. The tests explained in this section show that it is safe to operate this battery without the use of PCM and therefore this change is acceptable. In the TCO calculation the impact of PCM on the average battery temperature is taken into account to showcase the potential benefit of using it.

4.3. Welding process

A second problem was found when the decision of the modules manufacturing is taken: how to deal with the laser welding process.

During the assembly of the first prototype there were a lot of difficulties for the laser welding process. The current welding machine in CEGASA is specifically designed for the LFP cells used in the factory. In the case of the 160 Ah cells used in the energy modules, an original solution was found introducing special separator between cells in order to have the positive and negative tabs just in the same position than in 280 Ah cells. That trick allows the CEGASA production technicians to use the same tooling than in normal production process.
However, this is not possible for the 50 Ah NMC cells. The distances are completely different, the size is not correct and, moreover, the chemistry is different (and quite more dangerous).
For the prototype the welding spots were made one-by-one with a long process, inserting the module, adjusting the position, welding, extracting the module, analysing the joint and so on. Definitively it was not possible to use this procedure for the 28 joints of the 21 modules of the demonstrator.
Looking for a practical solution CEGASA decided to use the welding capabilities of the cell supplier. Once the cells were welded, they were sent to Spain for finishing the modules.

4.4. Module assembly

Although the design configuration of the power battery modules is different from the energy battery modules, conceptually it is quite similar: once the cells are soldered, the voltage and temperature sensors are placed with a terminal that is connected to the BMS. In parallel, the box is prepared with the connectors and the power busbars. The structural supports are placed inside the box, the wired cubicle block and the BMS are fixed and the box is closed, as shown in the following 3D drawing in Figure 11.

Figure 11. High power module rack 3D drawing

Figure 12 shows the similarity with the final HP module rack prototypes.

Figure 12. High-power module rack prototypes

Since in this case the design is based on rack type modules, it is necessary to prepare a cabinet containing the modules for a full battery pack. During the technical discussions between CEGASA and PRODRIVE (responsible of high-power battery and power electronics interface, respectively) a slight modification of the configuration was agreed, changing the 3s7p to 4s5p to optimize both the operation of the battery and converter. Indeed, the maximum input DC voltage of PRODRIVE's interface has been changed to 240V vs. 200V considered in the optimization performed in D3.1. Therefore, a new optimization run resulted in a slightly different optimal configuration of 4s5p. The modules remain the same and the final cabinet design is shown in Figure 13.

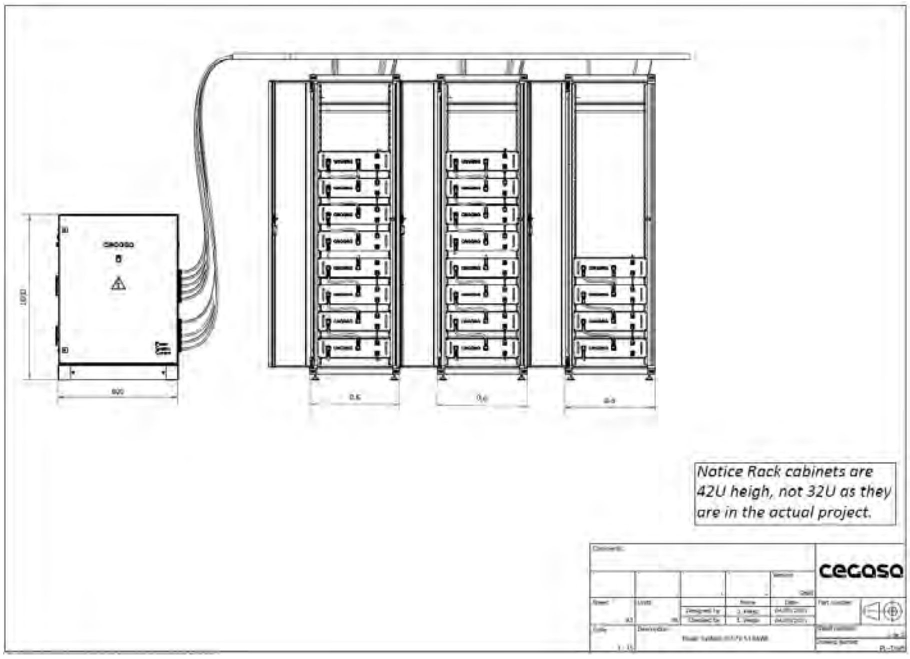


Figure 13. High power battery design

The 20 rack modules where manufactured and integrated into the 3 cabinets. Figure 14 and Figure 15 show the prototypes and one cabinet in detail.

Figure 14. High-power battery cabinets

Figure 15. High-power battery string

The PCC for the high-power battery has similar components but a different design, because of the parallelization need, see Figure 16.

Figure 16. Inside of PCC of power battery

5. Validation test of high-power battery

5.1. System: PCC & 20 NMC Battery 50.4V 50Ah modules

The Power System is formed by 20 *NMC Battery 50.4V 50Ah* modules of 50.4V connected in series and parallel following the scheme below to a *PCC 150V 500A* busbar cabinet through 5 power extensions for each battery string. The *PCC 150V 500A* includes the busbar and the required protection components. The PCC input cables from the batteries are connected in the right side and the output cables to inverter clusters are connected in the left side. Figure 17 shows the system set up.

Figure 17. Complete high-power battery system

The proposed validation test for the eBick Pro storage systems is divided in the following sections:

- Communication Testing
- Charge/Discharge Testing
- Protection Testing

5.2. Validation Tests

5.2.1. Communication Testing

Once communication and power cables between the batteries and the PCC are connected, the battery system is switched on using the master switch in the PCC and its screen turns on. Once the BMS configuration is fully loaded after one minute, the communication test between the battery modules and the PCC is carried out, see results in Table 10. This verification is made in each configuration prior to sending the equipment.

Table 10. Test of communication with the BMS

Test	Description of the test	Duration	Result
Communications with the BMS	1. Communication between the battery BMS and the PCC BMS.	**30 in**	
	1.1. Voltage and temperature values of the battery packs appear in the PCC screen.		OK
	1.2. There is no alarm in the screen. The main screen LED is on (green).		OK
	1.3. The PCC contactor is closed at the moment of switching on. The battery appears in connect state.		OK

The next step is the validation of the communications between the inverters and the batteries. For this test, the ethernet cable between the inverter and the PCC should be connected. In order to validate these communications, the next test should be done, see results inTable 11.

Table 11. Test of communication between the inversters and the batteries

Test	Description of the test	Duration	Result
Battery/inverter communications	2. Communication between the PCC BMS and the inverter	30 min	
	2.1. Inverter reads the state of the battery		OK
	2.2. Inverter reads the SoC of the batteries		OK
	2.3. Inverter reads the SoF of the batteries		OK

5.2.2. Charge/Discharge Testing

5.2.2.1. Balancing testing

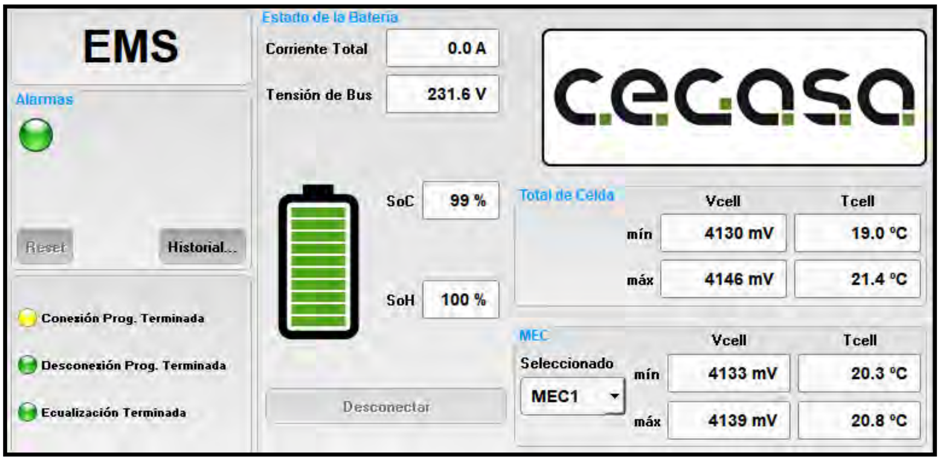
Prior to the charge and discharge testing, all modules have been charged up to 58.1V in order to bring them to the same voltage value. The results are shown in Table 12.

Table 12. Results of balancing tests for the high-power modules

Serial Number	Vtotal	Vmax	Vmin	Date	Time
231900002109970	58,1	4,142	4,131	16/05/2023	11:40
231900005109970	58,1	4,151	4,136	16/05/2023	12:51
231900008109970	58,1	4,15	4,14	16/05/2023	14:06
231900018109970	58,1	4,142	4,132	16/05/2023	15:05
231900010109970	58,1	4,143	4,135	16/05/2023	16:06
231900006109970	58,1	4,15	4,139	16/05/2023	17:03
231900016109970	58,1	4,153	4,143	17/05/2023	8:48
231900014109970	58,1	4,148	4,137	17/05/2023	9:54
231900011109970	58,1	4,15	4,14	17/05/2023	10:51
231900009109970	58,1	4,153	4,141	17/05/2023	12:03
231900004109970	58,1	4,157	4,128	17/05/2023	13:56
231900021109970	58,1	4,147	4,137	17/05/2023	15:21
231900001109970	58,1	4,147	4,133	18/05/2023	8:56
231900012109970	58,1	4,147	4,132	18/05/2023	10:15
231900015109970	58,1	4,136	4,124	18/05/2023	11:15
231900007109970	58,1	4,149	4,126	18/05/2023	12:15
231900017109970	58,1	4,146	4,132	18/05/2023	13:35
231900013109970	58,1	4,143	4,132	18/05/2023	14:45
231900003109970	58,1	4,146	4,131	18/05/2023	15:54
231900020109970	58,1	4,147	4,127	18/05/2023	16:59

In addition, so as to avoid disbalancing among the cells and the modules, each string has been balanced until the dispersion is lower than 5mV among the cells.

As shown in Figure 18, the dispersion is higher than 5mV, therefore the string was balanced until it reached 5mV.



Corriente Total: 0.0 A
Tensión de Bus: 231.6 V
SoC: 99 %
SoH: 100 %

Total de Celda

	Vcell	Tcell
mín	4130 mV	19.0 °C
máx	4146 mV	21.4 °C

MEC
Seleccionado: MEC1

	Vcell	Tcell
mín	4133 mV	20.3 °C
máx	4139 mV	20.8 °C

Figure 18. Battery Management System control interface

For the charge/discharge test, the power and communication cables among the batteries, the PCC cabinet and the inverter should be connected. Once communications are validated, and the battery contactor is closed, the inverter should charge and discharge the batteries following the power setting reference from the SCADA. The charge and discharge are validated through the inverter AC output, see results in Table 13.

Table 13. Charge/Discharge for high-power battery

Test	Description of the test	Duration	Result
Charge	3. Charge of the battery tests	1h	
	3.1. Charge of the battery through the inverter connected to the grid. Charge current is the same as SoF and the setting in the SCADA.		OK
	3.2. Charge of the batteries through the inverter connected to the grid. Charge current is the same as SoF and the setting in the SCADA.		OK
	3.3. SoF is adjusted automatically with the SoC and the cell temperature.		OK
	3.4. Charge of the battery until 100% of SoC. The value of SoC is refreshed correctly.		OK
Discharge	4. Discharge of the battery test	10min/bat.	OK
	4.1. Discharge of the batteries through the inverter connected to the grid. Discharge current is 30A.		OK
	4.2. While discharging the batteries, check the SoC correct updating when voltage lowers.		OK
	4.3. Inverter stops the discharge.		OK

5.2.3. Protection Testing

In order to validate the protection tests, different test that causes programmed protection alarms are carried out in this section. The correct behaviour of the inverter and the batteries against these alarms are validated, see results in Table 14.

Table 14. Protection test for high-power battery

Test	Description of the test	Duration	Result
Protection tests	5. Different errors are provoked to the batteries and the correct behaviour is checked	1h	
	5.1. A communication error is caused disconnecting the ethernet cable between the batteries. A warning will appear at 30 seconds of communication lost. After 60 seconds, an error appears and the contactor opens.		OK
	5.2. A communication error is caused disconnecting the ethernet cable between the PCC and the inverter. An		OK

	error in the inverter arises and the current flow stops.		
	5.3. An overvoltage warning is provoked to the battery. The inverter stops charging the battery.		OK
	5.4. An undervoltage warning is provoked to the battery. The inverter stops charging the battery.		OK
	5.5. An overcurrent warning is provoked to the battery. The inverter stops charging the battery.		OK
	5.6. An overcurrent error is provoked to the battery. The contactor of the battery opens.		OK
	5.7. An overtemperature warning is provoked to the battery. The inverter stops charging the battery.		OK
	5.8. An overtemperature error is provoked to the battery. The contactor of the battery opens.		OK

6. iSTORMY Hybrid Battery Pack Total Cost of Ownership

The Total Cost of Ownership (TCO) is a tool to compare a few solutions in terms of total CAPEX and OPEX in specified period. The object of the analysis is the prototype of iSTORMY hybrid battery pack and BMS. WP2 iSTORMY project goal is to develop solutions that reduce the TCO of energy storage systems by 15% with innovative design of the hybrid battery pack and advanced BMS functionality.

6.1. iSTORMY solution

The prototype of iSTORMY hybrid battery pack and BMS includes (see Figure 1):
- 7 modules of high-energy (HE) batteries and dedicated MBMS;
- 3 cabinets, together with 20 modules of high-power (HP) batteries each and dedicated MBMS;
- EMS.

6.2. Scope of the TCO analysis

The TCO analysis has been conducted for 3 energy storage solutions for comparison purposes:
- iSTORMY hybrid battery pack;
- HE battery pack supplying power at the level of iSTORMY Hybrid Battery Pack;
- HP battery pack supplying energy at the level of iSTORMY Hybrid Battery Pack.

The technical parameters of each solution are shown in Table 15.

Table 15. Technical parameters of the 3 considered energy storage solutions

Parameter	iSTORMY Hybrid Battery Pack			HE battery pack	HP battery pack
	HE part	HP part	Total hybrid battery pack		
Modules	80 kg; 48V; 160 Ah; 8 kWh, easy connection, no cooling	30 kg; 51V; 50Ah; 2,5 kWh, rack format, fan cooling	not applicable	4 pieces of: 80 kg; 48V; 160 Ah; 8 kWh, easy connection, no cooling	2 pieces of: 30 kg; 51V; 50Ah; 2,5 kWh, rack format, fan cooling
N. of modules	7	20	not applicable	28	40
Config	7s1p	4s5p	not applicable	7s1p	4s5p
Voltage (V)	336	204	not applicable	336	204
Capacity (Ah)	160	250	not applicable	640	250
Energy (kWh)	54	51	**105**	215	**102**
Power (kW)	32	92	**124**	**129**	189

The small discrepancies in Energy and Power between hybrid battery pack and alternative solutions (last 2 lines of Table 15) are caused by physical limitations of the battery cells used. These discrepancies have been removed within the TCO modelling by proportional modification of necessary values and associated CAPEX costs, in order to compare solutions with the same limiting parameters.

The TCO is calculated for each of the three Use cases considered in the project:
- UC1: Enhanced Frequency Response in a Pan-European grid scenario;
- UC2: Maximum power and ramp rate limitation in an EV charging scenario (based on simulation of 6 electric vehicles charging during one day);
- UC3: Fast frequency response and daily shifting in a microgrid scenario.

The number of charging cycles per year for each Use case are listed in the following Table 16, while one cycle represents equivalent full cycle, i.e. cumulative charging from 0% to 100% SoC. The numbers presented here are based on simulation data provided by MGEP. For the HE and HP battery packs, yearly number of charging cycles was determined to keep energy throughput of the solution at the level of iSTORMY Hybrid Battery Pack.

Table 16. Yearly number of cycles for 3 alternative energy storage solutions and 3 Use cases

Use Cases	UC1				UC2				UC3			
Battery variants	iSTORMY hybrid		Reference options		iSTORMY hybrid		Reference options		iSTORMY hybrid		Reference options	
	HE part	HP part	pure HE	pure HP	HE part	HP part	pure HE	pure HP	HE part	HP part	pure HE	pure HP
Yearly number of cycles	715	960	406	834	37	368	97	199	212	204	102	208

The cycle life for each energy storage solution in each of the 3 Use cases was calculated based on the ageing model provided by CEA. Cycle life is defined as number of equivalent charging cycles to reach 80% of original capacity.

Furthermore, cycle life has been calculated in 2 scenarios: with thermal management based on PCM and without any thermal management. Based on experiences of CEA, the effect of PCM was roughly estimated to be 5°C battery temperature reduction during cycling process. Resulting temperatures used in modelling are therefore 25°C (with PCM) and 30°C (no thermal management). The lifetime results are shown in Table 17.

Table 17. Cycle life analyses results

Use Cases	UC1				UC2				UC3			
Battery variants	iSTORMY hybrid		Reference options		iSTORMY hybrid		Reference options		iSTORMY hybrid		Reference options	
	HE part	HP part	pure HE	pure HP	HE part	HP part	pure HE	pure HP	HE part	HP part	pure HE	pure HP
Cycle life, T = 30°C	5 827	4 602	4 953	4 281	2 684	2 854	2 992	2 744	3 679	2 234	1 537	1 369
Cycle life, T = 25°C (with PCM)	7 342	5 466	6 415	5 167	3 122	3 315	3 746	3 294	4 175	2 415	1 670	1 466

It should be noted that capacity loss (and consequently cycle life) of both analysed battery cells is significantly affected by calendar ageing. As a consequence, Use cases with more intensive battery usage (e.g. UC1) have longer cycle life in comparison to Use cases where intensity of cycling is lower and calendar ageing exhibits significantly (e.g. UC2 and UC3).

6.3. TCO analysis assumptions

The TCO analysis has been conducted according to the following assumptions:

- 10 years of usage;
- CAPEX values are based on CEGASA's estimation of each component (see Table 18).
- The number of market implementations of energy storage thermal management based on PCM is limited, so only a rough estimation of cost of the PCM material and housing adjustments has been made;
- A battery module is replaced when battery capacity drops below 80%. Replaced battery is sold for 60% of initial CAPEX if replaced within 5 years, 30% if replaced between 6 and 10 years, and 0% if replaced after 10 years;
- The residual value at the end of the analysis period is estimated as described in case of selling (see point above).

The lowest initial CAPEX is for the iSTORMY Hybrid Battery Pack and is not dependent on the Use case. The HE battery pack is more expensive, as it has to be oversized in order to be able to deliver the requested power.

The total CAPEX in 10 years period (including renewals of the battery) depends on Use case and usage of thermal control. The overview of total CAPEX is shown in Table 18.

Table 18. CAPEX estimation

Position	Use case 1			Use case 2			Use case 3		
	iSTORMY Hybrid Battery Pack	HE battery	HP battery	iSTORMY Hybrid Battery Pack	HE battery	HP battery	iSTORMY Hybrid Battery Pack	HE battery	HP battery
Without thermal management (cycling temperature 30°C)									
HE battery cells (€/kWh)	250	250	N/A	250	250	N/A	250	250	N/A
HP energy cells (€/kWh)	395	N/A	395	395	N/A	395	395	N/A	395
Wires (€)	900	1 538	974	900	1 538	974	900	1 538	974
Housing (€)	1 550	1 154	2 673	1 550	1 154	2 673	1 550	1 154	2 673
Control system (BMS)	3 050	4 615	3 605	3 050	4 615	3 605	3 050	4 615	3 605
CAPEX - initial (€)	**39 085**	**61 067**	**48 633**	**39 085**	**61 067**	**48 633**	**39 085**	**61 067**	**48 633**
CAPEX - renewals (€)	**53 730**	**0**	**41 380**	**20 145**	**0**	**0**	**0**	**0**	**41 380**
Total CAPEX (€)	**92 815**	**61 067**	**90 013**	**59 230**	**61 067**	**48 633**	**39 085**	**61 067**	**90 013**
With PCM based thermal management (cycling temperature 25°C)									
HE battery cells (€/kWh)	250	250	N/A	250	250	N/A	250	250	N/A
HP energy cells (€/kWh)	410	N/A	410	410	N/A	410	410	N/A	410
Wires (€)	900	1 538	974	900	1 538	974	900	1 538	974
Housing (€)	1 800	1 154	2 923	1 800	1 154	2 923	1 800	1 154	2 923
Control system (BMS)	3 050	4 615	3 605	3 050	4 615	3 605	3 050	4 615	3 605
CAPEX - initial (€)	**40 100**	**61 067**	**50 454**	**40 100**	**61 067**	**50 454**	**40 100**	**61 067**	**50 454**
CAPEX - renewals (€)	**20 910**	**0**	**42 952**	**20 910**	**0**	**0**	**0**	**0**	**42 952**
Total CAPEX (€)	**61 010**	**61 067**	**93 406**	**61 010**	**61 067**	**50 454**	**40 100**	**61 067**	**93 406**

Table 18 is pretty complex, thus here is an example of how to read results for solutions without thermal management:

- Use case 1 – the lowest total CAPEX is for HE battery (61 067 EUR) due to no need of renewals. The iSTORMY Hybrid Battery Pack total TCO is 92 815 EUR and HP battery 90 013 EUR;
- Use case 2 – the lowest total CAPEX is for HP battery (48 633 EUR) due to no need of renewals and lower initial CAPEX. The iSTORMY Hybrid Battery Pack total TCO is 61 010 EUR and HE battery 61 067 EUR;
- Use case 3 – the lowest total CAPEX is for iSTORMY Hybrid Battery Pack (40 100 EUR) due to no need of renewals. The HE battery total TCO is 61 067 EUR and HP battery 90 013 EUR.

For the given Use cases, thermal management is lowering the total CAPEX of iSTORMY Hybrid Battery Pack only in Use case 1, because due to extended cycle life, there is no need to renew batteries within 10 years.

OPEX has been calculated as a cost of energy and distribution fees average in 2nd half of 2022 in EU (0,2333 €/kWh excluding VAT and other recoverable taxes and levies) [1]. The self-consumption (power consumed by internal electronics) of each solution has been calculated as 12W. The total volume of energy has been calculated based on energy (kWh) and number of charging cycles in year.

No other maintenance cost has been included, as any eventual failure is covered by the typical warranty and is not affecting the TCO.

---

[1] https://ec.europa.eu/eurostat/databrowser/view/NRG_PC_205__custom_6302096/default/table?lang=en

For calculation of TCO cash flow in each year of analysis has been recalculated to the present value, based on the discount rate, what represents money that capital investment could otherwise have earned from bank interest on savings. As a result, the TCO is not just a sum of CAPEX and OPEX. To calculate present value discount rate at 3.2%[2] yearly has been assumed, the applied discount factors are shown in Table 19.

Table 19. Discount factor with discount rate 3.2%

Year	1	2	3	4	5	6	7	8	9	10
Discount factor	1.00	0.96	0.92	0.89	0.85	0.82	0.79	0.76	0.73	0.70

6.4. TCO analysis results

Basing on the assumptions, the iSTORMY Hybrid Battery Pack has the lowest TCO in 10 years period in all Use cases (see Table 20). However, the iSTORMY project goal of reducing TCO by 15% is met only in Use case 3. It is worth noting that the self-healing EMS with optimal dispatch between the high-energy and high-power batteries should further reduce the TCO. Also, the iSTORMY solution has improved performance in terms of interoperability which is also a plus.

Table 20. TCO estimation for the Use cases

Position	**Use case 1**			**Use case 2**			**Use case 3**		
	iSTORMY Hybrid Battery Pack (25°C)	**HE battery (30°C)**	**HP battery (30°C)**	**iSTORMY Hybrid Battery Pack (25°C)**	**HE battery (30°C)**	**HP battery (30°C)**	**iSTORMY Hybrid Battery Pack (25°C)**	**HE battery (30°C)**	**HP battery (30°C)**
CAPEX - initial (€)	40 100	61 067	50 454	40 100	61 067	50 454	40 100	61 067	50 454
CAPEX - renewals (€)	20 910	0	42 952	20 910	0	0	0	0	42 952
OPEX (€)	204 104	204 104	204 104	48 775	48 775	48 775	51 184	51 184	51 184
Value of resold batteries and residual value at the end of analysed period (€)	22 851	16 128	38 656	22 851	16 128	12 885	10 305	16 128	38 656
TCO (€)	**212 859**	**221 905**	**227 165**	**80 498**	**90 880**	**81 054**	**76 242**	**92 912**	**97 257**
Difference in TCO iSTORMY@25°C/ Reference@30°C		-4,1%	-6,3%		-11,4%	-0,7%		-17,9%	-21,6%

---

[2] https://www.ceicdata.com/en/indicator/european-union/long-term-interest-rate

7. Discussion and Conclusions

This report presents the work carried out for the development and manufacturing of the hybrid battery pack of the iSTORMY project. This battery is formed by two different batteries, one optimized in energy and the other optimized in power.

The energy battery is a modification of the current CEGASA commercially available battery, so its development has been simpler and the company's production systems have been used to build the prototypes.

However, the power battery is a completely new battery. Both the design, the cells and the chemistry are different from what is usually used in CEGASA. This has been a major challenge that has generated numerous problems during its development and especially when manufacturing the prototypes. However, solutions have been found to each of the problems and all the modules of the two batteries have finally been manufactured, although in the second case with a slight delay with respect to the original planning.

Both batteries have been tested following CEGASA's Factory Acceptant Test (FAT) procedures and both have passed and are now being sent for integration with the power electronics.

The Total Cost of Ownership (TCO) is also analysed for the realised system and compared against standard energy storage systems (without any hybridisation and updated technology like advanced SoX algorithms and inclusion of Phase Change Material (PCM)). This analysis is done for the use-cases in iSTORMY and resulted in a potential TCO reduction of >17% for one of the use-cases while showing smaller, but still positive, difference for the other use-cases. The full analysis considering the benefits of the self-healing EMS will be carried out in WP5.

8. Risk Register

Not applicable, WP2 has ended with the delivery of this report and the associated deliverable D2.3 (actual Hybrid Energy Storage System).

Acknowledgement

The author(s) would like to thank the partners in the project for their valuable comments on previous drafts and for performing the review.

Project partners:

#	Partner short name	Partner Full Name
1	VUB	VRIJE UNIVERSITEIT BRUSSEL
2	PWD	POWERDALE
3	CEG	CEGASA ENERGIA S.L.U.
4	CEA	COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES
5	MGEP	MONDRAGON GOI ESKOLA POLITEKNIKOA JOSE MARIA ARIZMENDIARRIETA S COOP
6	ZIG	ZIGOR RESEARCH & DEVELOPMENT AIE
7	EDF	ELECTRICITE DE FRANCE
8	TNO	NEDERLANDSE ORGANISATIE VOOR TOEGEPAST NATUURWETENSCHAPPELIJK ONDERZOEK TNO
9	PT	PRODRIVE TECHNOLOGIES BV
10	GW	GREENWAY INFRASTRUCTURE SRO
11	AIT	AIT AUSTRIAN INSTITUTE OF TECHNOLOGY GMBH
12	UNR	UNIRESEARCH BV

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 963527