External Data File for

Measure the state of charge (SoC) and equivalent series resistance (ESR) of used, discarded, alkaline and zinc-carbon batteries for screening, reuse, and possible recharging with a homemade open-source Arduino-based instrument

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The instrument

The instrument shown in figure e1 was built following the 3R principle (i.e., reuse, recycle, and recovery) using parts that were already available in the laboratory. Only the Arduino, the relay and the battery holder were purchased.

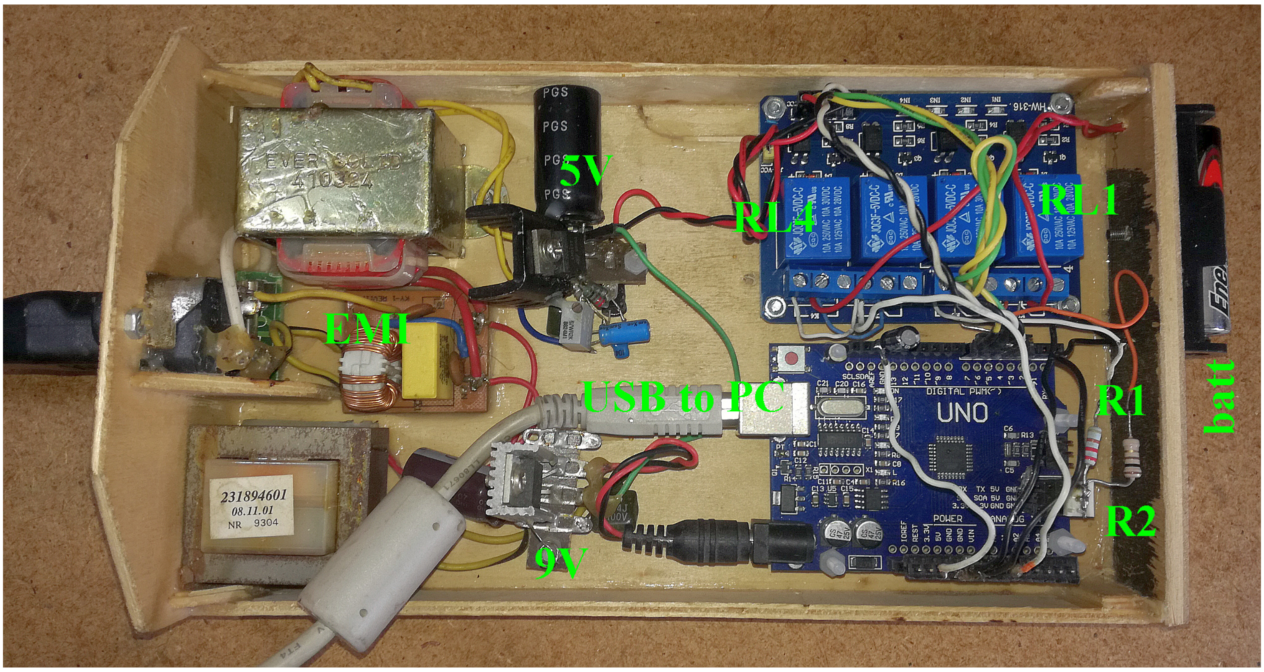


Fig.e1, instrument for measuring ESR and SoC; from the left: the EMI filter to block incoming radio frequencies, the two stabilised power supplies (5V and 9V), the Arduino UNO R3, the 4-relay module, the load resistors and the external battery holder. All photo, schematics, and component list are here presented under the Open-Source license (Copyright Creative Commons Public license, CC BY-NC-ND 4.0 EN)

In the photo, you can see the 4-wire measurement method; for example, in the top right-hand corner, you can see the two red wires coming out of the battery holder, one of which goes to the two relays RL3 and RL4 to connect the positive terminal directly to the Arduino, and the other to the two relays that connect R1 or R2 to the positive terminal as a load for the measurements

You can also see a white wire crossing the Arduino module to connect pins AREF to the V 3.3 pin supply to reduce the ADC converter’s reference voltage, and the stabilising capacitor recommended in the datasheet is also visible.

In the bottom right-hand corner, you can see a strategy for frequent Arduino users: instead of using individual pins, a pin header is employed, with only the relevant pins soldered in place. Anyone who has tried connecting to Arduino pins will have discovered just how fragile these contacts are; using a pin header keeps them all together, making the system more robust.

Power Supplies

The Arduino UNO R3 requires a DC power supply of at least 5V up to a maximum of 12V. The Arduino's internal voltage regulators then generate all the voltages required for its operation: 5V for the microcontroller, 3.3V as a reference voltage, and 1.1V as another internal reference. To ensure the Arduino and its voltage regulators operate at their best, it is advisable to power it with a 9V supply and ensure the power supply is capable of delivering at least 0.5A.

The instrument uses two separate AC-DC power supplies: a 9V supply for the Arduino and a 5V supply dedicated solely to the four relays. The use of two separate power supplies contributes to the instrument's accuracy and reproducibility, as the continuous operation of the relay switches does not cause electrical interference or fluctuations on the Arduino itself, given that the two power supplies are completely separate, see the 5V in figure e2.

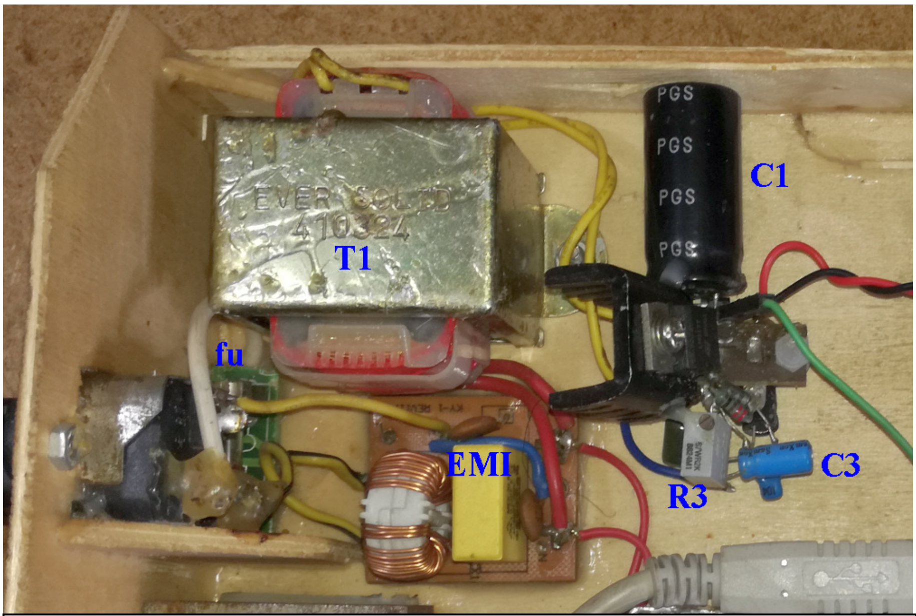


Fig.e2, photo of the 5V power supply: fu = fuse, EMI = filter on 230V, T1 = transformer, C1, C3, R3 = see the description below in the text. All photo, schematics, and component list are here presented under the Open-Source license (Copyright Creative Commons Public license, CC BY-NC-ND 4.0 EN)

The single power supply is built around a classic LM317 chip, which has proven to be reliable and 'quiet' in previous projects by our research group.
The power supply is of the linear, non-switching type, to reduce interference that could compromise the Arduino's reliability.
One trick, which is also described in some datasheets, for ensuring the LM317 operates correctly is to use an output load resistor that draws a current of almost 5mA even when there is no load connected. This ensures both continuous operation and thermal stability, which in turn improves the performance of the LM317. The circuit diagram is shown in fig. e3 .

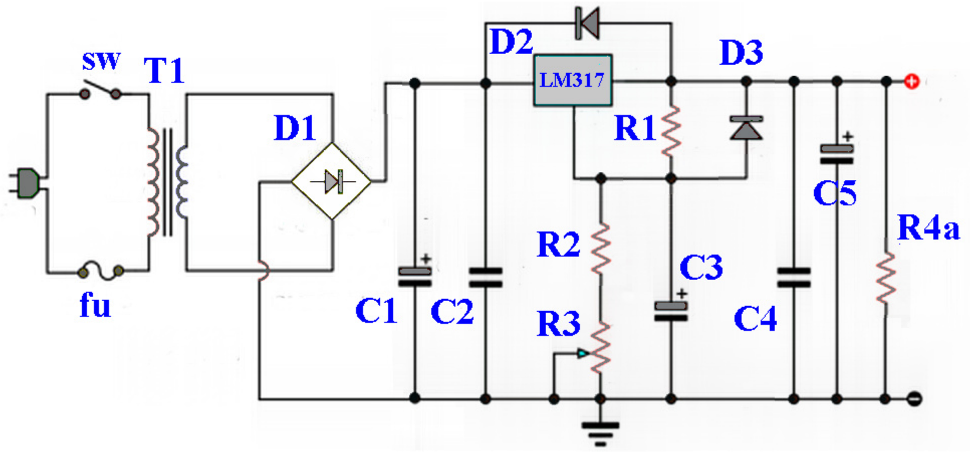


Fig.e3, schematics of the two identical AC-DC power supplies, the 5V one is shown in fig. e2. All photo, schematics, and component list are here presented under the Open-Source license (Copyright Creative Commons Public license, CC BY-NC-ND 4.0 EN)

In above figure e3 we see:
sw = the power switch
fu = the fuse with its insulated fuse holder
T1 = a 230V-12V transformer rated at least 10 VA (e.g. Triad VPP12-800)
D1 = 100V 1A diode bridge (e.g. Diotec B40R)
D2=D3 = 1N4004 diodes
C1 = 2200uF/25V axial capacitor
C2=C4 = 100nF/100V ceramic capacitors (for stability)
C3 = 22 uF/16V capacitor (to reduce output ripple)
C5 = 470uF/16V capacitor
R1 = 220 ohm 1/2W resistor
R2 = 560 ohm 1/2W resistor (to set output from 4 to 10V, or use 510 ohm)
R3 = trimmer resistor 1000 ohm 1/2W (to set output voltage)
R4a = resistor 560 ohm 1/2W, for the 5V output (to draw approximately 10mA from the LM317); for the 9V output a resistor 820 ohm 1/2W is used
LM317 = adjustable positive linear voltage regulator (e.g. TI LM317KCS) with small heatsink

Figure e1 and e2 shows the application of the 3R principles frequently mentioned in the paper; for the two power supplies, all the components were salvaged from old, decommissioned instruments, with only R3 being new.

Measuring the internal resistance of a spent battery

It is not the aim of this paper to describe all the electrical and electrochemical components of a typical battery; a description can be found in one of our previous papers [1].

2 wires measure

To describe the Equivalent Series Resistance (ESR), or internal resistance, the simplified diagram shown in the figure e4 is sufficient.

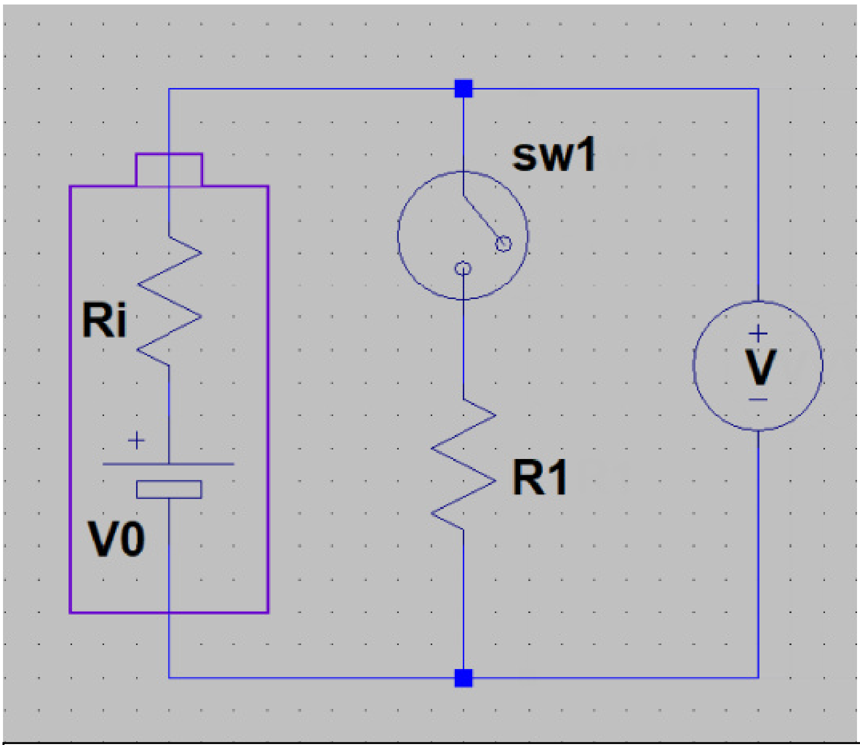


Fig.e4, a standard diagram showing how to measure battery voltage, both at no load and under load

Figure e4 shows the classic 2-wire measurement circuit, we see that V0 is the voltage produced by the electrochemical reaction, Ri is the internal resistance, a virtual quantity resulting from the resistance of the internal electrodes, their polarisation, ionic migration, reaction kinetics and other factors; V+/- is the instrument that measures the voltage across the battery's external electrodes, both when sw1 is open (open-circuit voltage) and when sw1 is closed across R1 (voltage under load).

The Equivalent Series Resistance (ESR), or internal resistance, of an alkaline battery increases significantly as it discharges. A new, fresh alkaline AA battery typically has an internal resistance of 0.1 to 0.3 ohms while a heavily used or nearly dead battery can see this resistance rise to several or tens of ohms.
So we can expect to measure ESR values for new/fresh AA alkaline from 0.15 to 0.3 ohm, for used/partially discharged AA, form 1 to 5 ohm and for dead/depleted AA, from 5 to 20+ ohms (as internal chemistry breaks down).

To measure the voltage, we can only connect the output terminals, not the generator, but with a few tricks, we can also estimate the generator's voltage. Following Lutron, a pH meter manufacturer, states:

The glass electrode used in pH measurement has an exceptionally high internal resistance, ranging from 10Mohm to 1000Mohm due to the thin glass membrane.
If the meter's input impedance were lower, it would draw current from the electrode. Because of the electrode's high resistance, even a tiny current draw would cause a significant voltage drop, leading to massive measurement errors.

High impedance allows the meter to act as an "electrometer," measuring the minute millivolt signals (roughly +/- 400mV) without disrupting the chemical potential being measured.

So, by using a pH meter, we could reduce the current flowing through Ri to such a small value that the voltage drop across it (V = Ri * Ii) would be negligible compared to the value of V0; consequently, by measuring V across the battery terminals, we would obtain a good approximation of V0.
Even with this method, the circuit in figure e4 cannot be used, as the current flowing from the battery to the resistor also ‘passes’ through the voltmeter’s measuring leads. The leads themselves and their contacts may have a resistance of 0.1 ohms, similar to the battery’s Ri.

4 wires measure

We must use the so-called ‘4-wire measurement system’ as shown in the figure e5. Contrary to figure e4, we can see that the voltmeter is directly connected to the battery terminals (via switch SW1 and SW2). Resistors R1 and R2, which have double the resistance value, are connected to the same terminals via switches SW1 and SW2; closing both switches results in a third resistance value.
This 4-wire measurement method is not affected by the resistance of the conductors between the battery and the resistors, the contact resistance of the switches, or other parasitic resistances on the load.

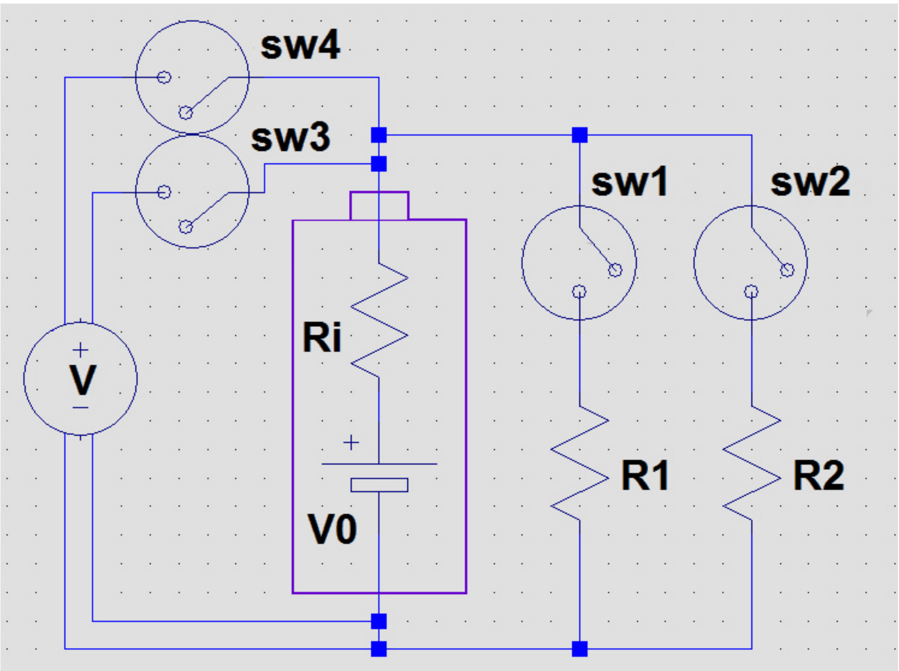


Fig. e5, Circuit used for measuring Ri, 4-wire configuration, the violet battery is the device under test (DUT)

To measure V0, we close switch sw3 and sw4, forming a circuit with Ri in series with the voltmeter’s internal resistance, producing a current Ii=Imeter which, passing through Ri, produces a voltage drop equal to Vi = Ri * Ii.
To reduce contact resistance and wire resistance, the measurement circuit is fully duplicated, as shown in figure e5.
Given this formula, we must use a voltmeter with very high internal impedance, 100 Mohm or 1 Gohm, such as that of a pH meter, to reduce Imeter as much as possible.

We cannot use a true pH meter, which usually measures voltages between +0.5V and –0.5V with an impedance of up to 10Gohm - more than sufficient for measuring pH between 0 and 14 - but not to measure 1.5V of battery.
Instead, we use a single analogue input on the Arduino, which, according to the Atmel datasheet, has an input impedance of 100Mohm at the AD converter.

One issue could be the resolution of the instrument; the Arduino has a 10-bit converter (1024 values) for a 5V input, meaning 5 / 1024 = 4.88mV, which may not be sufficient to measure the variations in an almost new battery.

However, with some hardware and software treaks, we can improve the situation; remember that we expect values of up to 2V for a new battery, perhaps a lithium AA.
The maximum voltage of the converter can be adjusted via an Arduino AREF pin, and it is very easy to obtain three values: 5V, 3.3V and 1.1V. The 3.3V value is the one we are interested in.
The 10-bit resolution can easily be increased by 1 or 2 bits in the presence of some experimental noise using the oversampling and decimation technique presented in our previous paper [1], easily achieving 11 bits, i.e. 2024 values.

Let’s recalculate the resolution: 3.3 / 2048 = 1.46 mV, which is now sufficient for our measurements.

To obtain accurate values, however, we need to plot a calibration curve using an external DC voltage generator, adjustable between 0 and 3.5 V, and a laboratory voltmeter to establish a relationship between the reading on the voltmeter and the output bits from the oversampling circuit.

To simplify matters from now on, let us define V0 as 1.5 V and assuming Ri = 1 ohm with only switch 3 and 4 closed (as shown in figure e5), and with a voltmeter impedance of 100 MΩ, we obtain.

Rtot = 100000 + Ri = 100001
Itot = V / Rtot = 1.5 / 100001 = 1.499985e-5 = 0.00001499985 A = 0.01499985 mA
VRi = Ri * Ii = 1 * 0.00001499985 = 0.00001499985 V = 0.01499985 mV

That is, we find that the voltmeter measures 1.5 - 0.000015 = 1.499985 V, with an accuracy of 99.999% relative to the V0 measurement.

And here is the approximation required for measuring Ri: *we define V with only the sw3 and sw4 closed as the V0 measurement*, a concept that becomes all the more valid as the voltmeter’s internal resistance increases.

With the circuit in figure e5, we define the measurement steps to be programmed in the software (in the sketch) using R1 = 220 ohms and R2 = 100 ohms (and R1//R2 = 70 ohms):

a) With only switch 3 and 4 closed, we measure V0, e.g. 1.5 V
b) We also close switch 1 (R1 = 220 ohm)
c) We measure V1, e.g. 1.4 V
d) We calculate the current IR1, I across R1: I1 = V1 / R1 = 1.4 / 220 = 0.006363636 = 6.36 mA
e) but 0.015 mA also flows through the voltmeter (Imeter) and comes from V0
f) we calculate the current Itot coming from V0 = IR1 + Imeter = 0.006363 + 0.000015 = 0.0063786 A

g) but IR1 is the 99.76% of Itot
h) given the values in g), we simplify the calculations and use Itot = IR1 = IRi
i) from which VRi = V0 - V1 = 1.5 - 1.4 = 0.1V
j) and finally Ri = VRi / IRi = 0.1 / 0.006363 = 15.714 ohms
k) which we can rewrite as (V0 – V1) / (V1 / R1)
l) from all of previous we can estimate the 99.7% of Ri with our measure system

which indicate a very discharged battery; this implies that the switch closure times must be short so as not to completely discharge the DUT; 2 seconds have been chosen as the measurement time.

Given the previous values (V0 - V1), it is clear that to measure an Ri of 0.5 ohms, a voltmeter resolution of approximately 1 mV is required, obtained with AREF and oversampling.

Timing

There are various standards regulating the measurement of Ri, which is a parameter required for the sale of batteries to manufacturers. For lithium batteries, the IEC and ISO standards have been gradually updated to keep pace with technological advancements.

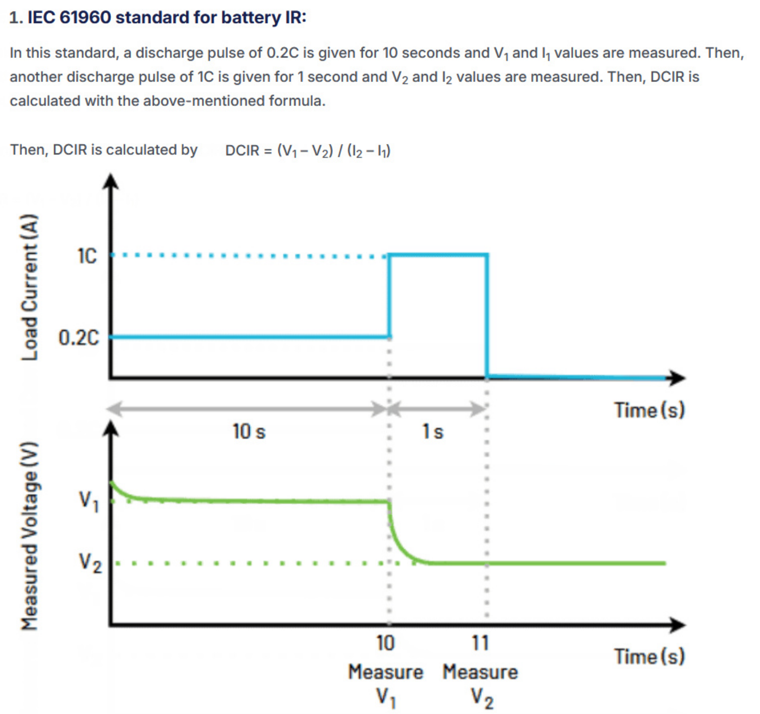


Fig.e6, the description of ESR measure from the Arbin Instrument web site

According to standards, there are two different approaches for measuring internal resistance: DCIR (Direct Current Internal Resistance) and ACIR (Alternating Current Internal Resistance). DC measurement is recommended for used batteries, whilst AC measurement is used to classify batteries for sale or for research purposes.
For DCIR measurement, the old IEC 61960 standard must be followed (which defines C as the battery's capacity in mAh and specifies measurement at 0.1C for 10 seconds and then at 1C for 2 seconds), figure e6.

However, complying with the regulations is difficult. Firstly, the capacity in mAh is not stated on alkaline batteries (usually 1900-2800 mAh for AA alkaline batteries and 600-950 mAh for zinc-carbon batteries), secondly, we cannot discharge an old battery, which might only produce a few tens of mA, at 200 mA for 10 seconds and then at 2000 mA for 1 second, so we select a different measure time.

The literature contains many methods for calculating the DCIR [2], whether accurate or simplified.

To avoid further draining the depleted battery, we have set a 2-second delay after switching off SW3 and SW4 to obtain a stable V reading; SW1 is then switched on and the resulting V is measured after 2 seconds, after all relays immediately opened. After 14 seconds, the procedure is repeated with SW2 switched on, and finally, after a further 14 seconds, it is repeated with both SW1 and SW2 switched on. For the SoC measurement, we then wait 45 seconds.

The Arduino-based device described in our previous paper [1] has been modified to perform 4-wire measurements, and the software has been rewritten to extract the various voltage values after the appropriate time delays as in flow-chart below.

Flow chart of the procedure

Figure e7 shows the flowchart of the Arduino sketch used to measure first the ESR and after the State of Charge. Referring to the circuit in figure e5, with step (1) the DUT is connected to the Arduino (with Zi > 100 MΩ, p. 319 of [22]) to measure initial voltage. In step (2) the DUT is connected to the 220 Ω to measure the first ESR. In step (3) the DUT is connected to the 100 Ω to measure the second ESR. In step (3) the DUT is connected to the parallel of 100 and 220 Ω to measure the third ESR. In step (4), after a long delay, the DUT is connected to the 100 Ω to measure the State of Charge [1]. All obtained values was sent to PC and collected by “serial monitor” of the Arduino IDE, copied to obtain a .txt file.

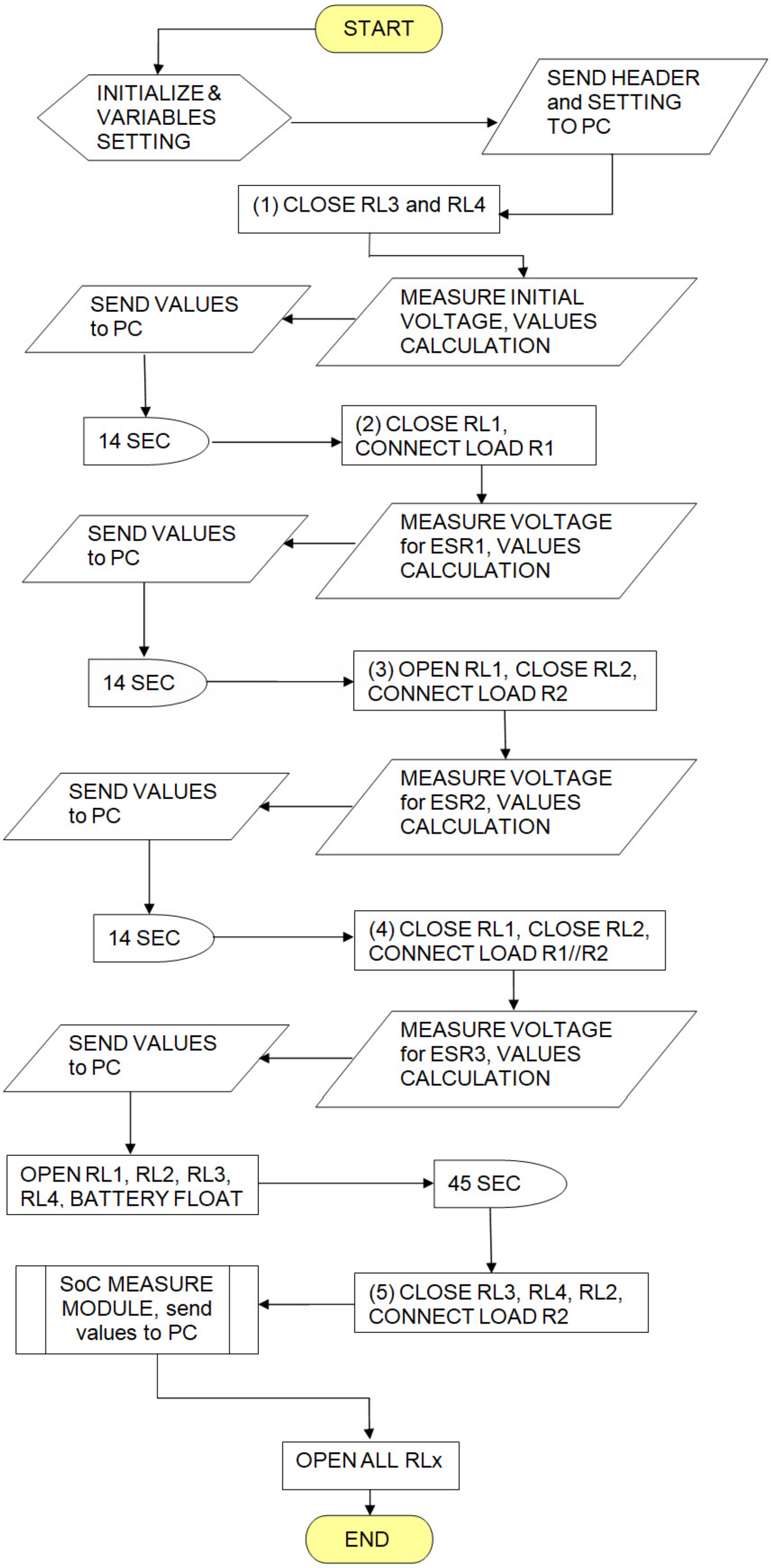


Fig.e7, the flowchart of the ESR and SoC measures, using our instrument of fig.e1

Results

The .txt files containing data copied from the Arduino serial monitor (see, for example, *Energizer-yellow-Test_12-30.txt* in EDF) are then imported into an Excel spreadsheet, the first two sheets of which contain a template for extracting data from the .txt files and generating tables and graphs. The file *Extract-data-battery-ESR-SoC.xls* is included in the EDF.
Within this file, a table is generated showing the battery in each row and the variables in each column, ready for a chemometric analysis.

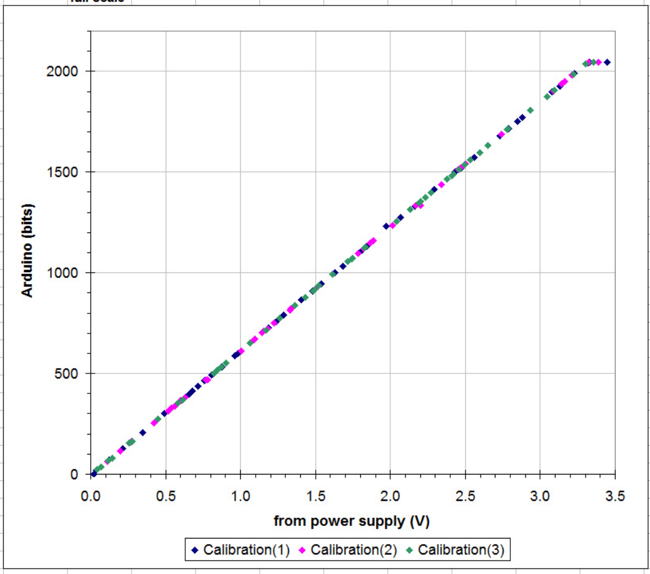
Measure State of Charge and ESR of Used Battery

ALL	Battery			State of Charge (V)						ESR (ohm)				Weight	Duracell
	brand	measure		V measured at 0s			V measured after 10s			Rint. mesured with ohm					BT-168
count	name	date	chemistry	V no load	V with R=1	V after	V no load	SoC with R	V after	ESR onR1	ESR on R2	ESR R1//R	ESR avg (	weight (g)	Pro (V)
1	A-force high power alkaline A 01-34	Mar 25 2026	alkaline	0.2952	0.2034	0.2887	0.2805	0.082	0.2788	450.80	229.80	170.57	283.7216	23.39	0.00
2	A-force high power alkaline B 01-34	Mar 25 2026	alkaline	1.3941	1.3876	1.3925	1.3941	1.3416	1.3941	4.24	4.29	3.68	4.068299	23.32	1.40
3	A-force high power alkaline C 01-34	Mar 25 2026	alkaline	1.3958	1.3892	1.3909	1.3941	1.3449	1.3941	4.24	4.53	3.49	4.08563	23.47	1.40
4	Decathlon onpower alkaline A 7-25	Mar 25 2026	alkaline	0.7922	0.7774	0.6889	0.7873	0.6593	0.6954	6.23	6.15	6.18	6.18878	23.32	0.84
5	Duracell plus A 03-30	Mar 25 2026	alkaline	1.3072	1.2908	1.3023	1.3056	1.2268	1.3039	4.24	4.11	4.19	4.180615	23.50	1.31

In the last two columns, we also reported the battery weight and the voltage measurement taken using the Duracell meter.

Calibration

The apparatus, being and handmade instrument, in figures e1 must be calibrate to obtain an accurate measure of volts and with formulae calculate the internal resistance.
To do this, we varied the supply voltage applied to the battery holder and read the bit values produced by Arduino and the sketch. We used Arduino UNO R3, Atmel MEGA328p SMD, and 11-bit oversampling to read the bits and different laboratory benchtop instruments to apply and read the voltage; specifically, we used two different DC power supplies (HP E3611A, TTi EX354D and three voltmeters (Agilent 34401A, HP 34401A, Philips PM2521) (respectively Hewlett-Packard Company, Loveland, Colorado, U.S.A; Thurlby Thandar Instruments Ltd, Huntingdon, Cambridgeshire, U.K.; Agilent Technologies, Loveland, USA; Philips Industrial & Electro-acoustic Systems Division, Eindhoven, Netherlands).
The figure e8 show the result of the 3 calibration.



	Calibration(1)		Calibration(2)		Calibration(3)
Slope	618.2776	Slope	617.7523	Slope	618.3722
Intercept	-6.55219	Intercept	-6.4008	Intercept	-6.7572
Pearson r	0.999968	Pearson r	0.999971	Pearson r	0.999998
V	bits	V	bits	V	bits
3.3	2034	3.3	2032	3.3	2034

Fig.e8, calibration chart with repeated 3 different measure obtaining a value of 2034 bits for 3.3V in input. Values used inside the sketch to calculate the Soc and ESR.

References

1) G. Visco, M.P. Sammartino, A. Marchetti, M. Castrucci, M. Tomassetti, *Proposal for a Protocol and a Handmade Arduino-Based and Open Source Device for Measuring the Residual Charge of Alkaline Batteries in View of an Attempt to Recharge Them*, Methods Protocols, 9(2), 66, 2026

2) Ying Tian, Qun Wang, Jiaqi Liu, *Analysis of Lithium-Ion Battery through Direct Current Internal Resistance Characteristic*, SAE International Journal of Electrified Vehicles, 12(2), 173-184, 2023