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Technical Report TA User Project

Efficiency Characterisation and Interoperability Validation of Lithium-Based Hybrid Power Plant for Rural Electrification-LiBRE

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Abbreviations

AC	Alternating Current
BMS	Battery Management System
DC	Direct Current
DER	Distributed Energy Resources
DG	Distributed Generation
DOD	Depth of Discharge
EuT	Equipment-under-Test
LV	Low Voltage
MG	Microgrid
MPPT	Maximum Power Point Tracker
PC	Personal Computer
PV	Photovoltaics
RES	Renewable Energy Sources
RMS	Root Mean Square
RTU	Remote Terminal Unit
SCADA	Supervisory Control and Data Acquisition
SOC	State of Charge
TA	Trans-national Access
TRL	Technology Readiness Level
UPS	Uninterruptible Power Supply
WG	Wind Generator

Executive Summary

This project deals with the performance analysis and testing of a commercial hybrid power plant that is based on Lithium Iron Phosphate ($LiFePO_4$) battery storage and can be used for rural off-grid and on-grid applications. The specific Equipment-under-Test (EuT), which was installed and tested at CRES, is a prototype device with a Technology Readiness Level (TRL) of at least 6. Through the specific project, the TRL level of the specific product is expected to reach value 8, since the device was tested in operational environment under real-world conditions with real loads and sources. The application areas for the specific device range from grid connected net-metering systems to off-grid telecommunication stations and it incorporates the main electrical characteristics of a LV microgrid. These characteristics include:

- AC and DC outputs for both types of loads
- PV converters equipped with Maximum Power Point Tracker (MPPT) that allow the connection of a wide range of PV panels
- DC/AC inverters that allow 4-quadrant operation
- $LiFePO_4$ batteries that present increased performance and reliability
- Fully air-conditioned enclosure which increases the performance of the storage system
- Supervisory Control and Data Acquisition (SCADA) that allows local or remote monitoring and control of the system

During the project implementation phase the device was installed at CRES' facilities in Pikermi, Greece, and in collaboration with the project user various tests were conducted in order to validate the high performance of the storage system. The scenarios for the efficiency validation included two different test cases, the round-trip efficiency tests and the long-term performance of the system as a whole. In addition to the performance tests of the device itself, several performance tests were carried out on battery cells of the same type based on standardised testing procedures. Last but not least, other tests were carried out in order to establish and validate the interoperability of the Battery Management System (BMS) and, in particular, the possibility of using a proprietary Modbus RTU protocol for the communication of data from the batteries to a locally installed Raspberry PI with a view to integrating all data acquisition modules of the EuT in one SCADA system.

1 General Information of the User Project

User Project	
User Project acronym	LiBRE
User Project title	Efficiency Characterisation and Interoperability Validation of Lithium-Battery-Based Hybrid Power Plant for Rural Areas Electrification
Main scientific/technical field	Energy
Keywords	DER, Microgrids, Lithium-Battery Srotage

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Activity type and legal status of organization	Private enterprise

Host Infrastructure	
Name of the Infrastructure/ Installation	Distributed Generation Laboratory (DG-Lab)
Location	CRES – Pikermi, Attiki, Greece
Web Site	*www.cres.gr*
Access Period	25.07.2018 – 22.08.2018

2 Research Motivation

Achieving a high-level RES penetration in today's power systems requires a number of measures that allow a more flexible management of electricity supply. One of the main technologies that are expected to foster the widespread use of RES is various storage technologies. Among others, Lithium battery is one of the most promising technologies due to its high efficiency and energy capacity. The latter advantages of lithium batteries are enhanced by the continuously decreasing cost of this technology, which has made it recently a very attractive solution for small-scale storage applications. This technology, combined with dispersed RES such as PVs are expected to play an important role in applications related to microgrids, urban, as well as rural distribution power systems.

In the frame of LiBRE testing and validation of the operation of a commercial hybrid power plant is conducted. The main characteristics of the specific plant include:

- Power supply by PV panels
- Electricity storage and balancing through $LiFePO_4$ batteries
- Ability to connect to distribution network or back-up diesel genset for balancing purposes

The specific system is commercialized and used in various applications, mainly focusing on electrification of off-grid telecommunication stations but with the ability to be used in several other applications too, including electrification of other off-grid or rural consumers, application in urban buildings electrification, microgrids, etc.

With the use of the ERIGrid laboratories the specific project aims at the following goals:

- Characterisation of the good performance of the various power components of the system. The main focus of the application will be on the round-trip efficiency of the Lithium batteries, which is the most vulnerable and expensive component of the system. In addition, the overall performance of the system was investigated in the long run.
- Interoperability testing in order to validate the communication protocols of the Battery Management as well as the Energy Management system.

The results of the specific tests significantly contribute to the validation of the proposed system's good operation as well as to ideas for improvement in future versions of the system. Also, due to ERIGrid's high publicity it will be possible for the manufacturer to achieve a better promotion of the specific product in the technology market.

2.1 Objectives

Considering the abovementioned new trends in DER and storage technologies the use of products that incorporate innovative characteristics is of great importance. Design and prototyping of such products is the first step in the procedure that allows for the technology to reach a readiness level of up to TRL6. In order to further demontrate the good performance of these products, testing under real conditions is required. This way, the readiness level of the technology reaches its maximum. In the specific project, we aim at testing of a commercial device (EuT) in a realistic environment in order to validate its performance and its high TRL level.

2.2 Scope

In this project the following tests were performed:

- Round-trip efficiency measurement for the $LiFePO_4$ batteries under three different scenarios. In the first scenario the loads used were one office air-conditioning unit and two smaller cabinet units used to regulate the temperature of the EuT's enclosure. In this case the charging power was supplied by the PVs via the two PV chargers of the system. In the second scenario, for the same loads, the charging power was supplied by the local electricity grid. Last but not least, a third round-trip efficiency test was conducted with only

one signle cell of the batteries with the use of the controllable charger/discharger equipment of our labs.
- Long-term performance of the device for continuous operation of loads and PVs.
- Interoperability tests, i.e. communication feasibility between the BMS and a personal computer or a Raspberry PI. The specific test aimed at establishing the communication code that would allow the integration of the BMS with a more generic SCADA system that monitors and controls all power modules of the EuT.

3 State-of-Technology

Microgrids (MGs) are parts of LV distribution grids organized in a way that allows the highest possible exploitation of RES energy produced by distributed resources [1]. The main types of RES that are used in MGs are PVs and Wind Generators (WG). In addition, MGs use different storage technologies ranging from batteries to fuel cells and ultra-capacitors in order to achieve a short and long-term power balancing. The latter balancing is also facilitated by the combined used of microturbines or small-scale diesel generators as well as use of flexible loads that can modify the consumption profile in order to match the generation from RES. MGs are designed in order to be self-sufficient in terms of energy, thus allowing their islanded operation when disconnection from the local distribution grid is required. Therefore, MGs are an ideal solution in terms of Uninterruptible Power Supply (UPS) in rural or urban applications. Several research studies and demonstrations have been conducted regarding various aspects of MGs. These include optimization, control strategies, stability, protection, energy efficiency and interoperability issues.

In this context, storage technologies play a crucial role in the operation of a MG. Battery storage in particular is the most favourable of these technologies due to its modularity, fast response and maturity of technology. Until recently, Lead-Acid batteries were the predominant technology in use with MGs. This type of batteries is gradually being substituted by Lithium batteries thanks to the rapid reduction in their cost which makes their use favourable in residential applications [2]. Therefore, the analysis of MGs and stand-alone power systems using this type of storage is of great importance.

4 Executed Tests and Experiments

The specific project was divided into three research activities dealing with different aspects and technical challenges of the study. Firstly, in order to assess the good performance of the device itself as a whole, a number of tests regarding the round-trip efficiency of the batteries as well as the long-term behaviour of the EuT were conducted. These tests involved the use of various components such as PV chargers, inverters and cooling units. These components were used either simultaneously or in different phases depending on the selected test. Overall, the scope of these tests was to show that the batteries have a high round-trip efficiency, ideally above 90% according to relevant literature, as well as to allow us the long-term recording of Voltage/Current data at various points of the system, which would help us assess the good performance of the device. As it will be shown in detail in the following sections, one of the major issues we came up against during these tests was the accuracy with which these electrical quantities are measured. At any rate, despite those uncertainties the test results showed the high performance of the batteries and the device itself.

In order to achieve a higher-accuracy efficiency estimation of the batteries, independent cells of the same technology were tested under fully controllable lab conditions with the use of our Battery Lab equipment. These tests showed that the efficiency of the cells can reach even higher levels, approximating 99%.

Last but not least, in order for the user to establish a good communication interface with the device that would include both the batteries and the power converters in one system, some interoperability

tests were conducted in respect with the BMS communication. These tests aimed at setting up the necessary proprietary code using Node-RED in order to achieve data communication of the BMS with and PC or a Raspberry PI.

4.1 Test Plan

The LiBRE project was divided into three different phases according to the tests scenarios described above. The major phase of the project included the round-trip and long-term performance tests. Each of these tests had duration of several days. Due to the limited time resources during the project, some preliminary tests were conducted during the preparation phase. These preliminary tests were used to better understand the behaviour of the device under different conditions as well as to calibrate the sensors attached to the EuT and used by the lab SCADA to record the electrical data of the device. In parallel with these tests, the other two scenarios were examined. Firstly, the efficiency test of single $LiFePO_4$ cells was carried out at a separate laboratory of CRES' PV dept., i.e. the battery testing laboratory. Apart from the accuracy that the specific lab's equipment offer to our tests, the use of completely different equipment made it possible for them to be run in parallel. The same plan was also followed during the interoperability tests with the BMS system communication since this latter test would not affect the execution of the efficiency and long-term performance test.

In a nutshell, the three different test phases for each of the selected scenarios were run in parallel allowing us to exploit as best we could the available time resources.

4.2 Standards, Procedures, and Methodology

The Equipment-under-Test in the specific project is a cabinet that contains all the $LiFePO_4$ batteries and the power converters.

Figure 1 shows a picture of the tested device while Figure 2 shows in a simplified form the main components and electrical configuration of the EuT. More detailed technical specifications can be found in Annex 9.3 (see model FBS40)

Figure 1 Picture of the Equipment-under-Test

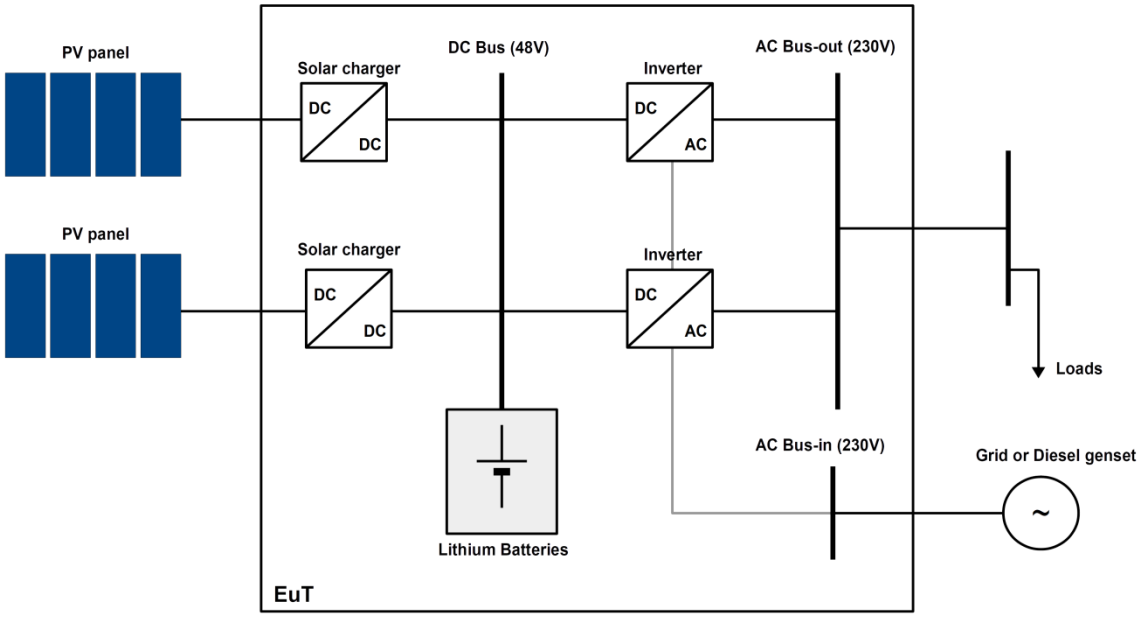


Figure 2 Simplified electrical diagram of the Equipment-under-Test

For the first set of tests the basic idea was to use the device's components in two different ways. In the first approach used for the measurement of the round-trip efficiency of the batteries, each test started from a state where the batteries were fully charged. Following that, a discharge phase was commenced with the use of an external AC load (office air-conditioning unit) in combination with the cooling equipment of the cabinet. The combined load (up to 2kW) allowed for a deep discharge of the batteries reducing the estimated SOC from 100% at the beginning of the test to a minimum

of 50% at the end of the discharging phase. The lowest allowable SOC was selected only for safety reasons although the specific battery technology can theoretically cope perfectly fine with deeper discharges as well. During the discharge phase, all sources that could cause recharge of the batteries (i.e. PVs, grid) were disconnected. This way, we achieve a faster discharging in combination with fewer uncertainties introduced in the measurements.

Once the discharging phase was complete, the recharging of the batteries took place either by means of the PVs or by means of the grid connection. In the case of the PVs the used panels were the ones mounted on the single axis-tracker of the CRES' microgrid. In both cases, the load of the cabinet was minimised to nearly zero, since the only load present was the no-load losses of the inverters and the power consumption of the data logging and monitoring devices. Thus, we increase the accuracy of the measurement as much as possible. The recharging phase was considered complete when the battery was fully charged. By monitoring the current and voltage of the battery during the two phases it is possible to calculate the round-trip efficiency as the energy drown from over the energy injected to the battery:

$$eff_{round-trip} = \frac{E_{discharge}}{E_{charge}} \times 100\% \quad (1)$$

For the accurate measurement of all quantities we implemented a sampling time of instantaneous and RMS values at 1sec. The specific sampling time was the limitation posed by our data logging system. The latter was implemented by using an Interbus Master Controller on a PC inside the laboratory and an Interbus RTU equipped with 16 analog inputs. This way, it was possible to capture as much details regarding the variations of the signals as possible. This approach worked fine for the input-output signals of the PV chargers which did not show any significant ripple during to switching operation. However, the operation of the inverters and the accurate measurement of their input current was challenging due to the nature of the devices. In particular, the device's AC output supplies single-phase AC loads, the instantaneous power of which is given by:

$$p_{ac}(t) = V_{rms}I_{rms}cos\varphi - V_{rms}I_{rms}cos(2\omega t - \varphi) \quad (2)$$

In other words the instantaneous output power is a sinusoidal waveform with 100Hz frequency and an offset that is the active power to the load. If we assume that the efficiency of the inverter is ideally 100% and due to the fact that the battery voltage remains rather unaffected during the operation by any ripple in current, the same ripple appears in the input current of the inverters. In order to calculate the active power supplied by the battery, the calculation of the mean value is necessary. The latter boils down to calculating the mean current of the battery supplied to the inverters multiplied by the nearly constant voltage. Due to the fact that our measuring equipment allowed measurement of instantaneous and RMS currents only and not of mean values, we had had to come up with a method for calculating the mean current of the battery through its measured RMS value. After mathematical calculations we conclude that the relationship between the RMS and the mean current that the battery supplies to the inverters is given by:

$$\frac{I_{dc,rms}}{I_{dc,mean}} = \frac{\sqrt{(cos\varphi)^2 + \frac{1}{2}}}{cos\varphi} \quad (3)$$

The above formula indicates that in order to calculate the mean current from its RMS value it is necessary to know the power factor of the AC load. The latter is calculated using an Active/Reactive power transducer at the AC side and dividing the two values in the SCADA. The detailed configuration and measurement points are presented in the next section of this report.

The data-logging process produces a file that contains all the instantaneous and RMS values of currents, voltages and AC power. From this file it is possible to calculate the energy flows by integrating the values over time. It is worth noting that the exact same approach was used for the long-term test too. This test combines the operation of both the PV charges and inverters. In this case,

the accurate round-trip efficiency of the battery is difficult to measure because of the different initial and final SOC of the battery, as well as due to ripple in the charger's output current introduced by the presence of the inverters that operate simultaneously with the chargers. This ripple is due to the fact that part of the current to the inverters is fed directly by the charger.

In the case of one single cell's round-trip efficiency test it was possible to more precisely measure the efficiency of this technology. In this testing scenario one cell of the same technology is connected to a controllable charger/discharger unit at the Battery Testing lab of CRES. The power converter provides accurate measurements of current and voltage since the latter do not depend on the nature of loads of interconnected converters. The methodology followed is similar to the previous test, namely from a full-charge initial state (where the voltage of each cell is maximum e.g. 4.2V) the cell is initially discharged at a constant rate and then recharged until it reaches its maximum voltage again. The calculation of the energy exchange results again in the round-trip efficiency as in eq. 1.

Last but not least, the interoperability tests required the connection of a PC with the BMS via an RS-485 interface. In order to achieve compatibility of the physical means, between the RS-485 line and the PC one RS-485 to USB adaptor was attached. The specific BMS is equipped with a proprietary communication protocol which is very similar to Modbus RTU. With the use of Node-RED, which is a flow-based programming tool, it was possible to establish communication and retrieve data from the BMS in real time.

4.3 Test Set-up(s)

Scenario 1 (Round-trip efficiency and long-term tests): The diagram of

Figure 1Figure 3 provides an illustration of the installation of the sensors and the signals measured for this set of experiments. The specific setup involves the use of current transducers CS1-CS6 for the measurement of the RMS current values except for CS3 which is an instantaneous current sensor. The selected transducers use Hall-effect sensors to sense the current value. Apart from these current measurements three different voltage measurements are conducted with sensors VS1-VS3. These sensors are resistors connected to isolation/amplification modules. Last but not least, the combined AC output of the inverters is monitored with the use of one Active/Reactive (PQ) power transducer and a current transformer. This transducer is used to measure the total AC power of loads and when the input of the inverters is connected to the AC grid, the sensing device is switched to the AC input of the inverter. All signals are analogue and are acquired by an Interbus RTU with 16 analogue input channels. The Interbus RTU communicates with a lab SCADA PC that records the real-time data of the EuT and performs real-time calculations.

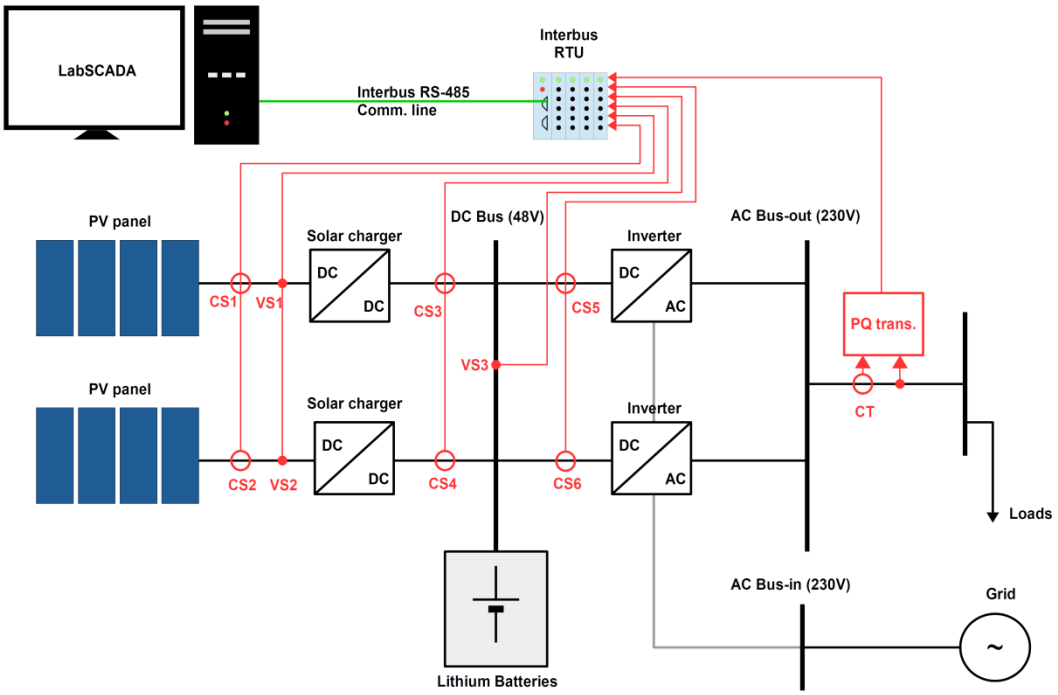


Figure 3 Implementation of sensors and data acquisition

Scenario 2 (Individual cell efficiency test): In this scenario the setup involves a simple topology in which one battery cell is connected to a controllable charge/discharge device controlled and monitored via a PC (see Figure 4).

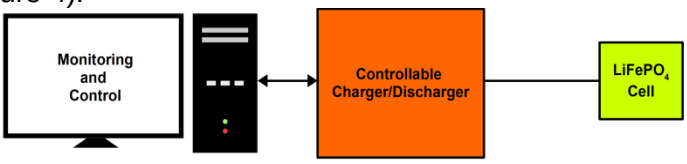


Figure 4 Single-cell test setup

Scenario 3 (Interoperability test): In order to test the interoperability of the BMS the following setup (Figure 5) was selected. In this setup the battery bank is connected via its RS-485 port to a communication line that terminates to a RS-485 to USB converter and then to a lab PC. The latter is equipped with a Node-RED application that allows to send commands to the specific COM port and to read back the response of the BMS. Since each battery of the bank is equipped with its own BMS, the Node-RED application queries sequentially all 10 batteries used in this test.

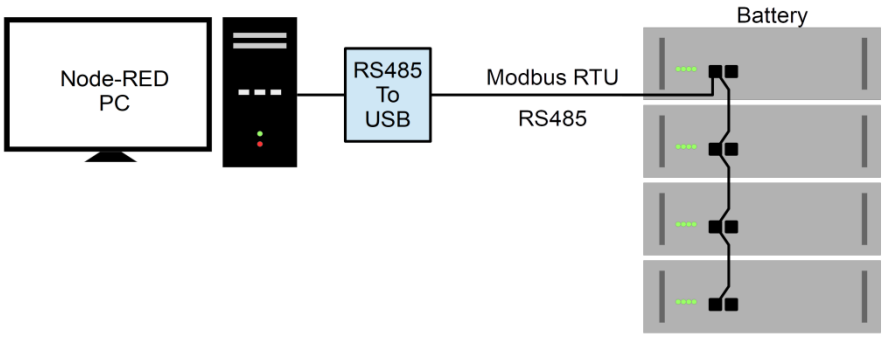


Figure 5 Interoperability test setup

4.4 Data Management and Processing

Data in all three test scenarios are stored in *.txt and *.xls format files from which they are then post-processed using Excel. The data are stored in the form of columns. The first column of each file contains the time stamp of the experiment.

5 Results and Conclusions

Scenario 1: This scenario includes three round-trip efficiency tests and one long-term performance test. The first test (Test1) had duration of slightly longer than 3 days and resulted in a calculated round-trip efficiency of 96%. This value is considered very satisfactory as it agrees with the specifications of this battery type provided by most manufacturers and scholars. The load profile over the test is shown in Figure 6. It is evident that the load is used only during the discharge phase which takes place only during the first day of the experiment. Variations of the load are due to temperature variation in the room where the air-conditioning unit was as well as in the cabinet's temperature. The latter aspect results in activation/deactivation of the cooling equipment. A better overview of the load behaviour during this test is provided by zooming into the interval in which the load is active (see Figure 7). In this figure the base load is the office's air-conditioning unit which operates continuously at almost constant power. Also, the switching on and duration of the cooling equipment in the cabinet is distinct. The diagram shows that, in principle, the specific day resulted in little use of the cooling system due to relatively low ambient temperature. It should be pointed out that during the recharge phase when the load ought to be zero there is always a small offset approximately equal to 24W due to calibration error of the transducer.

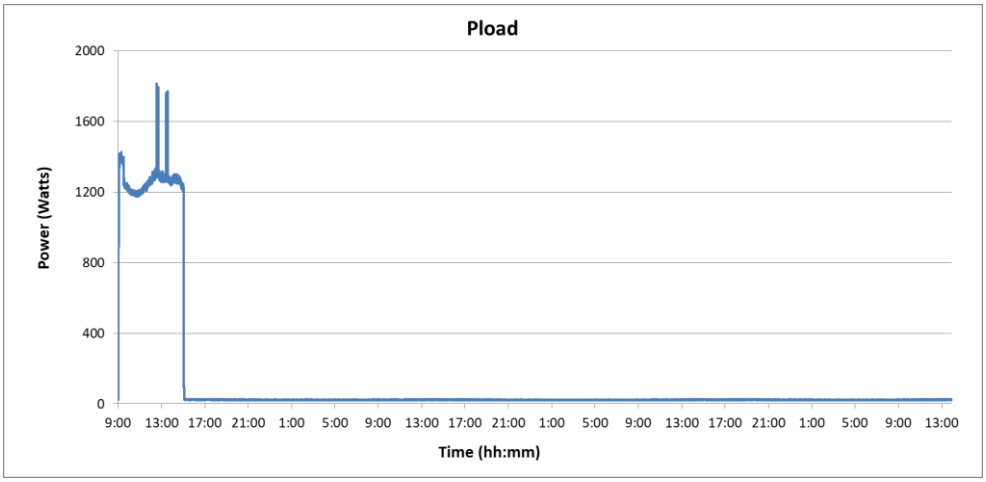


Figure 6 Load profile during the whole 3 days of Test1's duration

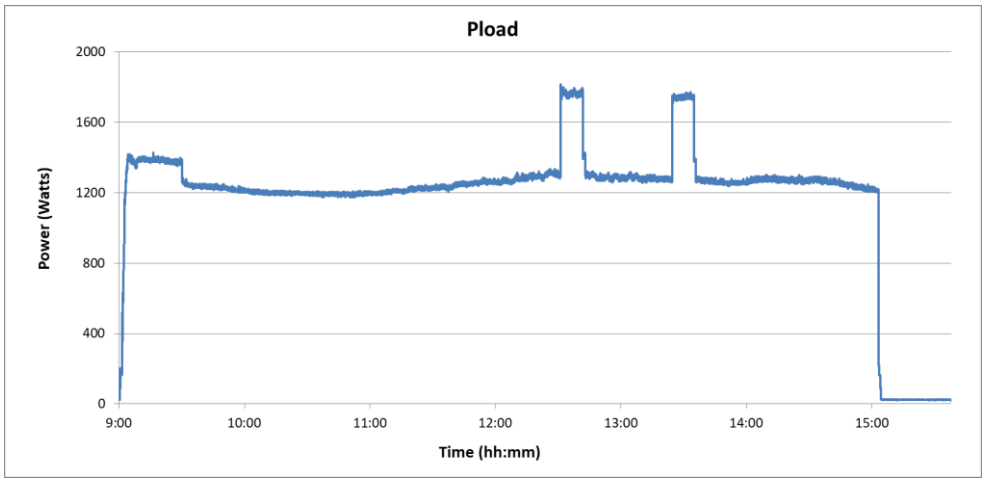


Figure 7 Load profile during the first six hours of Test1

In addition to the load profile in Figure 6 it is worth examining the profile of the power at the input of the two inverters. The examination reveals that the inverter power is always higher than the AC load power by a factor that is approximately equal to the efficiency factor of the inverter. During the recharge phase the inverters still run without load. Therefore, as it can be seen from the diagram, there is a small amount of power above zero that accumulated over time results in a significant

amount of energy consumed during the recharging phase of the test.

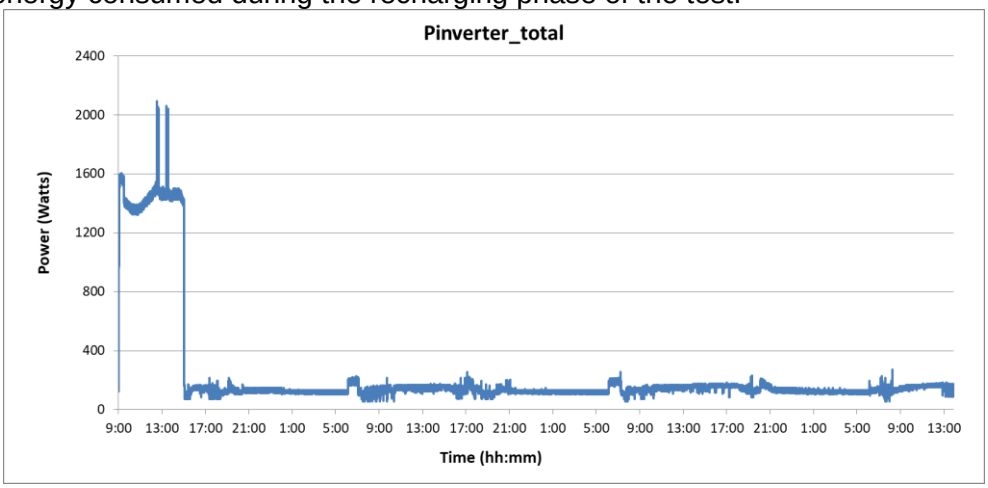


Figure 8 Total power absorbed by the inverters during Test1

In addition to the above results, Figure 9 shows the profile of the PV power to the battery (output of the chargers) for the 3 days of Test1.The diagrams show that there was no PV power available during the first six hours of the test (discharging phase), whereas the power reaches up to 1600W in total during the recharging phase. Apart from the fluctuations in the PV power due to insolation changes there is another factor that leads to some regularly occurring fluctuations. The specific, regular fluctuation is of short duration and is accounted for due to the MPPT algorithm of the chargers.

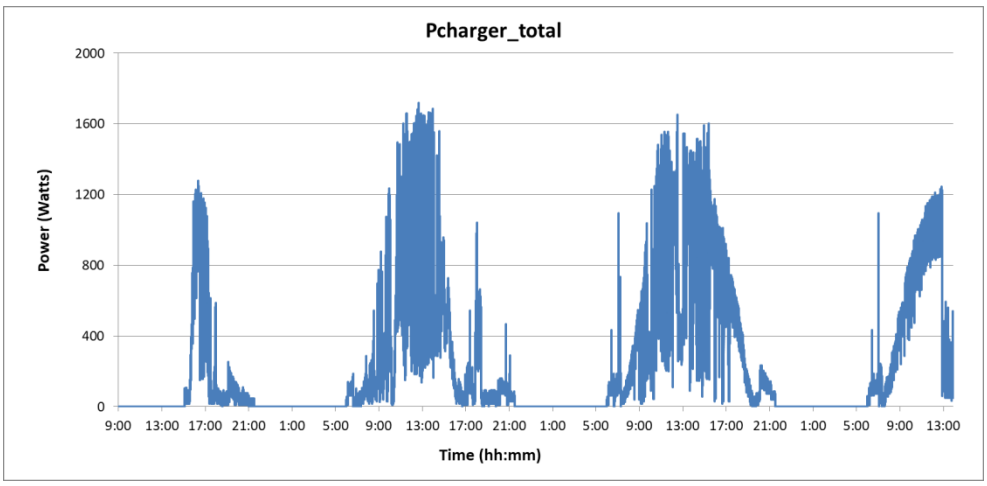


Figure 9 Total power supplied by the PV chargers during Test1

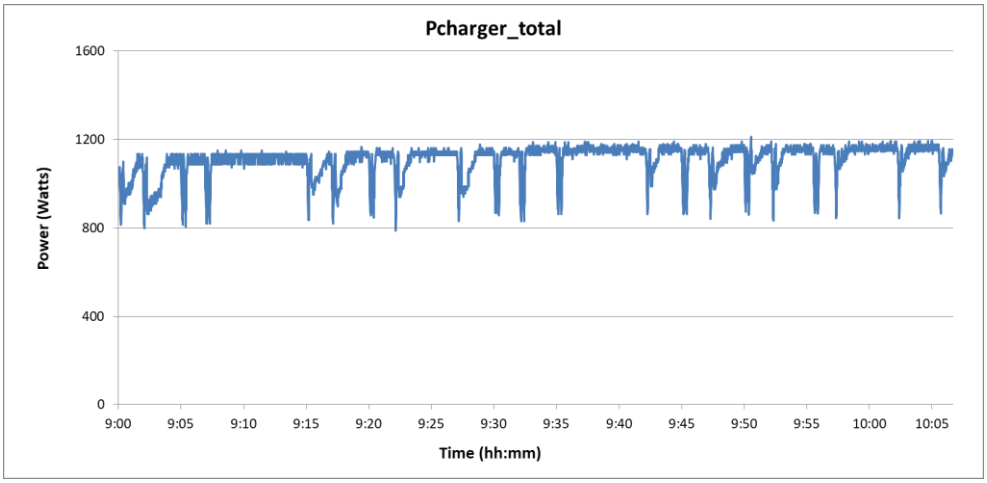


Figure 10 Total power supplied by the PV chargers during a short duration of Test1

This is better shown in the diagram of Figure 10 which illustrates a part of the PV power profile during the test. Last but not least, Figure 11 shows the battery voltage profile. As it is obvious, the voltage of the battery presents a very stable profile most of the time, which is in line with the specifications of the specific technology. During the 3rd day of the test, at around noon, the battery is fully charged and the voltage increases to 56.5V. This indicates also the end of the specific test.

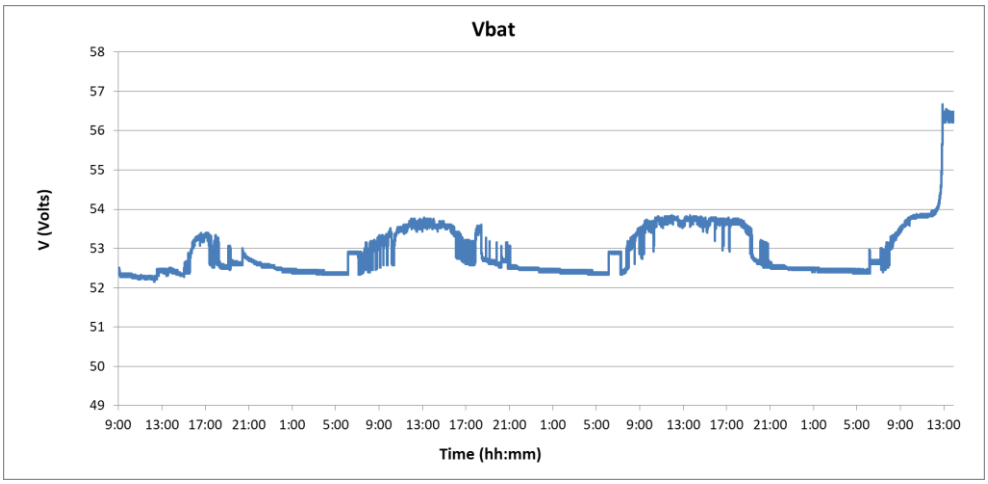


Figure 11 Battery voltage profile during Test1

The second test (Test2) is a repetition of Test1 in order to validate the obtained results. The duration of the experiment is also slightly longer than 3 days and it results in an efficiency calculation slightly above 100%. This is due to the uncertainties in the measurement of the signals and the implemented formulas but in any case, a more accurate measurement of the efficiency would show significantly high (>90%) efficiency which is an acceptable result. From the data of this test, Figure 12 shows the voltage profile which is similar to the one in Test1.

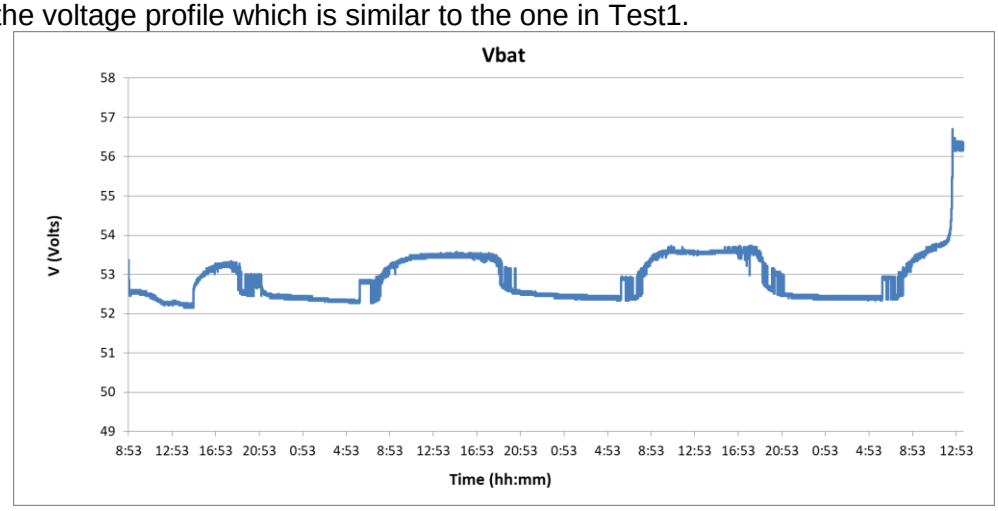


Figure 12 Battery voltage profile during Test2

It is worth mentioning that in both the above tests the SOC of the battery never dropped below 81% proving so the reliability and good performance of the system.

A similar to the above test is repeated with the only difference that for the recharging phase of the battery the inverters are used instead of the PV chargers. During the recharging phase, the inverters draw power from the grid while they are not loaded. The specific test had duration of approximately 2 days and the round-trip efficiency from this experiment is calculated at 89.14%. The lower value compared to the previous tests is accounted for due to the discrepancy in the calculation of the battery mean current based on eq. 3. Some key results from the specific tests are shown in Figure 13 which illustrates the profiles of the AC load and the grid supply during the test. In the same diagram the battery voltage is also depicted.

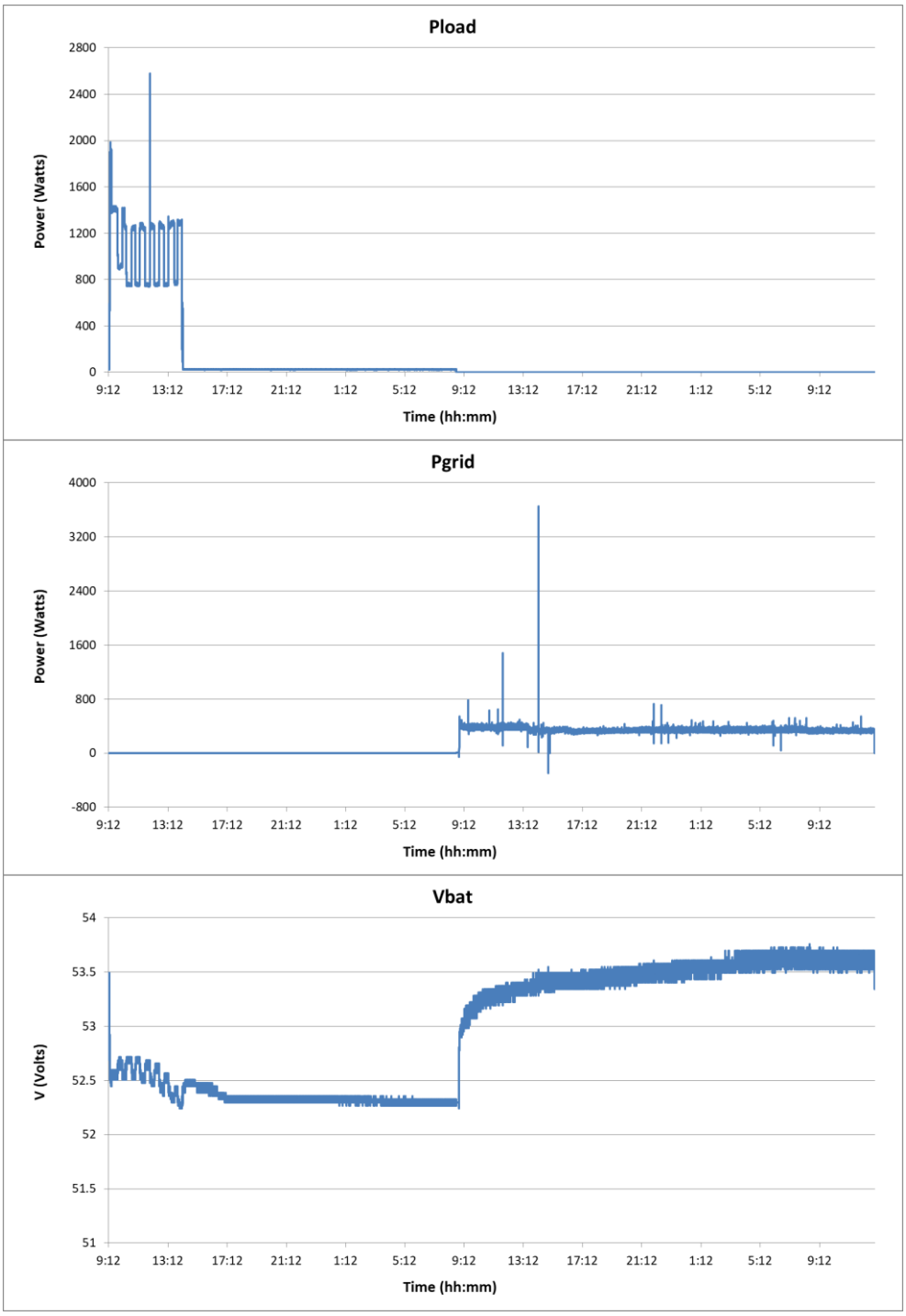


Figure 13 Test results for round-trip efficiency test with the use of inverters only

The last test of this scenario involves the operation of the EuT in the long run. Scope of this experiment was to illustrate that the device is capable of properly operating within its specification for duration of 8 days with the combined operation of all charger and inverter units. In this scenario the battery efficiency measurement is out of scope and the main focus is on the battery voltage and SOC. In Figure 14 the load and inverter power profiles for the specific test are shown. The loads were used only during working hours of the laboratory, thus the power consumption shows substantial interruption intervals. In conjunction with these profiles we can see the PV chargers' power profile in

Figure 15 which shows the continuous PV production throughout the experiment. As a result of this combination of production and consumption, the battery voltage remains always above 52V which

means that the battery is never deeply discharged, whereas in four days during the test the voltage of the battery reaches its maximum (absorption charging phase) which indicates that the battery was full. The indication of the EuT's own monitoring system regarding SOC shows that the specific value never fell under 83% during the experiment. It is worth noting that the initial SOC was nearly 100%.

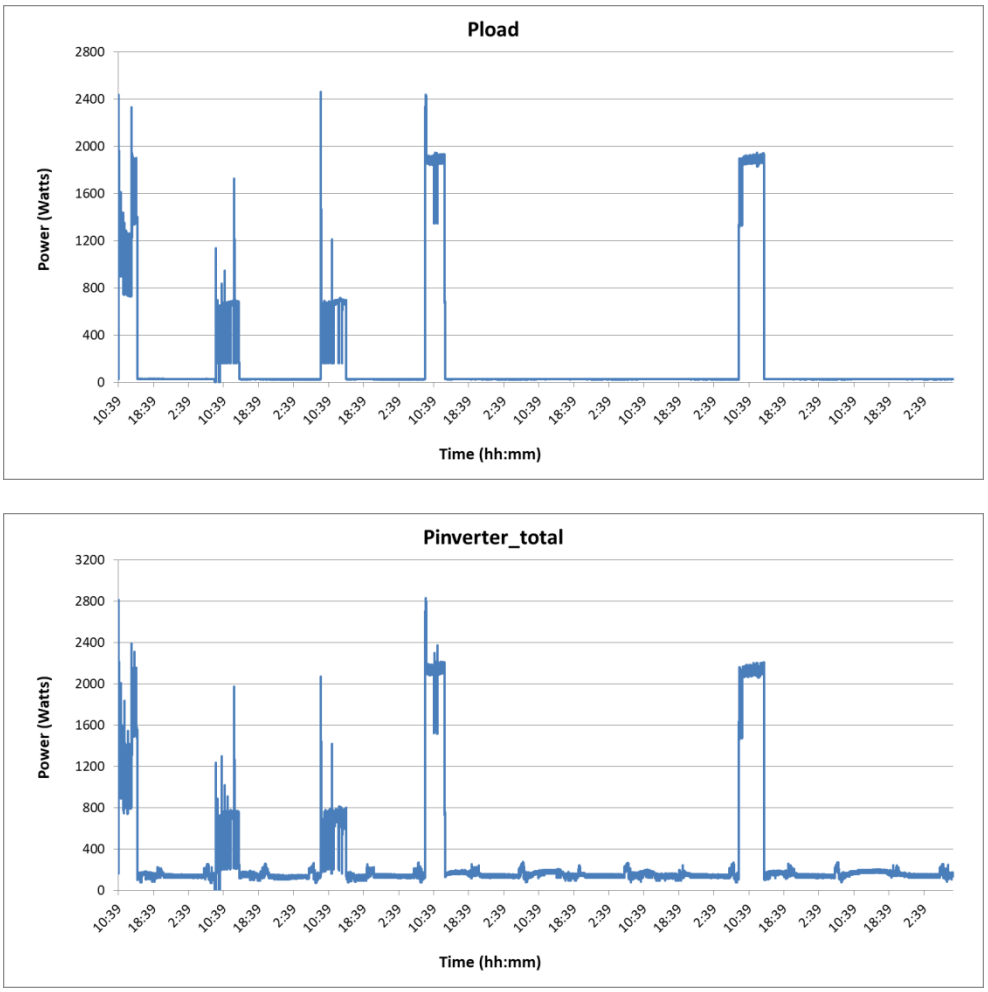


Figure 14 Load and inverter power during the long-term test

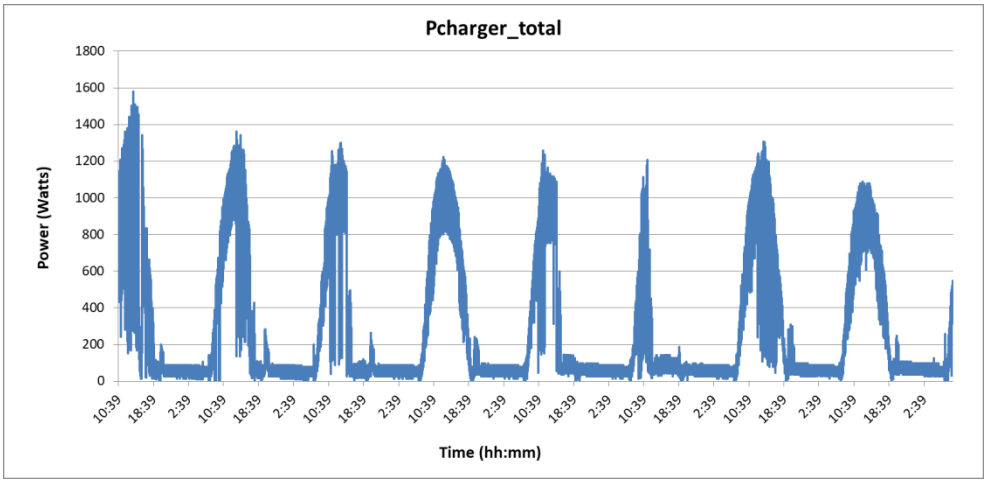


Figure 15 Power supplied by the PV chargers during the long-term test

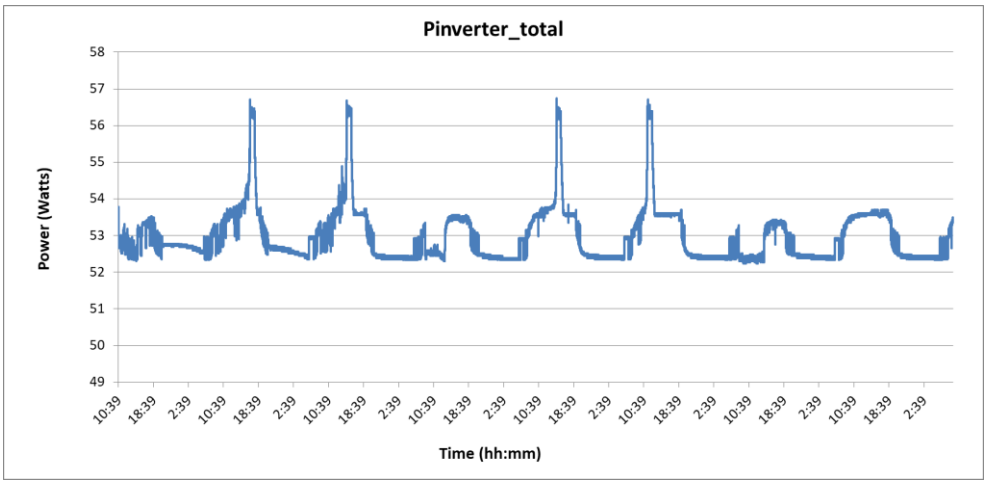


Figure 16 Battery voltage profile during the long-term test

In order to verify the good performance of the components during the long-term operation test a number of thermal images was taken. Some of these measurements are shown in Figure 17. According to the infrared images the operating temperature of the components is within acceptable limits.

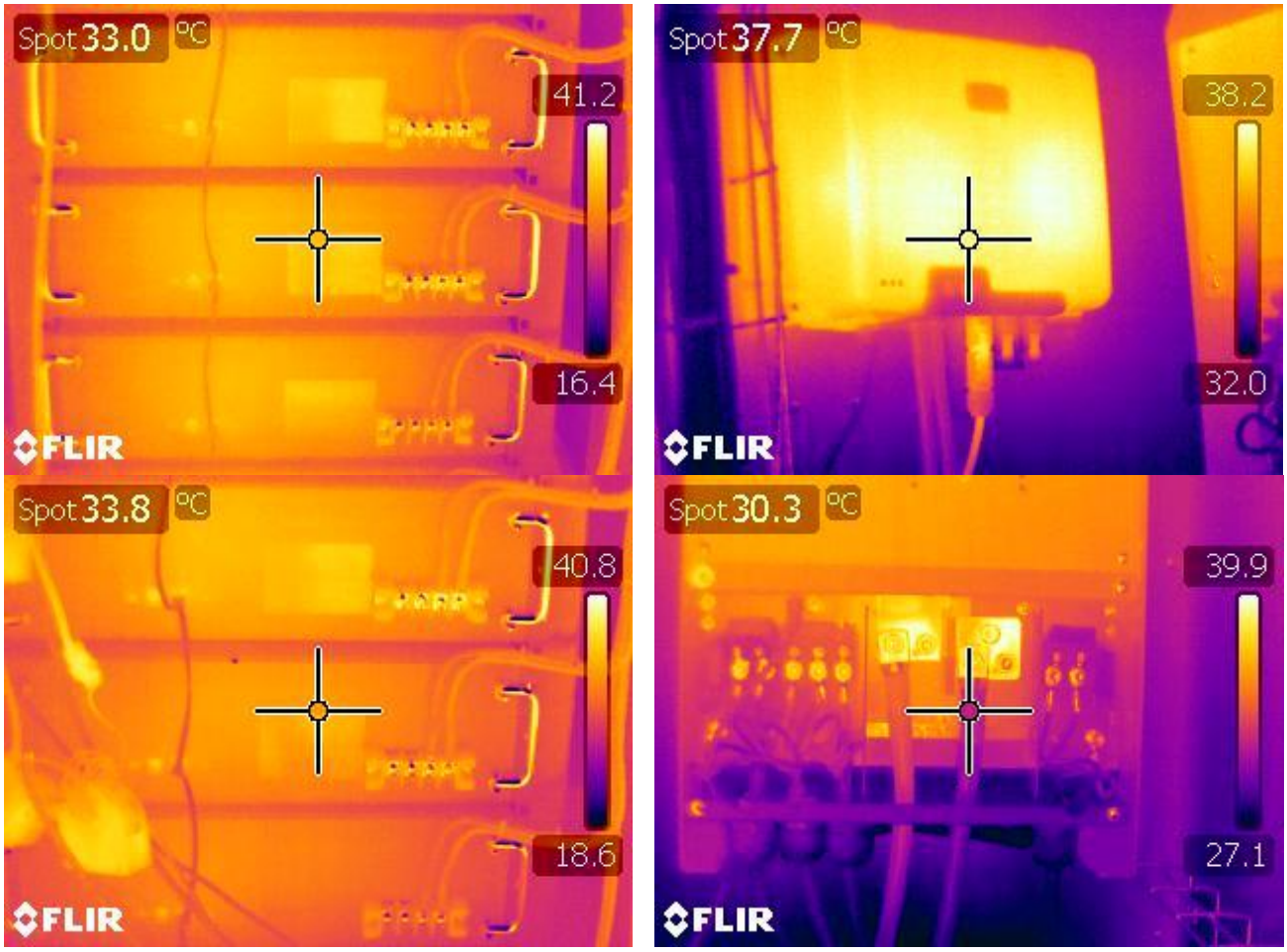


Figure 17 Thermal images of batteries (left column) and charger (right up) and inverter (right down)

Scenario 2: This scenario deals with the performance characterisation of single battery cells of the

same technology as with the main battery of the EuT. In order to do so, we have used the equipment of the battery testing laboratory in which with the use of a controllable charger/discharger device and data logging with a lab PC we obtain the operating characteristics such as round-trip efficiency and voltage. Table 1 provides an overview of the measured efficiency for one of the cells. According to the results of this table the efficiency of the cells is as high as 98.4% for low discharge/recharge current while on average it is 97.52%. Moreover, the diagrams in Figure 18 and Figure 19 show the voltage behaviour of these cells during charging and discharging respectively. The test results reveal the high stability and reliability of the voltage level at a wide range of SOC (or DOD respectively).

Table 1 Round –trip efficiency of a single battery cell

Test no.	Ah discharged	Ah charged	Wh discharged	Wh charged	Efficiency (%)
2	81.8 (@7.5)	82 (@7.5)	301	307	98.0
3	81.8 (@15)	81.9 (@15)	301	308	97.7
4	82.2 (@25)	82 (@25)	302	310	97.4
5	83.4 (@3.75)	83.8 (@3.75)	307	312	98.4
7	81.9 (@37.5)	82 (@37.5)	299	311	96.1

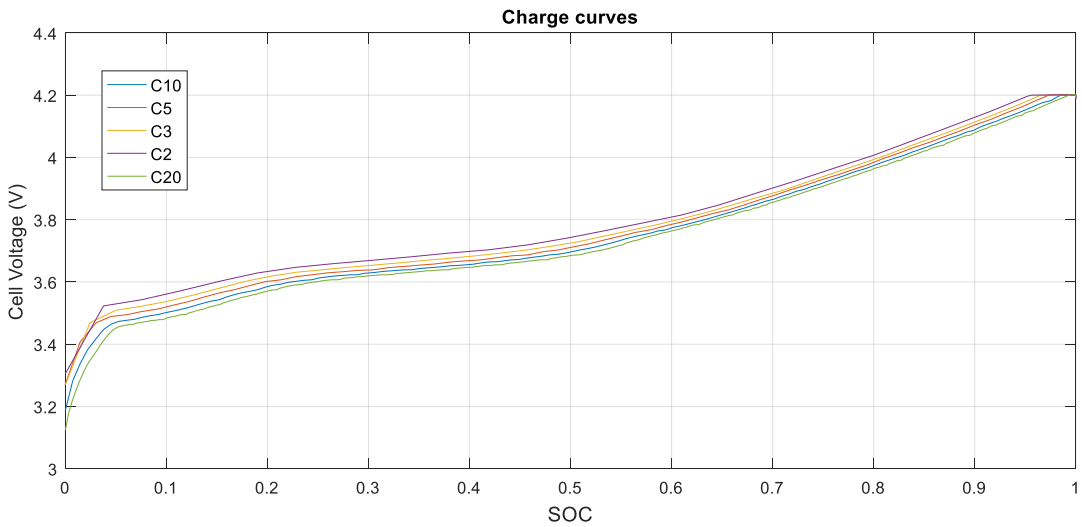


Figure 18 Single cell voltage variations as a function of SOC during charging tests

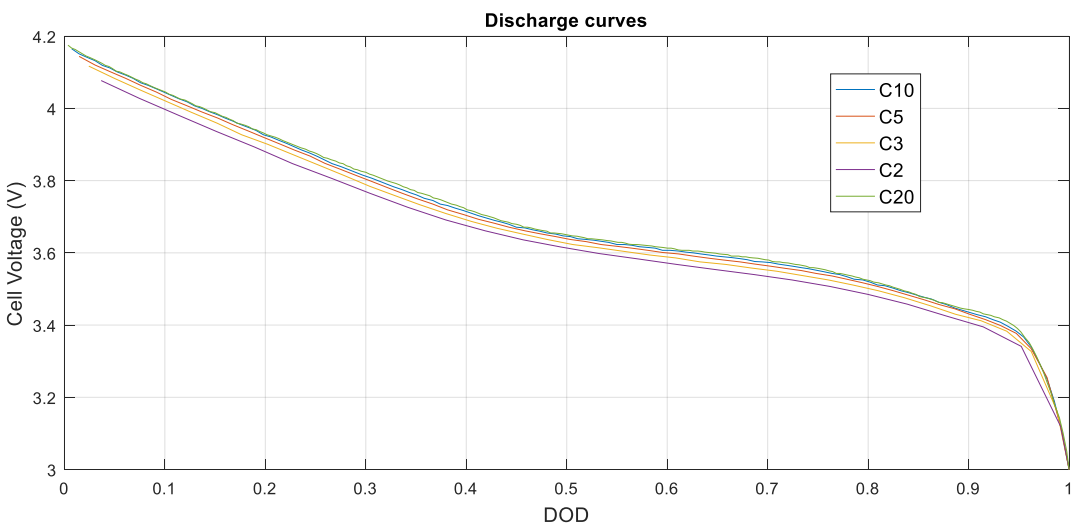


Figure 19 Single cell voltage variations as a function of DOD during discharging tests

Scenario 3: Interoperability tests with regard to the BMS were realised by means of a Node-RED application that uses a proprietary (Modbus RTU like) protocol in order to acquire various readings from the BMS. A snapshot of the specific Node-RED application is show in Figure 20. This application consists of two parts. One is concerned with reading data from the EMS of the EuT while the other queries sequentially 10 batteries of the EuT in order to acquire their measurements.

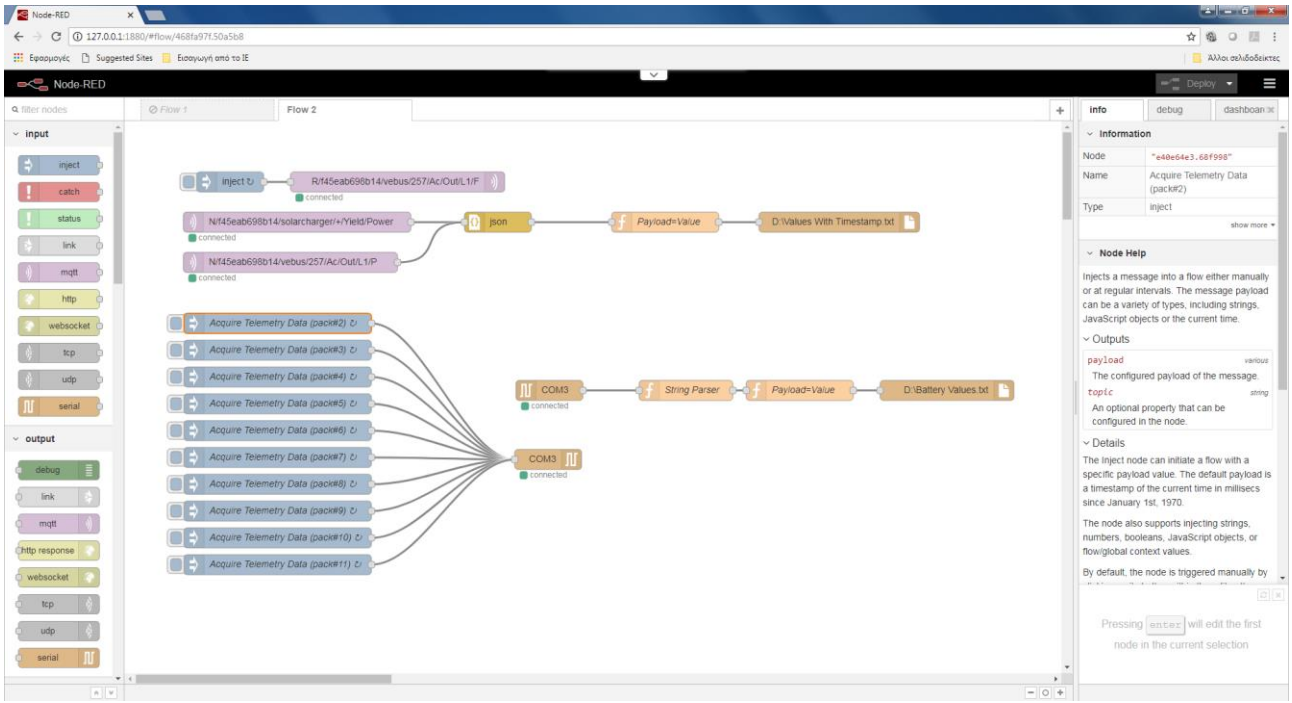


Figure 20 Node-RED application used for the interoperability tests

The type of information that the application sends to the specific COM port of the PC in order to get the data of one battery is the following ASCII code:

~ 2 6 0 0 4 6 4 2 E 0 0 2 0 2 F D 2 F

This command regards one battery only and is appropriately modified for the other batteries. The result of this querying process is stored to a *.csv file that contains all available measurements of the BMS. This file contains information such as the timestamp, battery address, battery remaining Ah, battery voltage etc.

```
43263.37493372685|10|49.7|53.44|654.44|00|02
43263.37498001158|11|49.21|53.38|0|00|02
43263.375234583335|2|49.72|53.4|0|00|02
43263.375281053246|3|49.71|53.44|0|00|02
43263.37532716435|4|49.7|53.07|651.86|00|02
43263.37537363426|5|39.87|53.36|0|00|02
43263.375443067125|6|49.69|53.36|0|00|02
43263.37548935185|7|49.74|53.38|0|00|02
43263.37553564815|8|49.67|53.41|0|00|02
43263.375581932865|9|49.69|53.4|0|00|02
43263.375628229165|10|49.62|52.87|650.77|00|02
43263.37567450231|11|49.21|53.34|0|00|02
43263.37592909722|2|49.69|52.89|648.23|00|02
43263.37597538195|3|49.66|52.9|648.34|00|02
43263.37602167824|4|49.62|52.84|650.63|00|02
43263.37606795139|5|39.87|53.34|0|00|02
43263.37613738426|6|49.66|52.86|646.14|00|02
43263.37618368056|7|49.74|53.32|0|00|02
43263.37623015046|8|49.67|53.35|0|00|02
43263.376276435185|9|49.69|53.34|0|00|02
```

Figure 21 Node-RED data file containing measurements from the BMS

All in all, the tests of all scenarios showed that the EuT is a high-performance device with increased reliability and efficiency even under some of the hardest operating conditions (outdoor

placement, operation with real sources and loads etc.). The tests that regarded the efficiency of the EuT itself showed very high efficiency and reliable performance under highly variable loading and generation conditions. In particular, the performance of the $LiFePO_4$ batteries was according to the specifications since it presented stable voltage profile under varying power conditions and high capacity which allowed for prolonged discharging at relatively high load. The performance of the technology has also been validated by testing the operation of single cells in fully controllable environment. Last but not least, the communication of third-party applications with the BMS system was feasible which validates the interoperability of the EuT.

6 Open Issues and Suggestions for Improvements

From a technical point of view there are various measures that could be taken in order to measure the efficiency of the EuT with better precision:

-One issue is related to the calibration of the sensors which could have been done more effectively before the tests. In fact, the calibration of the sensors was done after installing them on the EuT and comparing their out values to the ones of portable meters.

-Another measure towards improvement of the tests would be to measure the mean instead of the RMS values of the quantities which would then be acquired by the SCADA system. This was not possible during the tests due to lack of proper kind of sensors.

-Operation of the inverters during the recharging phase was also a critical issue due to their standby losses. The latter contributed in discrepancies in the efficiency's measurement

- The duration of the experiment was another issue that could be improved. The main challenge during the experiments was the rather small charging power from the PVs. Interconnection of a larger PV panel would result in faster recharging of the batteries.

7 Dissemination Planning

The dissemination plan of the LiBRE project involves submission of conference papers. The specific conferences have not been selected yet.

8 References

[1] N. Hatziargyriou, Microgrids: Architectures and Control, Wiley/IEEE Press, 2014.

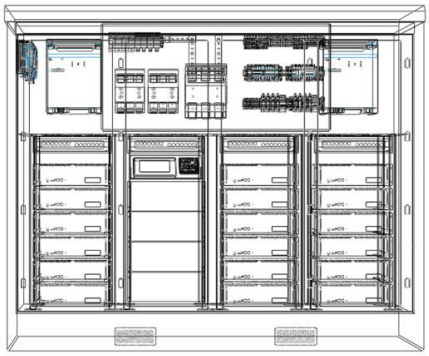
[2] M. Legraive, Realisation of a Lithium-ion Battery Model for Microgrid Applications and Validation with Real-time Simulation Platform, Master's Thesis, 2017.

9 Annex

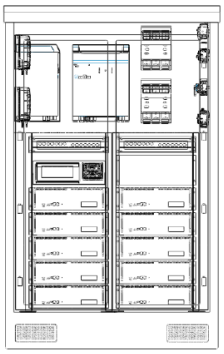
9.1 List of Figures

9.2 List of Tables

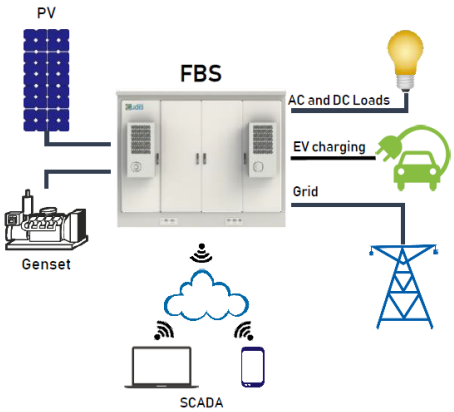
9.3 Technical Specifications of the EuT



FBS40



FBS25



	FBS25	FBS40
Power		
AC Output	8 kW / 10 kVA	8 kW / 10 kVA
Peak AC Output	20 kW	20 kW
AC Voltage / Frequency	230 V_{AC} / 50 Hz [1]	230 V_{AC} / 50 Hz [1]
DC Output	20 kW	40 kW
DC Voltage (nominal)	48 V_{DC} [2]	48 V_{DC} [2]
AC Inputs	2	2
Max Feed Through Current	2 × 200 A	2 × 200 A
Battery Charging Current	140 A	140 A
Photovoltaic Power	11.6 kW_p	11.6 kW_p
Max PV voltage	250 V	250 V
MPPT Trackers	2	2
Storage		
Battery type	$LiFePO_4$	
Battery Nominal Voltage	51.2 V (16 cells × 3.2 V)	
Battery Module Capacity	50 Ah	
No. of Battery Modules	10	18
Energy Capacity	24 kWh [3]	43.2 kWh [3]
Max Charge Rate	0.2C (C5)	
Max Discharge Rate	1C	
Enclosure		
Construction	1.5 mm double layer galvanized steel - PEF thermal insulation	
Dimensions (H × W × D)	2050 × 1200 × 1100 mm	2050 × 2500 × 1100 mm
A/C Cooling capacity	2000 W	4000 W
Enclosure IP	IP65	IP65
Fire Suppression	Category A,B,F	
Enclosure Weight	< 500 kg	< 900 kg
Total Weight	< 810 kg	< 1470 kg
Monitoring and Control		
PCS	SCADA + on site display	
Battery	SCADA + on site intelligent display [4]	
Battery interface	RS485	
Remote monitoring	TCP/IP - 3G/4G GSM router	
Alarms	on site Alarm Board – TCP/IP communication	

[1] 120 V_{AC} and 60 Hz options available upon request
[2] Actual DC voltage varies according to the battery SOC (48 V_{DC} is the minimum)
[3] Corresponds to the maximum number of battery units installed in the racks
[4] SCADA can be switched temporarily to on site touch screen display – on battery display optional