Design, Implementation and Performance Testing of a Flexible Battery Storage System

Dionysios Baltas
EUDITI LTD.

Charalampos Nikopoulos
EUDITI LTD.

Evangelos Rikos
CRES

John Nikoletatos
CRES

Abstract

The market for Battery Storage Systems is showing significant growth due to the decrease of photovoltaic module prices but also due to decreases in Lithium battery costs. Battery storage can be used in conjunction with net metering systems, as UPS systems for extended power outages, in partially electrified grids in developing countries or in autonomous operation. Our goal has been to design a Flexible Battery Storage system (FBS) that can be used in all above cases, as well as being an intelligent component of an Internet-of-Things (IoT) environment.

Net metering and telecom applications generally have limited space for the PV arrays and the inverter/storage cabinet, so the system was designed to be compact. Reliable operation requires function of the batteries at normal temperatures. For this reason, the system enclosures have to include active cooling which is an additional load and should be accounted in the overall system efficiency.

The system that was designed and tested contains inverter units, MPPT chargers for coupling with solar arrays, and Lithium-Ion Batteries. These offer multiple benefits compared to lead-acid ones. They are easier to parallel and the storage capacity can be field adjusted. However, Li-Ion Batteries require a central control system to regulate their charging and to check their health conditions. As such, software development is paramount to the safe, reliable and cost-effective operation of the battery system.

Optimal operation of battery systems for net metering applications depends on load characteristics and in most cases requires prediction of the solar production for the next day. Thus, monitoring and control is very important and due effort was put to the design and implementation of such a system. It contains a GSM router and a single-board computer which exchange data with a remote server which can be used to oversee the system. Smart software has been developed to appropriately control the system's interaction with the grid, e.g. using stored energy over grid energy when a renewable energy surplus day is predicted.
Performance testing has been performed by researchers in the CRES. The testing included using the PV chargers with PV arrays on site for round-trip efficiency tests to establish the long-term behavior of the system as well as testing of the individual battery cells in lab conditions. Lab tests have shown efficiency of the lithium battery cells close to 99%.
The design principles and a detailed account of the performance testing are presented.

Περίληψη

Η αγορά των συστημάτων αποθήκευσης σε μπαταρίες έχει σημαντική ανάπτυξη λόγω της μείωσης του κόστους των φωτοβολταϊκών στοιχείων και των μπαταριών λιθίου. Η αποθήκευση σε μπαταρίες χρησιμοποιείται σε εφαρμογές net metering, σε συστήματα UPS για εκτεταμένες πτώσεις ισχύος, καθώς και για εν μέρη ηλεκτροδοτημένα δίκτυα σε αναπτυσσόμενες χώρες ή σε αυτόνομη λειτουργία. Ο στόχος μας ήταν ο σχεδιασμός ενός ευέλικτου συστήματος αποθήκευσης με μπαταρίες το οποίο μπορεί να χρησιμοποιηθεί σε όλες της παραπάνω περιπτώσεις, και επίσης να αποτελεί ένα έξυπνο στοιχείο μίας εφαρμογής Internet-of-Things (IoT).
Οι εφαρμογές σε net metering και σε τηλεπικοινωνίες χαρακτηρίζονται από τον περιορισμένο διαθέσιμο χώρο για τις συστοιχίες φωτοβολταϊκών του Inverter και των μπαταριών, οπότε το σύστημα σχεδιάστηκε για να μην καταλαμβάνει περιττό χώρο. Για αξιόπιστη λειτουργία απαιτείται οι μπαταρίες να λειτουργούν σε ιδανικές θερμοκρασίες, και για αυτό το λόγο ο έγκλειστος χώρος του συστήματος πρέπει να περιέχει ενεργή ψύξη. Η ψύξη αποτελεί ένα επιπλέον φορτίο το οποίο πρέπει να υπολογίζεται για την συνολική απόδοση του συστήματος.

Το σύστημα το οποίο σχεδιάστηκε και ελέγχθηκε περιέχει μονάδες inverter, φορτιστές MPPT για σύζευξη με συστοιχίες φωτοβολταϊκών και μπαταρίες λιθίου-ιόντων. Οι μπαταρίες λιθίου προσφέρουν πολλαπλά οφέλη σε σχέση με τις μπαταρίες μολύβδου. Είναι πιο εύκολο να παραλληλιστούν και η χωρητικότητα του συστήματος μπορεί να προσαρμοστεί στο πεδίο. Όμως, οι μπαταρίες λιθίου απαιτούν ένα κεντρικό σύστημα ελέγχου το οποίο ρυθμίζει την φόρτιση τους και ελέγχει την κατάσταση της υγείας τους. Για αυτό τον λόγο, η ανάπτυξη λογισμικού είναι καθοριστική για την ασφαλή, αξιόπιστη και οικονομικά αποδοτική λειτουργία του συστήματος μπαταριών.
Η ιδανική λειτουργία του συστήματος για εφαρμογές net metering βασίζεται στα χαρακτηριστικά του φορτίου και στις περισσότερες περιπτώσεις χρειάζεται πρόβλεψη της ηλιακής παραγωγής της επόμενης ημέρας. Έτσι, η επίβλεψη και ο έλεγχος είναι πολύ σημαντικά και έγινε ανάλογη προσπάθεια για τον σχεδιασμό και την εφαρμογή ενός τέτοιου συστήματος. Περιέχει έναν GSM router και έναν single-board υπολογιστή μέσω του οποίου ανταλλάσσονται δεδομένα με έναν απομακρυσμένο server, ο οποίος χρησιμοποιείται για την επίβλεψη του συστήματος. Έξυπνο λογισμικό έχει αναπτυχθεί για την σωστή αλληλεπίδραση του συστήματος με το δίκτυο, π.χ. για την χρήση αποθηκευμένη ενέργειας έναντι ενέργειας από το δίκτυο όταν προβλέπεται η επόμενη μέρα να έχει μεγάλη παραγωγή ενέργειας από ανανεώσιμες πηγές.
Πραγματοποιήθηκαν δοκιμές της απόδοσης του συστήματος. Οι δοκιμές περιλάμβαναν χρήση των MPPT φορτιστών με συστοιχίες φωτοβολταϊκών για να ελεγχθεί η round-trip απόδοση και να δοκιμαστεί η μακροπρόθεσμη λειτουργία του συστήματος, καθώς και δοκιμή της απόδοσης των επιμέρους κελιών των μπαταριών σε εργαστηριακές συνθήκες. Οι δοκιμές στο εργαστήριο έδειξαν σχεδόν 99% απόδοση των κελιών μπαταριών λιθίου.
Στο άρθρο παρουσιάζονται οι αρχές σχεδιασμού και αναλυτική περιγραφή των δοκιμών απόδοσης.

Introduction

The price of solar energy production has been steadily decreasing according to the latest reports. Solar energy is projected to become cheaper than coal and gas-fired turbines by 2024. To most effectively utilize Renewable Energy Sources (RES), forms of storage are required. Lithium-ion batteries are a perfect candidate for that job, as they offer great round-trip efficiency and large cycle count compared to the currently commonly used lead-acid batteries. In addition, the cost of them has been rapidly decreasing and is projected to further decrease.

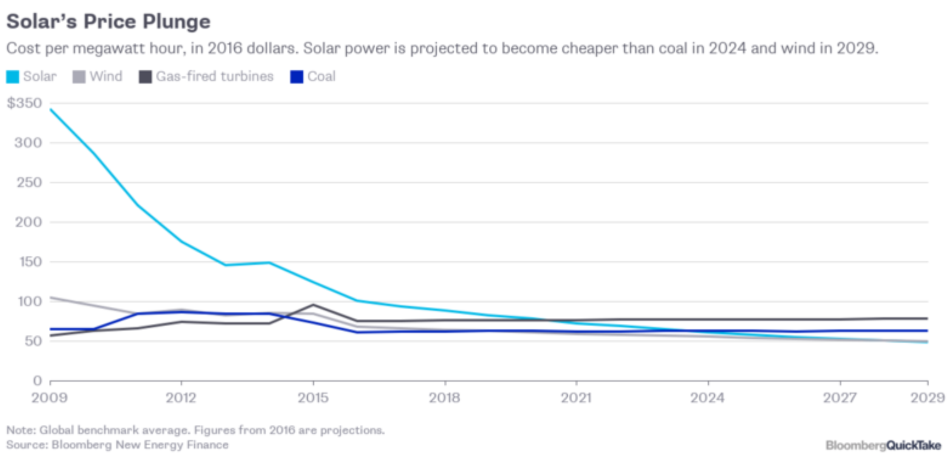


Figure 1 Bloomberg Report on Solar Energy cost

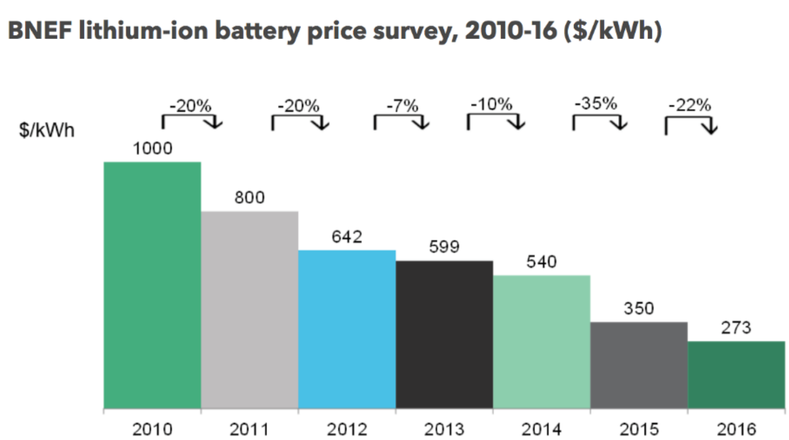


Figure 2 Bloomberg Report on lithium battery prices

Battery storage can be used for peak-shaving, in RES-coupled UPS systems, in partially electrified grids in developing countries or for fully autonomous off-grid operation. The goal while designing our systems has been to accommodate all previous cases, as well as making it capable of being a component in the ever-increasing number of Internet of Things (IoT) applications.

System Design

There were a number of goals to be met in the design of the system:

- Compact design

  Such systems are often to be installed on rooftops, next to houses or other space-limited sites, so it was important that the system has a small footprint. Adding to that, a compact design increases the ease of transportation to the installation site.
- Intelligence capabilities and Network accessibility

  The vast advancements of modern computing and ease of information network access have made it possible for most devices to acquire a degree of smart automation and remote monitoring. Our system was designed to have both basic remote monitoring and AI functions, as well as to be expandable to more complicated ones should the need for those arise.
- Multi-purpose use

  Expecting the need of multiple different applications, the system was designed to be adaptable to use in applications such as net metering, off-grid electricity supply, telecom stations and electric vehicle charging with RES.
- Field-adjustable

  Needs for higher or lower capacity of storage are likely to arise in many applications. Having lithium batteries which have a battery management system for their charging makes it easy to change their amount without compromising the electric stability of the system.
- High efficiency

  For net metering applications to be viable, the ratio between the energy we store in the batteries and the energy they can give back has to be high. Lithium batteries serve that purpose with efficiencies higher than 95%. MPPT chargers were included for efficient use of the coupled PV arrays.

- Low switch-over time

  For Uninterruptible Power Supply (UPS) applications, it is important that the system can switch between AC and DC supply without a delay in power supply. The inverter chosen for this system fulfills that criterion.

Figure 3 Pictures of the installation

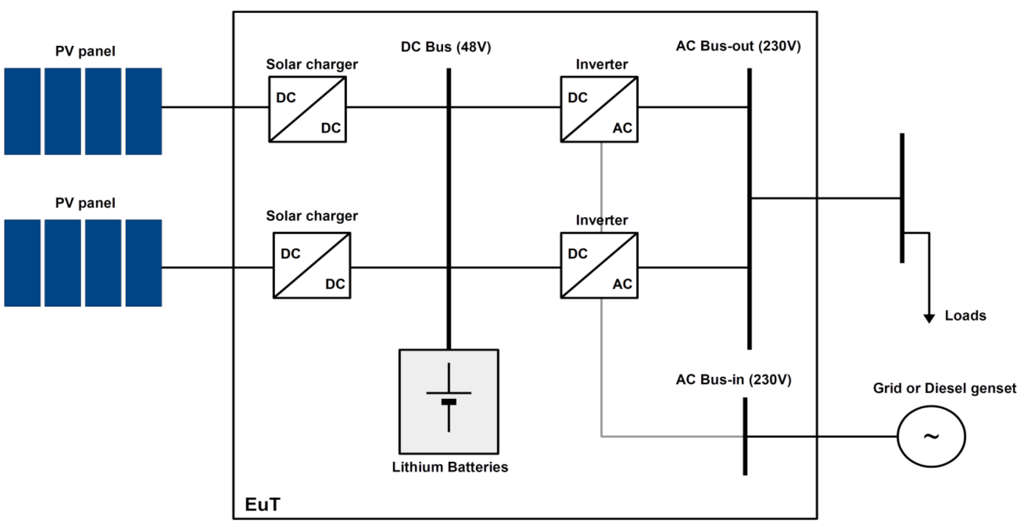


Figure 4 System Block Diagram

System communication is facilitated via a single-board computer. It was fitted with hardware interfaces capable of communicating with the inverters, chargers and batteries of the system, as well as a GSM router for network access in remote areas. Software was developed for the communications with the various different protocols of the equipment, using node-red, a flow-based development tool based on Javascript. The batteries communicate via a custom MODBUS like protocol through a RS485 connection, while the acquisition of data from the inverters and chargers is done via a local MQTT server. The computer also receives binary signals installed on the system (ex. doors opened or closed).

The data acquired is sent to a remote server which serves for storing the data for possible long-term uses. The server is also capable of sending information to the installation, allowing for remote control. Of course, local control is also possible, both through connection to the local network, as well as through displays installed on the system.

The software developed offers several advantages:

- The user interface designed is easily customizable because of the advantages of the development platform chosen
- The data acquired is rounded up in a common interface, something that the market is currently lacking an integrated solution for.
- The system can be a platform for easily implementing smart charging and consumption efficiency software.

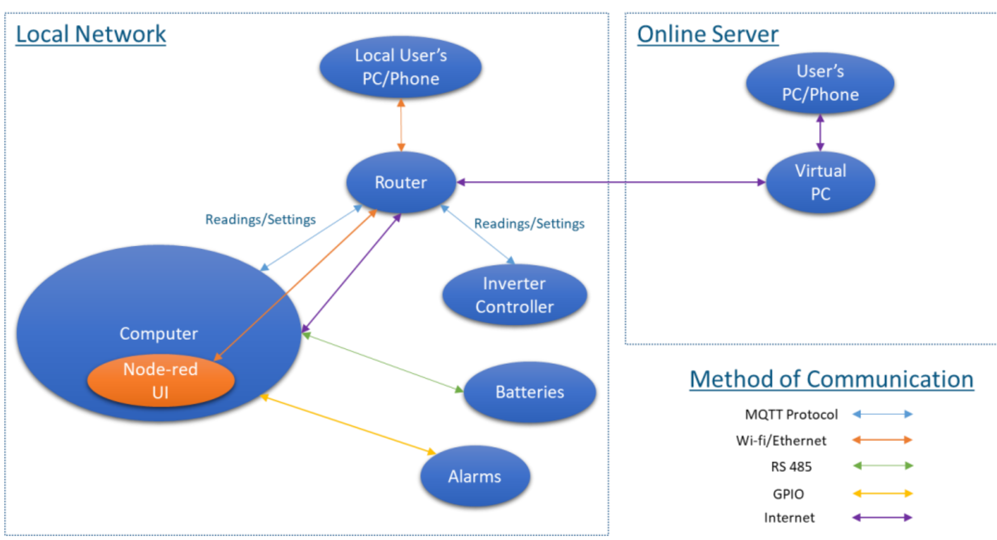


Figure 5 Communication Scheme

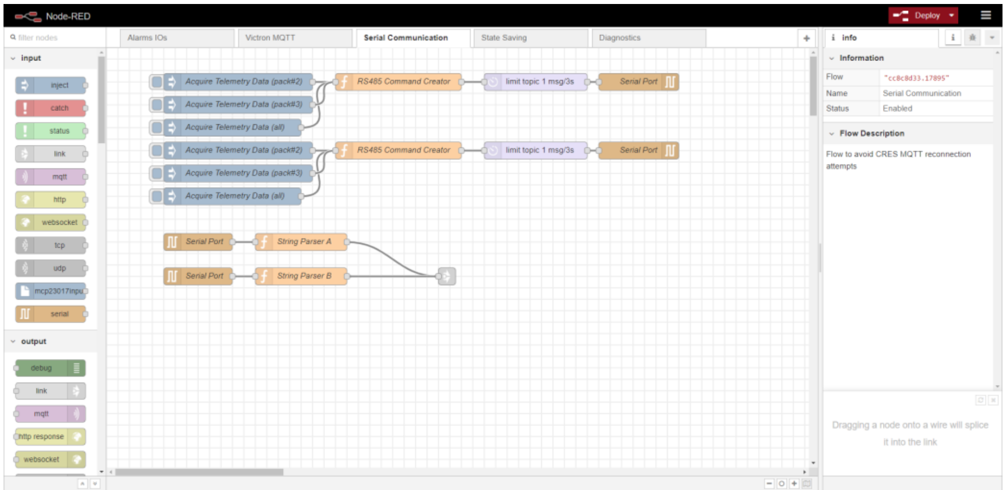


Figure 6 Node-RED software development tool

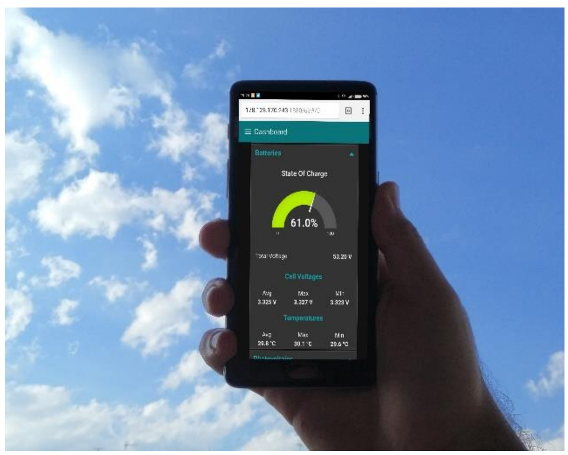


Figure 7 User Interface

Testing Results

Testing of the system was performed in the facilities of the Centre for Renewable Energy Source (CRES) in Pikermi, Attica.

Three types of tests were performed. The first included round-trip and long-term performance tests. Each of these tests lasted several days. The second type included an efficiency test of single lithium cells and was carried out at a separate laboratory of CRES' PV department, i.e. the battery testing laboratory. Apart from the accuracy that the specific lab's equipment offered to our tests, the use of completely different equipment made it possible for them to be run in parallel. The third type included interoperability tests of the communication with the Battery Management System (BMS), inverters and chargers that could be carried out without affecting the execution of the efficiency and long-term performance test.

<u>Type 1 Tests</u>: This type includes three round-trip efficiency tests and one long-term performance test. The first test (Test1) had a 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 8. 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 the cabinet's temperature. The latter aspect results in activation/deactivation of the cooling equipment. A better overview of the load behavior during this test is provided by zooming into the interval in which the load is active (see Figure 9). 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.

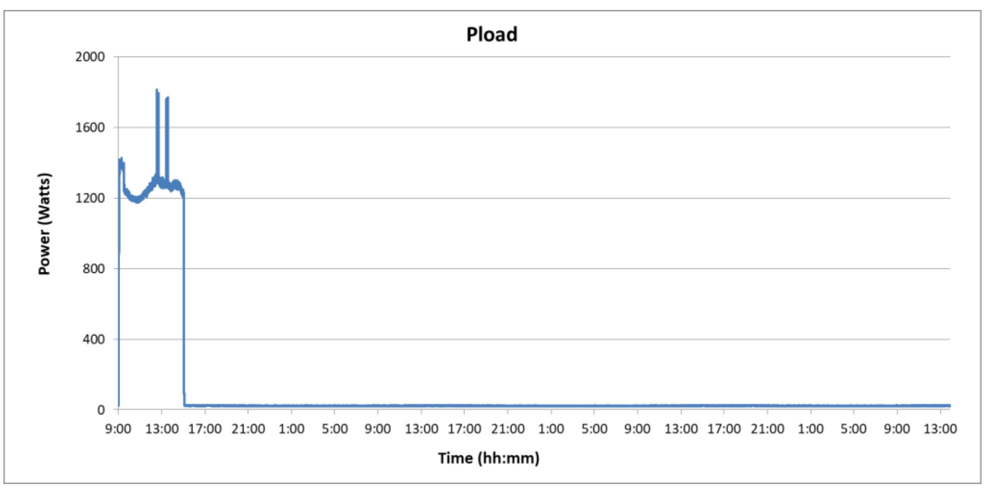


Figure 8 Load profile during the whole 3 days of Test1's duration

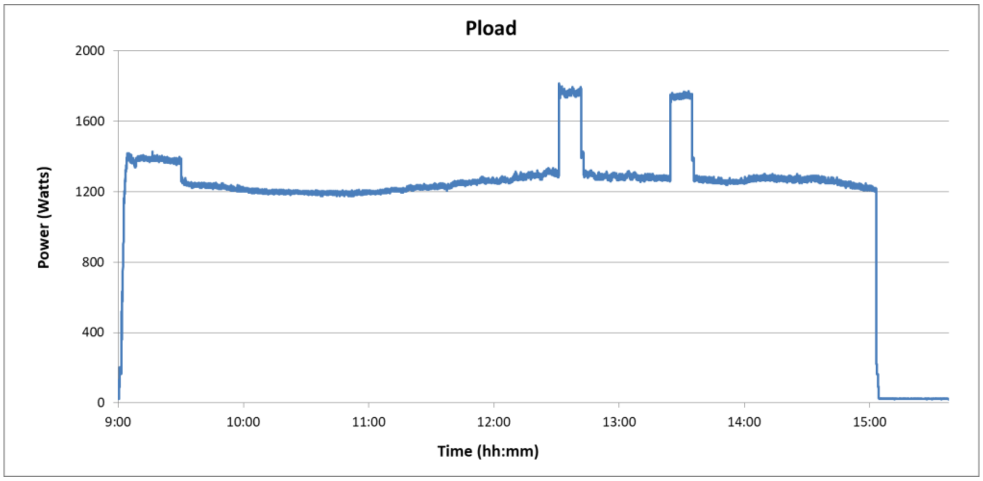


Figure 9 Load profile during the first six hours of Test1

In addition to the load profile in Figure 8 we examined 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 which results in a significant amount of energy consumed during the recharging phase of the test.

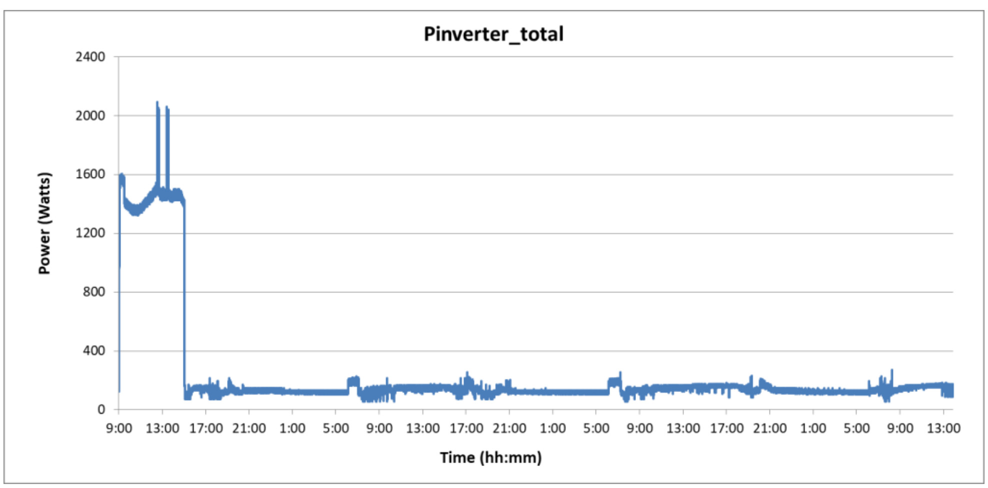


Figure 10 Total power absorbed by the inverters during Test1

In addition to the above results, Figure 11 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 reached 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. This specific, regular fluctuation is of short duration and is due to the Maximum Power Point Tracking (MPPT) algorithm of the chargers.

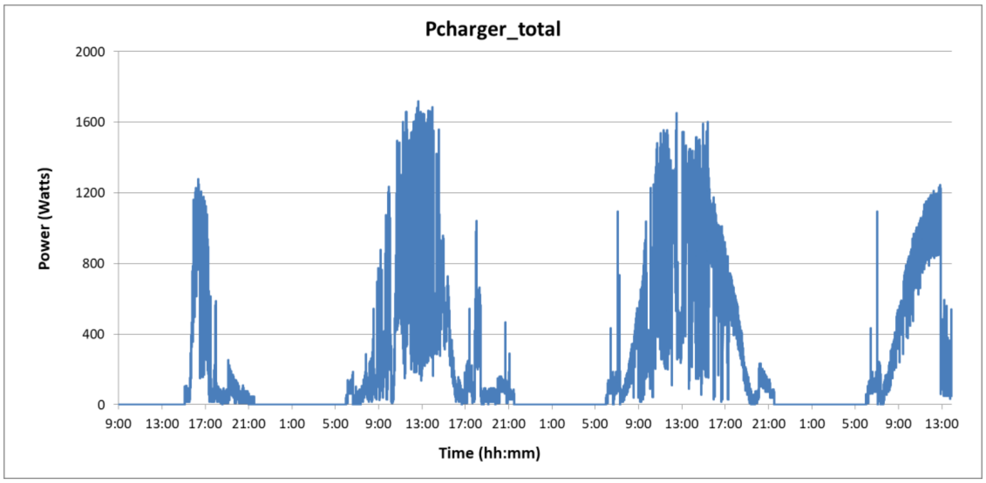


Figure 11 Total power supplied by the PV chargers during Test1

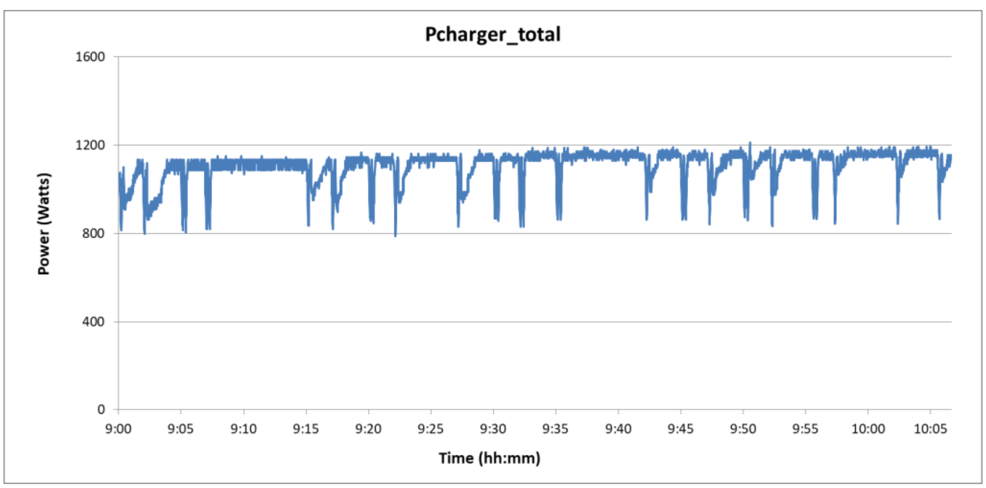


Figure 12 Total power supplied by the PV chargers during a short duration of Test1

This is better shown in the diagram of Figure 12 which illustrates a part of the PV power profile during the test. Last but not least, Figure 13 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, around noon, the battery is fully charged and the voltage increases to 56.5V. This indicates the end of the specific test.

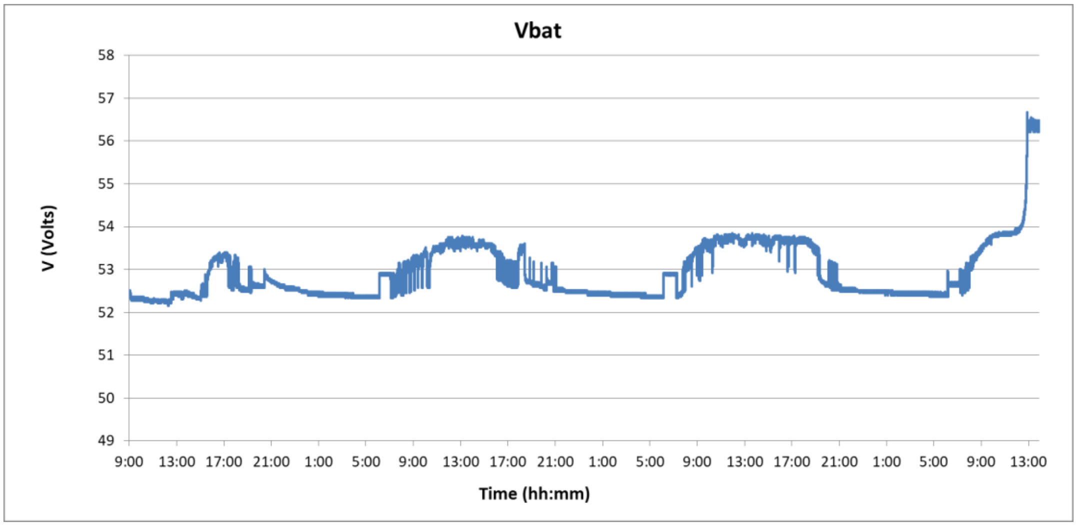


Figure 13 Battery voltage profile during Test1

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. From the data of this test, Figure 14 shows the voltage profile which is similar to the one in Test1.

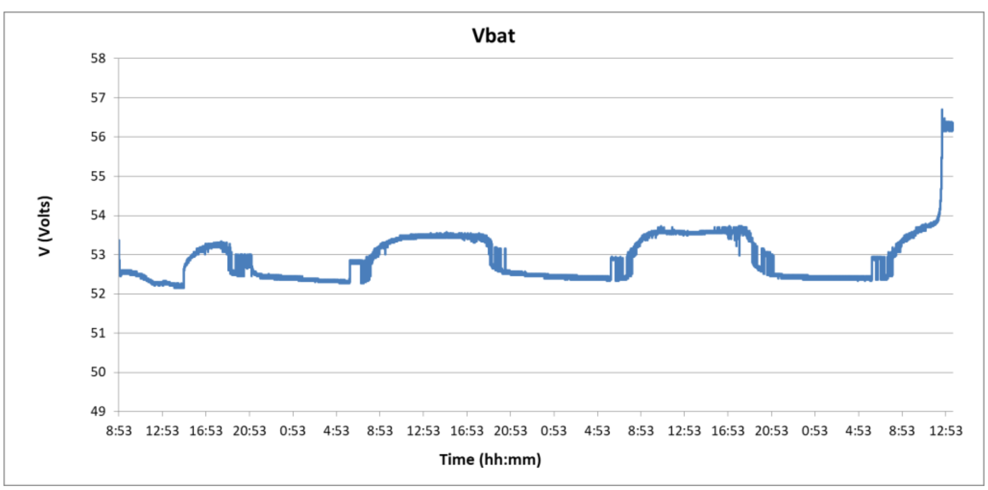
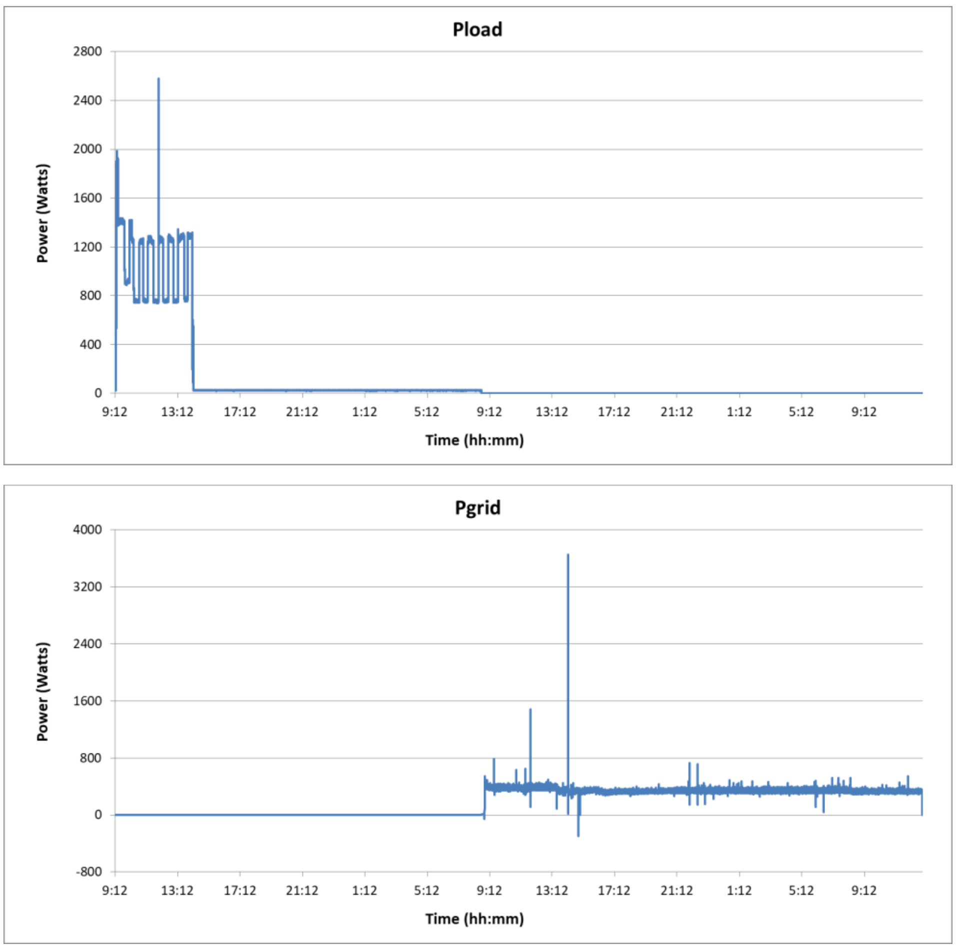


Figure 14 Battery voltage profile during Test2

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%. Some key results from the specific tests are shown in

Figure 15 which illustrates the profiles of the AC load and the grid supply during the test. In the same figure the battery voltage is also depicted.



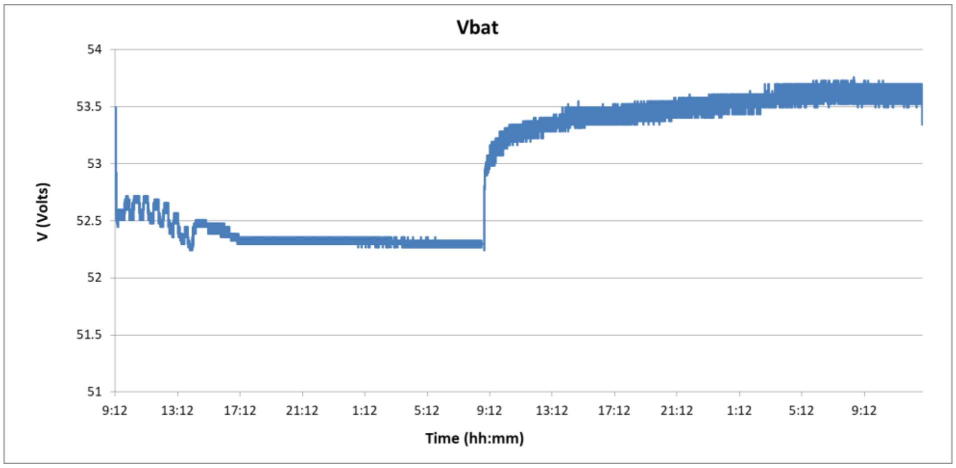
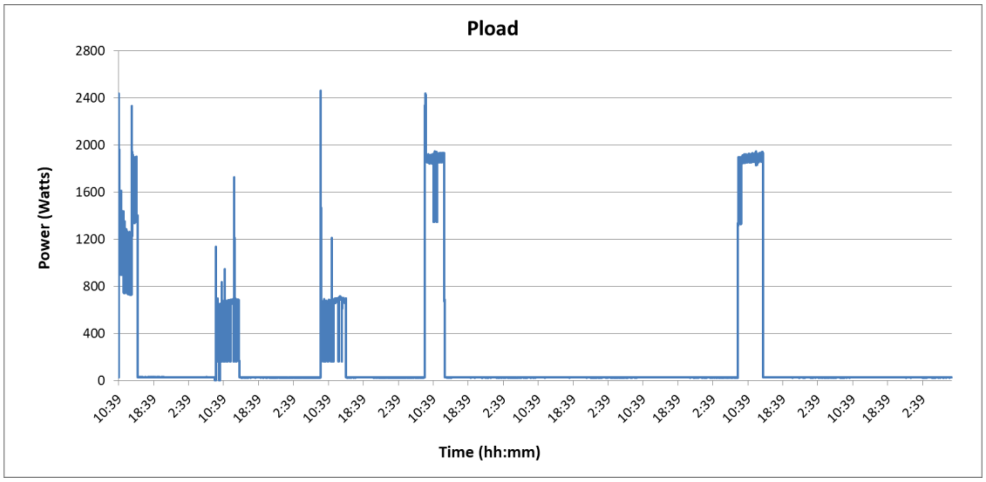


Figure 15 Test results for round-trip efficiency test with the use of inverters only

The last test of this type involves the operation of the equipment in the long run. The purpose of this experiment was to illustrate that the device is capable of properly operating within its specification for a duration of 8 days with the combined operation of all charger and inverter units. In this case the battery efficiency measurement is out of scope and the main focus is on the battery voltage and SOC. From Figure 16 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 17 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, and four days into the test the voltage of the battery reaches its maximum (absorption charging phase) which indicates that the battery was full. The indication of the equipment's own monitoring system regarding SOC showed that the specific value never fell under 83% during the experiment. It is worth noting that the initial SOC was nearly 100%.



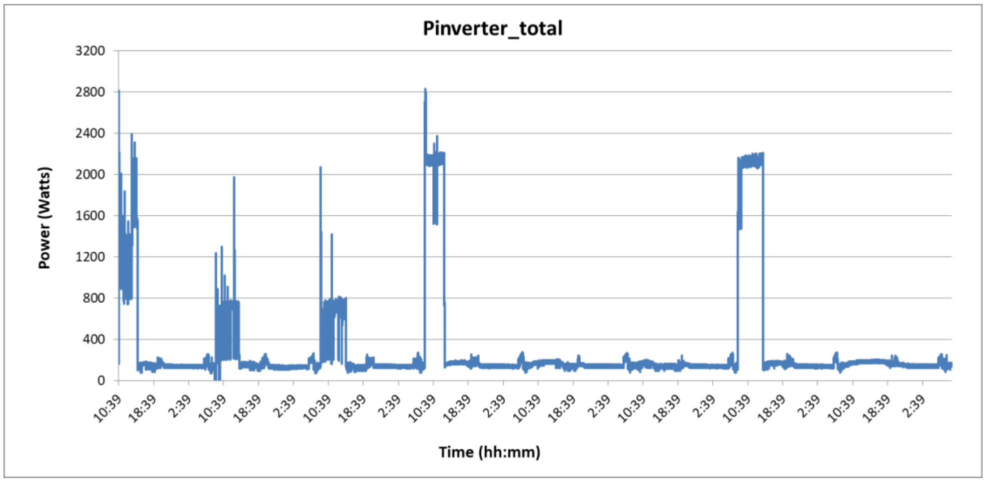


Figure 16 Load and inverter power during the long-term test

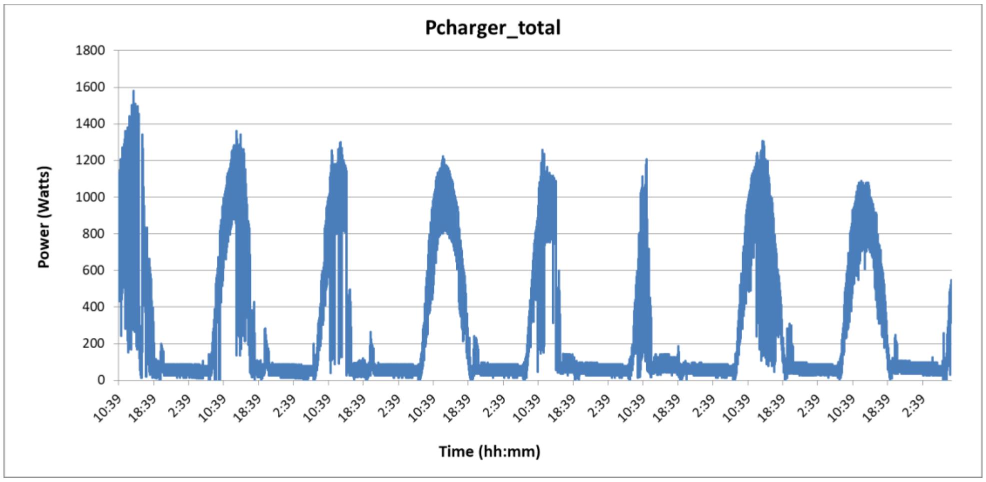


Figure 17 Power supplied by the PV chargers during the long-term test

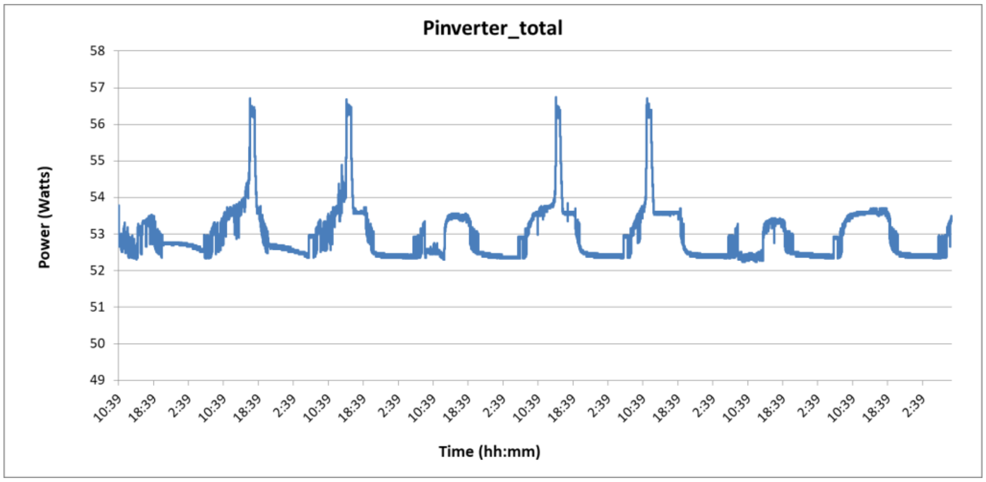
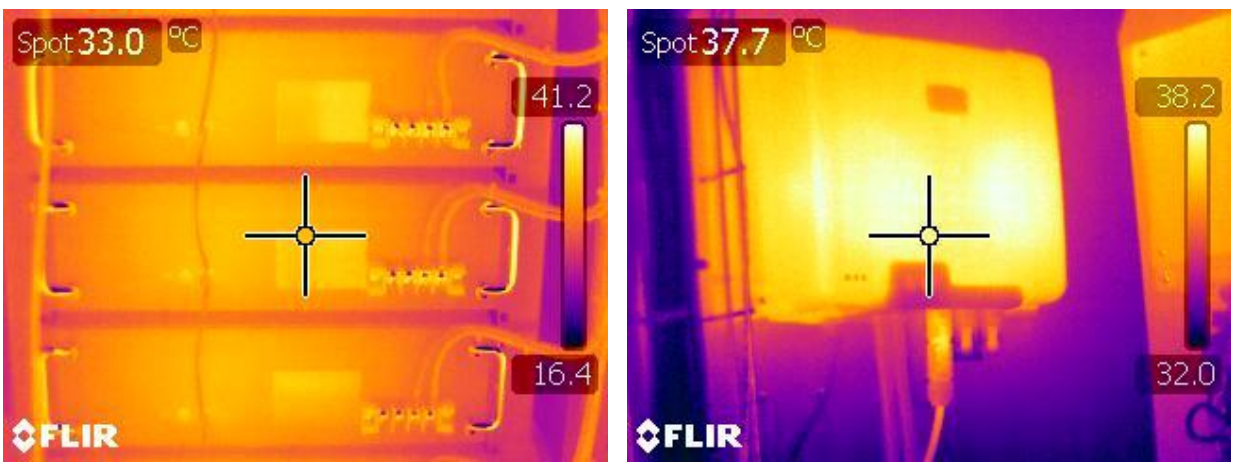


Figure 18 Battery voltage profile during the long-term test

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 19. According to the infrared images, the operating temperature of the components is within acceptable limits.



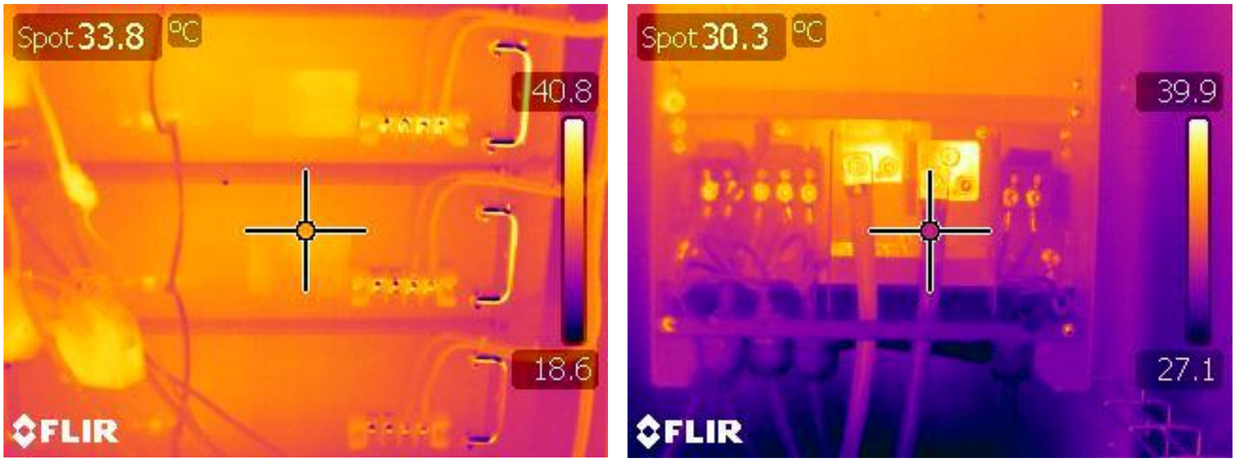


Figure 19 Thermal images of batteries (left column) and charger (right up) and inverter (right down)

Type 2 Tests: This type of tests deals with the performance characterization of single battery cells of similar technology to the main battery of the equipment. 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 20 and Figure 21 show the voltage behavior 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

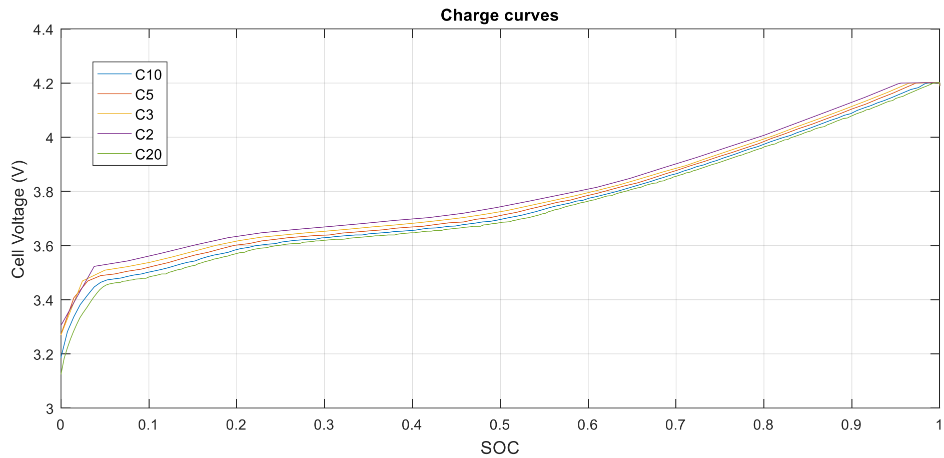


Figure 20 Single cell voltage variations as a function of SOC during charging tests

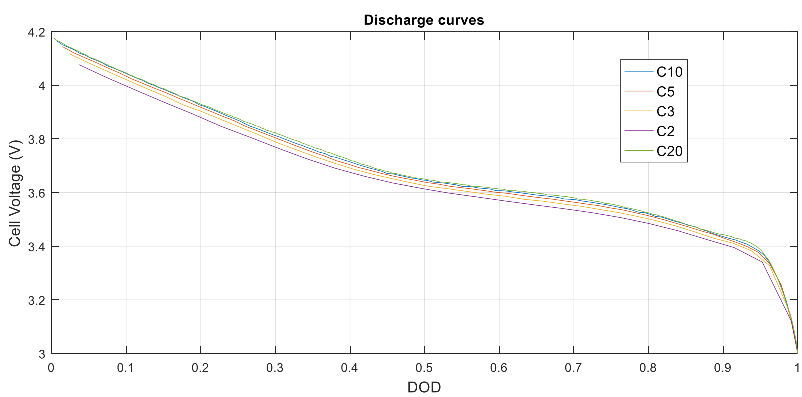


Figure 21 Single cell voltage variations as a function of DOD during discharging tests

Type 3 Tests: Interoperability tests with regard to the BMS were realized by means of a Node-RED application that uses a proprietary (Modbus-like) protocol in order to acquire various readings from the BMS. A snapshot of the specific Node-RED application is shown in Figure 22. This application consists of two parts. One is concerned with reading data from the management system of the equipment while the other sequentially queries the batteries of the equipment in order to acquire their measurements.

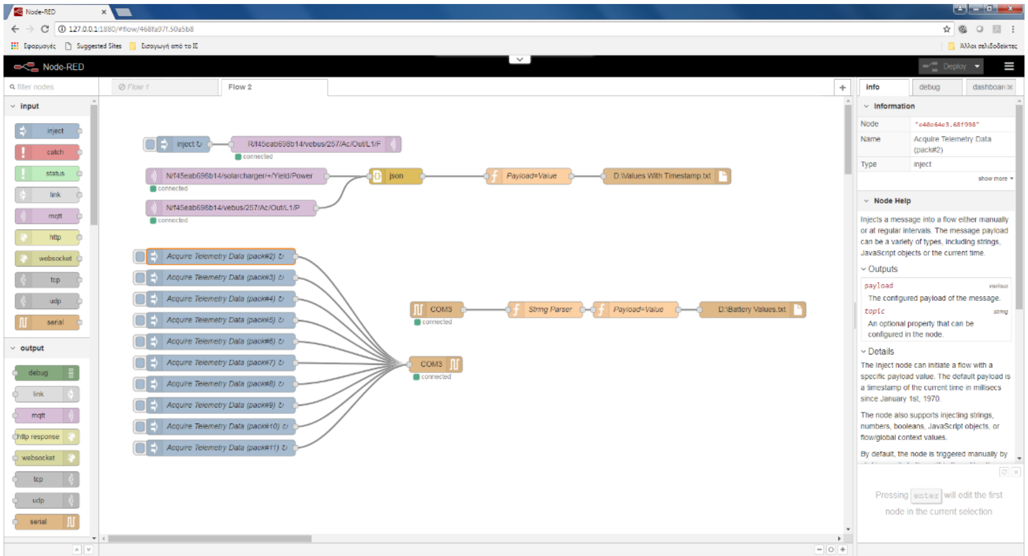


Figure 22 Node-RED application used for the interoperability tests

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 an ASCII code such as: ~26004642E00202FD2F

This particular command regards one battery only and is appropriately modified for the other batteries. The result of this querying process is stored a *.txt 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 23 Node-RED data file containing measurements from the BMS

All in all, the tests of all types showed that the equipment 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 equipment 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 equipment.

Conclusions

All in all, the designed system has shown great efficiency because of the lithium batteries it includes and is considered to be ideal for a variety of applications. The control unit we developed for this system can host IoT and machine learning/artificial intelligence applications. These can be used in smart grids. The drop of lithium battery prices as well as PV panels, coupled with the increased RES penetration, introduction of electric vehicles and the popularity of Internet of Things applications is expected to make systems such as the one we developed, increasingly present in the coming years.

References

1. https://data.bloomberglp.com/bnef/sites/14/2017/07/BNEF-Lithium-ion-battery-costs-and-market.pdf
2. https://www.bloomberg.com/quicktake/solar-energy
3. https://www.scientificamerican.com/article/battery-storage-poised-to-expand-rapidly/

This research has been performed using the ERIGrid Research Infrastructure and is part of a project that has received funding from the European Union's Horizon 2020 Research and Innovation Programme under the Grant Agreement No. 654113. The support of the European Research Infrastructure ERIGrid and its partner CRES is very much appreciated.