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GHOST

InteGrated and PHysically Optimised Battery System for Plug-in Vehicles Technologies

D4.1 Methodology test, characterization test and electro-thermal battery model report

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Table of Contents

List of Figures

List of Tables

1 Introduction

The aims of the project include the design of a novel and modular battery system with higher gravimetric energy density up to 20% and an increase of the volumetric energy density of the battery system up to 30% in comparison to the market and to the previous pack assembled in the Ecochamps project (5.7 kWh as nominal energy). Moreover, it is proposed to develop a mass-producible innovative and integrated design solution to reduce the battery integration cost at least by 30% through smart design. The design of novel prototyping, manufacturing and dismantling techniques, is aimed to benefit next generation of lithium-ion battery systems.

New test methodologies and procedures are to be evaluated towards reliability, safety and lifetime of different battery systems. The modular battery system should demonstrate ease of process for two target applications (BEV bus with ultrafast partial charge capability and PHEV).

On one hand, a dedicated test methodology will be developed to reflect the battery behaviour as close to the reality. It will be based on different developed techniques:

- The experiences from the standardization organizations regarding batteries
    - such as IEC, ISO, SAE, JAR
- Measured real load profiles of batteries from electric vehicles heavy duty vehicles, covered in WP2
- Characterization techniques
    - such as advanced pulse testing, recently optimized for batteries at VUB.

The latter one is a promising identification technique, which can be used online to determine parameters for advanced battery models and for state of functions estimation.

On a second hand, a needed in-depth cell characterization will be conducted. It will provide a detailed understanding of the short- and medium term behaviour of the battery cells. This characterization will take into account electric and thermal aspects of the cells as well as statistical spread on battery cell behaviour for the development process of the electrical and thermal models in Task 4.4. The electrical and thermal behaviour of the battery cells will be investigated at different and well-selected operating conditions: in particular at different temperature levels, with different current rates and at different values of the state of charge. The models will be validated according to the requirement of Task 4.6.

Finally, a last task will consist in developing a dynamic electric-thermal battery model able to predict, accurately the electrical and thermal responses and behaviours of the battery cell under a wide range of stress conditions.

2 Development of test methodology for characterization of batteries

In the report D2.2, potential cells for designing the battery pack of the PHEV and eBus have been evaluated. Among all candidates, the mentioned LTO cell (Toshiba 23 Ah) meets all requirements for the PHEV, most requirements for the eBus application and some for second use in stationary application. Therefore, the test methodology and characterisation will be focused around this selected cell.

2.1 Cell datasheet

In order to reflect the battery behaviour as close to the reality, a dedicated test methodology is developed based on the LTO 23Ah Toshiba cell. The characteristic of the prismatic LTO-based cell is reported in Table 1, while Figure 1 is a picture depicting the cell.

	Toshiba 23Ah
Material	
Chemistry	LTO
Shape	Prismatic
Voltage	
Nom. Voltage (V)	2.3
End of charging voltage (EOCV V)	2.7
End of discharging voltage (EODV)	1.5
Energy	
Capacity (Ah)	23
Specific Energy (nominal - Wh/kg)	96
Energy Density (nominal - Wh/L)	202
Current DCH	
Continuous rms DCH (A)	93 – 4C
max DCH pulse **10s** (A)	184 - 8C
Current CHA	
Continuous rms CHA (A)	184 – 8C
max CHA pulse **10s** (A)	
max CHA pulse **60s** (A)	
Fast charge max **360s** (A)	184 - 8C
Mechanical	
Weight (kg)	0.550

Volume (L)	0.260
Dimensions LxWxH (mm)	115*22*103
Cost	
Price per piece (€/ piece)	41.2

Table 1. LTO 23AhToshiba cell characteristics

Figure 1. LTO 23Ah Toshiba cell

2.2 Characterisation protocol

One of the main objectives of this test methodology is to secure the development process of the electrical and thermal models in Task 4.4 and lifetime model in Task 4.5. The development process of the battery modelling consists of a series of standard testing procedures used for many years in the automotive industry in order to capture efficiently the electrical and thermal behaviours. Table 2 gives an overview of the available standard testing procedures for specific tests for reviewing the characteristics and performance parameters of lithium ion batteries for BEV and for HEV applications.

Test item	Test	Condition	Pack/System ISO/CD 12405-1/2	Extended	Cell IEC 62660-1	Extended
Pre-conditioning	Cycling	Temperature	25 °C		25 °C	
		Charge	standard charge		Standard Charge	
		Discharge	2C		0.2C	$2I_t$
		# Cycles	5		5	
Energy and capacity	CC discharge	Temperature	−18 °C, 0 °C, 25 °C, 40 °C		−20 °C, 0 °C, 25 °C, 45 °C	
		Charge	standard charge	# I_t-rates until max charge I_t-rate (as $1/3I_t$, $1I_t$, $2I_t$, ...)	standard charge	# I_t-rates until max charge I_t-rate (as $1/3I_t$, $1I_t$, $2I_t$, ...)
		Discharge	1C, 10C, 20C, I_{max}	$1/3I_t$, $2I_t$, $5I_t$	1C, 10C, 20C, I_{max}	$1/3I_t$, $2I_t$, $5I_t$
		# cycles	2		2	
Power and resistance	Pulse charge/ discharge	Temperature	−18 °C, 0 °C, 25 °C, 40 °C		−20 °C, 0 °C, 25 °C, 45 °C	40 °C instead of 45 °C
		Discharge	I_{max}, dis	$1/3I_t$, $2I_t$, $5I_t$, $10I_t$	0.2C, 1C, 5C, 10C	$1/3I_t$, $2I_t$, I_{max}
		Duration	0.1 s, 2 s, 10 s, 18 s		10 s	
		Charge	$0.75*I_{max}$, dis	$1/3I_t$, $2I_t$, $5I_t$, $10I_t$, I_{max}	1/3C, 1C, 5C, 10C	$2I_t$, I_{max}
		Duration	0.1 s, 2 s, 10 s		10s	
		SoC	80%, 65%, 50%, 35%, 20%		50%	80%, 65%, 35%, 20%
Energy efficiency	Pulse charge/ discharge	Temperature	0 °C, 25 °C, 40 °C	−18 °C	−20 °C, 0 °C, 25 °C, 45 °C	40 °C instead of 45 °C
		Discharge	See sequence in Table 4	$1/3I_t$, $1I_t$, $2I_t$, $5I_t$, $10I_t$, I_{max}	1/3C, 1C, 5C, 10C	$2I_t$, I_{max}
		Duration		10s	10s	
		Charge	See sequence in Table 4	$1/3I_t$, $1I_t$, $2I_t$, $5I_t$, $10I_t$, I_{max}	1/3C, 1C, 5C, 10C	$2I_t$, I_{max}
		Duration		10 s	10 s	
		SoC	65%, 50%, 35%	80%, 20%	50%	80%, 65%, 35%, 20%

Table 2. Overview of the defined tests in the standard ISO/CD 12405 ½ and IEC 62660-1

2.3 Electrical characterisation

The electrical characterization of the cells is performed by implementing a characterization testing scheme derived from Table 2 and composed of the following subsequent characterisation tests:

- Pre-conditioning
- Discharge Capacity test
- HPPC test
- OCV test
- Validation test
- EIS test

Almost all of the tests will be conducted at different temperatures in order to have a wide range of mobility for the model. The testing temperatures are selected in order to have different conditions and

to represent the cell in extreme environmental conditions. A set of 3 cells for each temperature will be characterized for accuracy, performing different tests at:

- 0°C and 10°C for low temperature environment
- 25°C for ambient temperature environment
- 35°C and 45°C for high temperature environment
- Extreme low-temperature (-15°C) will be also investigated if timing allows it.

Then, while performing the second-life evaluation for stationary application, this set of tests will be redone on aged cells at 25°C.

The next sub-sections are dedicated to the description of each of these listed tests.

2.3.1 Pre-conditioning

The pre-conditioning test consists of a number of discharge and charge cycles of the battery to prepare the battery (initiating Lithium/electron flow) for future testing procedures. Additionally, through this test the first initial capacity value of the battery is calculated. The test is performed at controlled ambient temperature (25°C) and starts with a status check of the battery, continuing with a standard charge at constant current followed constant voltage phases (CCCV) and discharge with constant current (CC). It continues by charging and discharging for 3 times in a row. The C-rates (or It) are a compromising value between time and degradation. Each time a discharge or charge is finished, a 3h pause is implemented. The pre-conditioning test is described below:

Pre-con Test			
Step	**Action**	**C-Rate**	**Limit**
		LTO	
1	Tempering		3h
2	Standard charge	1C	> EOCV <0.05 C-Rate
3	Pause		3h
4	Discharge	1C	EODV
5	Pause		3h
Steps 1-5 are repeated 3 times			

Table 3. Preconditioning test sequence

2.3.2 Discharge capacity test

The objective of this test is fairly straightforward. The discharged cell capacity expressed in Ah at different discharge C-rates (or It) and temperatures are obtained from the test results. Basically, it consists of performing full charges and discharges at different C-rates to obtain stable capacity measurements. This test is an important step as this capacity value is the reference value used for the other tests composing the characterization testing procedures. In addition, the C-rates chosen in this test are also used in the next tests.

The "Discharge Capacity test" is conceptually described below:

Capacity Test			
Step	**Action**	**C-Rate**	**Limit**
		LTO	
1	Tempering	T = 0°C, 10°C, 25°C, 35°C and 45°C	3h
2	Standard charge	1C	> EOCV <0.05 C-Rate
3	Pause		30 min
4	Discharge	C/3; C/2;1C; 2C; 4C, 8C	EODV
5	Pause		30 min

Steps 1-5 are repeated for each T.

Table 4. Discharge capacity test procedure

2.3.3 OCV vs SoC test procedure

In order to determine the relation between the open circuit voltage (OCV) and the state of charge (SoC) of the battery, the OCV-test is performed according to the description given here below.

The test profile consists of a complete charge following by a complete discharge of the cell in steps of 5% between 100% and 0% SoC window of the available discharge capacity of the battery at 1C. The capacity related with this C-rate will be already available from the calculation during the "Discharge Capacity Test" at the 1C discharge pulse for each temperature. After each step, a relaxation period of 3h has been implemented, as it can appear as a long but necessary rest time for relaxation. The OCV value at that specific SoC levels is then defined as the voltage at the end of the 3h-relaxation period. Then, the battery is completely discharged and a series of charge pulses is applied in order to have the discharging and charging OCV behaviours. The voltages during each rest period are recorded to establish the cell's OCV behaviour. From these data, OCV against SOC values can be estimated by straight-line interpolation or by curve fitting through the measured data points. Based on the obtained OCV values, a look-up table can be generated for the prediction of the OCV in function of the battery SoC for future battery models.

Additionally, by performing this procedure during both discharging and charging, the entropic changes for the reversible heat generation can be investigated. [1].

OCVvsSOC			
Step	Action	C-Rate	Limit
		LTO	
1	Tempering	T = 0°C, 10°C, 25°C, 35ºC and 45°C	3h
2	Standard charge	1C	> EOCV <0.05C-Rate
3	Pause	3 hours	
4	Discharge	1C	ΔDOD = 5%
5	Pause	3 hours	
6	Standard discharge	1C	> EODV
7	Pause	3 hours	
8	Charge	1C	ΔDOD = 5%
9	Pause	3 hours	
For each T, repeat steps 4 - 5 until EODV and 8-9 until EOCV for each temperature			

Table 5. OCVvsSOC test procedure

2.3.4 qOCV vs SoC test procedure

In complement to the OCV vs SOC test, quasi-OCV test is performed. The idea of this test is to measure the voltage against the SoC under very low current in order to get a voltage response close to the OCV values. The test profile consists of a standard full charge following by a complete discharge and charge of the cell at the C/25 C-rate.

The OCV test procedure is conceptually described in the table below:

Quasi-OCV Vs SOC			
Step	Action	C-Rate	Limit
		LTO	
1	Tempering	T = 0°C, 10°C, 25°C, 35ºC and 45°C	3h
2	Standard charge	1C	> EOCV <0.05*C-Rate
3	Pause		30 min
4	DCH	C/25	EODV
5	Pause		3 Hours
6	CHA	C/25	EOCV
7	Pause		30 min

Table 6. Quasi-OCV Vs SOC test procedure

2.3.5 HPPC test procedure

The hybrid pulse power characterization (HPPC) test is intended to measure the battery impedance using a test profile that incorporates both discharge and charge pulses, as shown in Figure 2. The primary objective of this test is to establish the DC internal resistance of the three tested cells. The internal resistance is responsible for the irreversible heat generation and a measurable degradation is expected that increases its value at every SoC and C-rate. Hence, as a function of the SoC, of the current rate, and of the temperature, the internal DC resistance is determined on a large range of SoC points, currents, and temperatures.

The idea of this test is to apply a 10-second discharge-pulse and 10-second charge-pulse power capabilities at each given SoC and for different C-rates. A 600s-rest period is scheduled between each HPPC pulse. From the result data, an algorithm will afterwards determine the DC internal resistance of the cell.

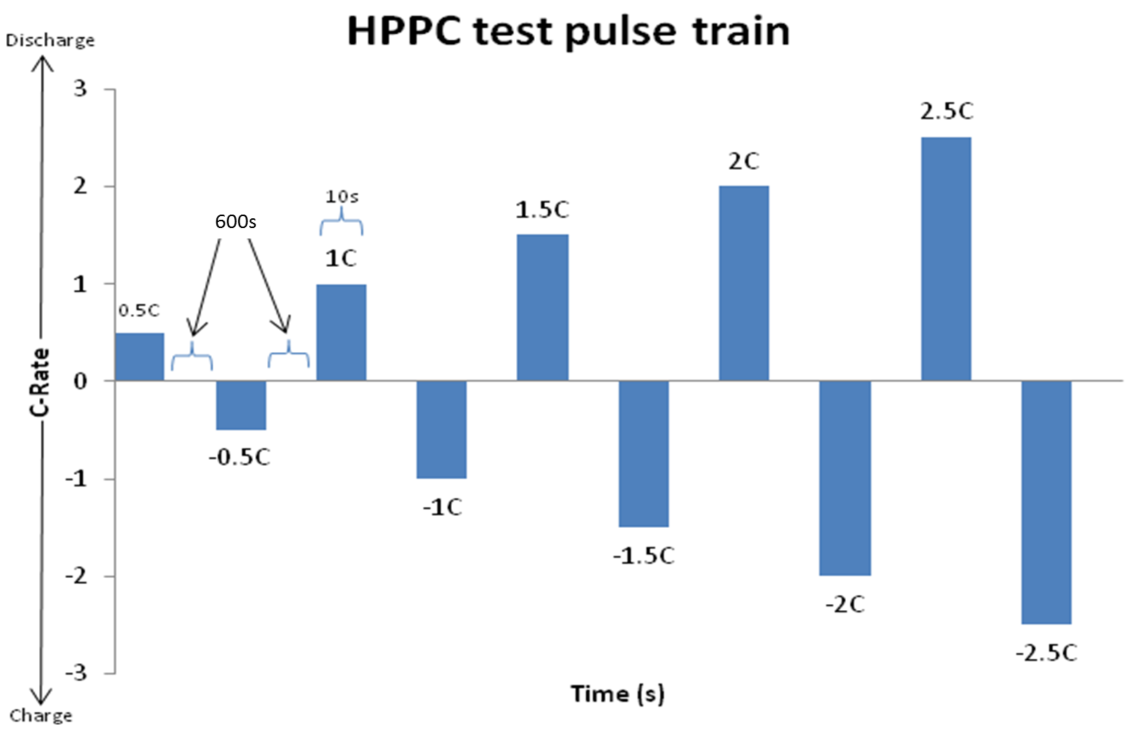

Figure 2. Example of a HPPC pulse train

The HPPC test procedure is conceptually described in the table below:

HPPC Test			
Step	**Action**	**C-Rate**	**Limit**
		LTO	
1	Tempering	T = 0°C, 10°C, 25°C and 45°C	3h
2	Standard charge	1C	> EOCV <0.05 C-Rate
3	Pause		3 h
4	Discharge	1C	ΔDOD = 5%
5	Pause		3 h
6	HPPC (see below)		

HPPC		
Time (s)	Acc T (s)	**LTO**
10	10	C/3
600	610	PAUSE
10	620	- C/3
600	1220	PAUSE
10	1230	C/2
600	1830	PAUSE
10	1840	- C/2
600	2440	PAUSE
10	2450	1C
600	3050	PAUSE
10	3060	- 1C
600	3660	PAUSE
10	3670	2C
600	4270	PAUSE
10	4280	- 2C
600	4880	PAUSE
10	4890	4C
600	5490	PAUSE
10	5500	- 4C
600	6100	PAUSE
10	6110	8C
600	6710	PAUSE
10	6720	- 8C
600	7320	PAUSE

Repeat steps 3 - 6 until DoD 90%

Table 7. HPPC test procedure

2.3.6 Validation tests

In order to correctly validate the electrical models created based on the parameters acquired from the different characterization tests, some independent validation tests are additionally performed. These tests can be used to compare the output of the model with the voltage response of the cell.

The worldwide harmonised light vehicles (WLTC) test procedure has been selected in order to perform the validation of the electrical model. During the 1990s, the emergence of electric road vehicles powered by alkaline batteries pushed the development of suitable test procedures and standards. Conventional constant current discharge tests, as were defined for lead-acid batteries, did not reflect the actual use pattern of the batteries in electric vehicles. The WLTC test procedure used for electrical validation is based on the WLTC driving cycle that was developed in collaboration of the EU, Japan and India under the guideline of UNECE World Forum for Harmonization of Vehicle Regulations. In the framework of GHOST and Task 4.1, a current load profile representing a high-power application has been derived based on the WLTC driving profile as shown by Figure 3. This profile is meant for the PHEV case

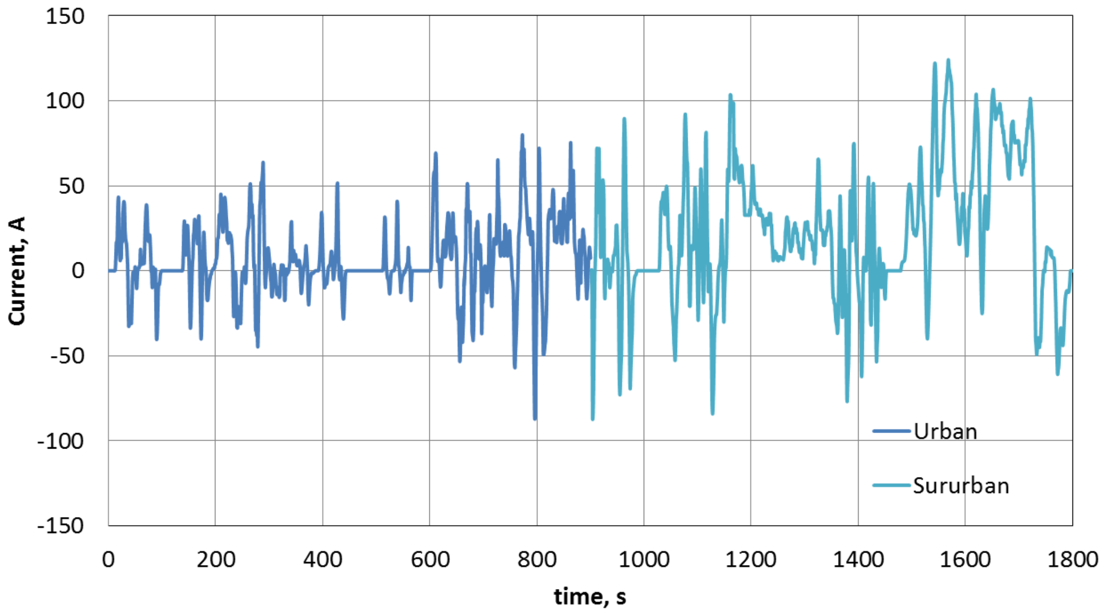

Figure 3. WLTC driving profile

The WLTC validation consists of standard charge procedure followed by the continuous repetition of WLTC current load profile as shown by the example in Figure 4.

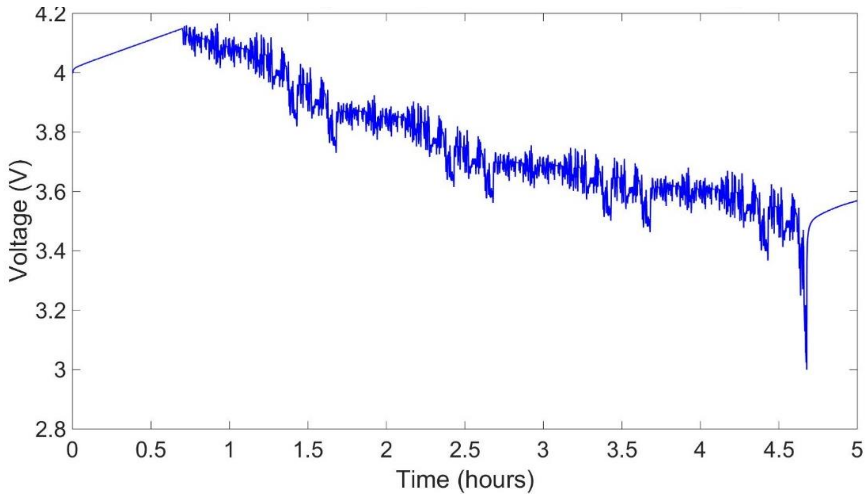

Figure 4. WLTC profile with repetition for a sample cell at 25 degrees

Electrical validation Test			
Step	**Action**	**C-Rate**	**Limit**
		LTO	
1	Tempering	T = 0°C, 10°C, 25°C, 35ºC and 45°C	3h
2	Standard charge	1C	> EOCV <0.05 C-Rate
3	Pause		30 min
4	DCH	1C	ΔDOD = 5% to 90%SoC
5	Pause		30 min
6	Cycle	WLTC	From 90%SoC to 10%SoC
7	Pause		30 min
Steps 2-7 are repeated three times for accuracy and for each T			

Table 8. Electrical validation test procedure

2.3.7 EIS tests

The purpose of the EIS tests is to build a comprehensive database which can be used in order to derive reliable temperature estimation methods form the measurement of the cell AC impedance. Nevertheless low frequency points of the spectrum will also be collected for SOH studies. The estimation techniques should cover the following aspects

- Different charge/discharge current rates, relaxation
- Different temperature imposed from outside
- Temperature transients due to self- heating in charge/discharge
- Different SOC levels
- Ageing of the cell (tracking of the estimation method along the cycles)
- Different cell samples

The selected cells do not allow direct sensing of the internal temperature. Temperature sensors will be placed on the cell surface. The location of the thermocouple is discussed in the next section.

The figure below shows the test sequence that will be implemented in order to create the database.

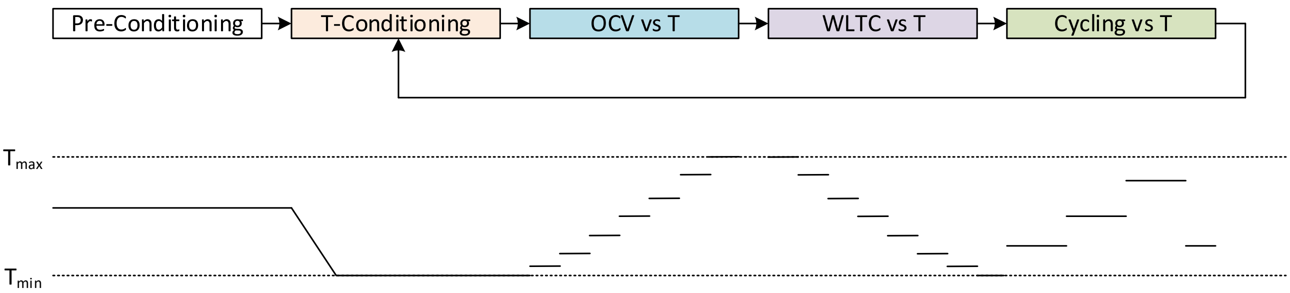

Figure 5. Measurement sequence for EIS

A set of new cells (8) are first pre-conditioned as in 2.3.1. Then the following test sequence is repeated:

- OCV test – as described in 2.3.3. The same temperature range will be used: 0, 10°C, 25°C, 35°C, and 45°C. Full spectrums are collected during the measurement .During charge and discharge the spectra are collected continuously. During relaxation periods every 10 minutes.
- Checkpoint 1 – collected data is checked in order to find a target temperature estimation method
- Driving Test WLTC as in 2.3.6. In this case the charge/discharge current cannot exceed the 100A due to the limitation of the IFAT lab equipment. Depending on the estimation method selected, a reduced number of frequency point (max 4) is continuously measured.
- Checkpoint 2 – the data is analysed and the estimation method is checked against the measured temperature. If needed the Driving test is repeated on different frequency points.
- Cycling – the purpose of the Cycling tests is to age the cells. Cycling is performed until the targeted total number of cycle is reached (targeted total number of cycles is defined to be 100 for D4.1, for cycling over a higher number of cycles – for aging considerations - it is

referred to D4.2). The basic cycle is the pre-conditioning cycle of 2.3.1. The temperature is set to 0°, 25° 35°C 45°C. The discharge cycle is run at 0.5C/ 1C / 2 C before the temperature is changed (roughly 30 cycles per temperature). The cycling stops as soon as the target number of cycle for the cells is reached.

The table below add to the description of the previous tests (2.3.1, 2.3.3, 2.3.6), the description of the additional EIS tests, in terms of frequency range and time interval. The excitation current amplitude will be within -100mA and -500mA average.

EIS test				
Step	**Test type**	**Action**	**Frequency steps**	**Repititions**
1	OCV vs. SOC	Tempering Standard	whole spectrum (1Hz - 5kHz)	10min
2	OCV vs. SOC	Charge	whole spectrum (1Hz - 5kHz)	continuously
3	OCV vs. SOC	Pause Standard	whole spectrum (1Hz - 5kHz)	10min
4	OCV vs. SOC	Discharge	whole spectrum (1Hz - 5kHz)	continuously
5	OCV vs. SOC	Discharge	whole spectrum (1Hz - 5kHz)	continuously
6	OCV vs. SOC	Charge	whole spectrum (1Hz - 5kHz)	continuously
7	WLTC vs. T	Tempering Standard	whole spectrum (1Hz - 5kHz)	10min
8	WLTC vs. T	Charge	max. 4 frequency points	continuously
9	WLTC vs. T	Pause	whole spectrum (1Hz - 5kHz)	10min
10	WLTC vs. T	Discharge	max. 4 frequency points	continuously
11	WLTC vs. T	Cycle	max. 4 frequency points	continuously
12	Cycling	Tempering Standard	whole spectrum (1Hz - 5kHz)	10min
13	Cycling	Charge	max. 4 frequency points	continuously
14	Cycling	Pause	whole spectrum (1Hz - 5kHz)	10min
15	Cycling	Discharge	max. 4 frequency points	continuously

Table 9, EIS test protocol

2.4 Thermal characterisation

The thermal characterization of the cells are performed by implementing a characterization testing scheme derived from Table 2 and composed of the following subsequent characterisation tests:

- Thermal heat capacity test
- Thermal conductivity test
- OCV thermal test
- Validation test

The next sub-sections are dedicated to the description of each of these listed tests.

2.4.1 Temperature measurement

For every test, a maximal allowable temperature is defined to prevent gassing and critical failure of the cell resulting from overheating and thermal runaway. Also, the evolution of the temperature is an important parameter for designing a thermal model. Thus, it is necessary to have a reliable way of measuring battery temperature.

Because with the test equipment available, only one point of the battery can be measured for temperature, this point has to be carefully chosen. To select the right temperature point, IR images of the cell will be captured by a Ti25 thermal imager (FLUKE®, Everett, WA, USA) at regular time intervals during a high-current discharge capacity test (4C or 92A). The IR thermography will show the highest temperature point of the cell for which the thermocouple will be place.

2.4.2 Thermal heat capacity test

Adiabatic calorimetry will be used as the method for the heat capacity measurements. This method consists of heating one cell with a known amount of power supplied by a planar resistance placed between them in an adiabatic environment provided by an accelerating rate calorimeter. This value is responsible of the heat accumulation inside the cell, but it is not expected any big variation of its value due to ageing or SoC changes.

The heat capacity test consists of performing different external heating tests in order to evaluate the temperature increase of the cells when no heat is lost to the surrounding area. All the supplied heat is ideally accumulated in the cell's body. By knowing the mass of the cells and the voltage and current supplied to the heater, the heat capacity value can be calculated at any temperature or over any temperature range as:

$$C_p = \frac{Q}{m\Delta T} \quad (1)$$

where C_p is the specific heat capacity (kJ/kg.K), Q the heat generation rate (W), m the mass of the cell (m) and ΔT the temperature difference.

2.4.3 Thermal heat conductivity assessment

Most of the reported methods of thermal conductivity characterization are generally extensive, cost-intensive and cell destructive. Therefore, the conductivity coefficients will be directly obtained from a parameter estimation technique for which the experimental and simulation results will be compared. Then, through an iterative methodology it will find the most appropriate value to match the experimental and simulation results and gives a good estimate of the parameters. Nonetheless, the values will be compared to the ones that Toshiba; the manufacturer; provided for which a picture is shown in Figure 6.

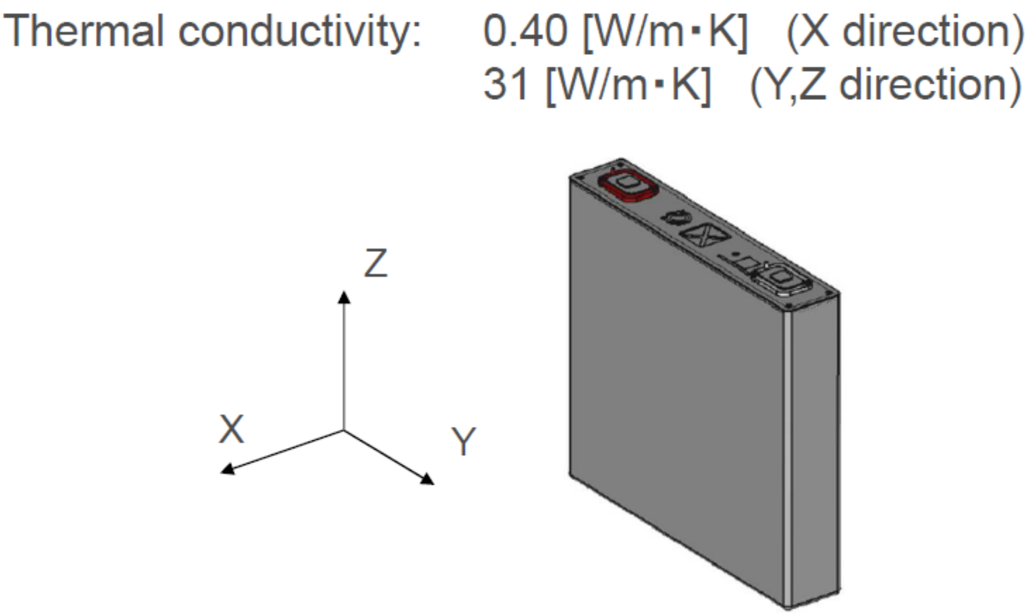

Figure 6. LTO 23Ah Toshiba conductivity coefficients

2.4.4 OCV thermal test

In order to determine the variation of the entropic heat coefficient with the SOC, the OCV measurements will be performed over the whole SOC interval by considering a 10% SOC resolution (10%:10%:90%). An example of the thermal cycle used during the test is shown in Figure 7. Basically it consists on performing OCV measurements at different temperatures to see their derivative relation at different SOC levels. The SOC level is changed with a 10% of variation due to the very non-linear nature of the variable. Then the thermal cycle is performed to obtain reliable mean variation of the OCV with the temperature steps.

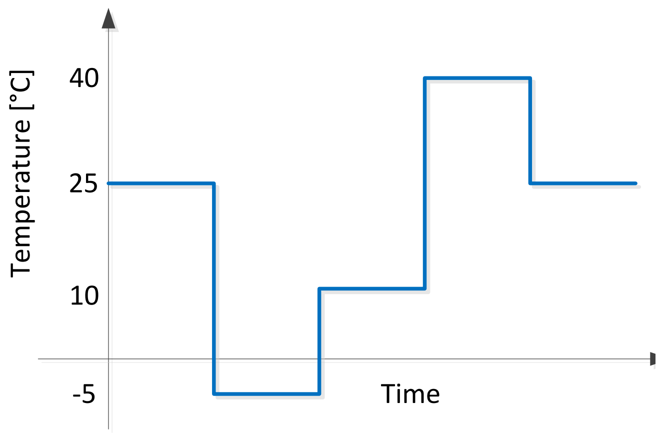

Figure 7. Example of a thermal cycle.

The voltage will be recorded during each of the tests at different SOCs. The entropy coefficient at each SoC, is given by the slope dU^{avg}/dT =A where V = f(T)=A T+B with V in [V] and T in [K]. After that the $dU^{avg}/dT=g(SoC)$ will be obtained.

For comparison, the OCV measurements performed for the electrical characterisation will be used.

2.4.5 Validation tests

In order to correctly validate the thermal models created based on the parameters acquired from the different characterization tests, two independent types of validation tests are additionally performed: the constant current and dynamic current test. These tests can be used to compare the output of the model with the temperature response of the cell.

The constant current validation test consist of discharging and charging profiles at high C-rates and 100% SOC levels will be performed using the cells. To ensure the maximum heat generation, a discharging current of 4C (92A) will be applied.

The dynamic validation consists of using the same Driving Test WLTC as for the electrical characterisation.

Thermal validation test			
Step	Action	C-Rate	Limit
		LTO	
1	Tempering	T = 0°C, 10°C, 25°C and 45°C	3h
2	Standard charge	1C	> EOCV <0.05 C-Rate
3	Pause		30 min
4	DCH	4C / dynamic profile	to 0%SoC
5	Pause		30 min
Steps 2-5 are repeated three times for accuracy			

Table 9. Thermal validation test procedure

22

2.5 Text matrix for electro-thermal characterisation

A summary of the testing procedure can be found in the test matrix reported below:

Electrothermal matrix					
Temperature (°C)	45				
Type of test	Capacity	OCV	qOCV	HPPC	Validation test
Number of cells	4				
Temperature (°C)	35				
Type of test	Capacity	OCV	qOCV	HPPC	Validation test
Number of cells	4				
Temperature (°C)	25				
Type of test	Capacity	OCV	qOCV	HPPC	Validation test
Number of cells	4				
Temperature (°C)	10				
Type of test	Capacity	OCV	qOCV	HPPC	Validation test
Number of cells	4				
Temperature (°C)	0				
Type of test	Capacity	OCV	qOCV	HPPC	Validation test
Number of cells	4				
Total cells	10				

Legend	
Capacity	Multiple capacity tests done at different c-rates (typically 2C, 1C C/2, C/3, C/5)
HPPC	Hybrid pulse power characterisation for internal resistance assessment
OCV	Open circuit voltage for open voltage assessment
qOCV	quasi-Open circuit voltage for SOC and OCV relationship
Validation test	Dynamic test to validate the electrical model / high current tests to validation the thermal model

Table 10. Text matrix for electro-thermal characterisation

2.6 Ageing characterisation

The ageing characterisation of the LTO will be explained in more details in the D 4.2 Ageing (calendar and cycling) analysis and lifetime model report. Nonetheless, since all the three aspects (thermal, electrical and ageing) are linked, the ageing test matrix and the common points will be briefly discussed.

In order to characterize the lifetime behaviour of the LTO cell, a large test-matrix including various combinations of cycling temperatures, DoD-levels and charge and discharge current rates is developed and each test condition will be carried out on at least 3 cells. An overview of this test-matrix is given in Table 11 where the numbers indicate the amount of cells subjected to each cycling condition. All different conditions and specific testing will be fully detailed in D4.2 but a short remark can be done.

Regarding the influence of the charging – discharging current on the lifetime of the cell, the minimum and maximum c-rate conditions should match the boundaries of the electrical characterisation, otherwise, discrepancies might happen and temper with the efficiency of the model. This means that the lifetime model should be based on those limits.

Moreover, in order to have a more representative lifetime behaviour aspect, a condition for which 8C (184A) has been identified as important for the project.

Cycling Matrix

DOD			100			60			40			20			
Mid-SOC			80	50	20	80	50	20	80	50	20	80	50	20	
Temperature (°C)	Charge (C-rate)	Discharge (C-rate)													Total cells
0	1C			3											3
10	1C			3			3						3		9
25	1C	1C		3			3		3	3	3	3	3	3	24
	1C	2C		3											3
	2C	2C		3											3
	4C	1C		3											3
	8C	1C		3											3
35	1C	1C		3											3
45	1C			3			3					3			9
Total cells				27			9		3	3	3	6	6	3	60

Total cells	90

Legend

(yellow)	100/50 1C 1C is the base case, shared for all temperatures so we can calculate temperature influence
(light grey)	Simulating "Cold start", load cycles at high mid-SOC
(light green)	Simulating cold environnement, load cycles at 10°C.
(grey-blue)	Influence of discharge and charging current rate, only at 25 deg
(brown)	Baseline of tests, this will provide the influence of DOD and Mid-SOC, which we will transform to different temperatures, using the base case
(green)	Effect of Fast-Charging (one 100% charge, one partial charge)
(blue)	High-temperature cycling, both high and medium-depth

Calendar matrix

Storage-SOC	100	80
Temperature (°C)		
10		3
25	3	3
45		3
Total cells	3	9

Legend

(orange)	High-SOC storag
(blue)	Base-case for c
(yellow)	I

Table 11. Overview of the ageing test matrix.

3 Electro-thermal characterization results of LTO cells

A set of 10 cells has been characterized performing different tests described in the section earlier. In this section, the electrical and thermal results are presented.

3.1 Results from standard data collection for electrical modelling

3.1.1 Results from the discharge capacity test

This data from the discharge capacity test is processed and the Peukert values at different temperatures are calculated. A first electrical characterization test is the “discharge capacity test”. In this test the discharge capacity is determined at different values of the current rates. This test allows evaluating the G1 cell performance at different current rates. An example of these results can be seen in the Figure 8.

From this figure, the typical behaviour of the battery cell that has a decreasing capacity value with increasing discharge current rate can be seen. Another result from this graph is the behaviour of the G1 cell at different temperature levels. One can state that the cells have a better capacity value for higher temperature values. Further, this graph also shows the variability of the different cells. The variability clearly increases with rising discharge current rate as well as with decreasing temperature.

Figure 8. Discharge capacity evolution at different temperatures and different C-rates of the G1 cell

Figure 9 shows the energy density calculated from the discharge capacity tests.

Figure 9. Energy density evolution as a function of current and temperature

The capacity values are shown in at Table 12 at different C-rates and temperature values.

Table **12**. Capacity values at various temperatures and C-rates

3.1.2 Results from the OCV test

The OCV tests were performed by normal method as mentioned in the previous section. The normal characterisation at 25 ˚C for one of the cell is shown in Figure 10. It can be seen that the values at low and high SoC in the OCV characterisation reflect clearly the non-linear voltage evolution. The values can be used for the electrical model for the battery voltage equation.

Figure 10. OCV test results for one of the cells at 25°C

3.1.3 Results from the qOCV test

The qOCV tests were performed by normal method as mentioned in the previous section. The normal characterisation at 25 ˚C for one of the cell is shown in Figure 10. It can be seen from the comparison with the normal OCV test that the values are pretty similar.

Figure 11. qOCV test results for one of the cells at 25°C

3.1.4 Results from the HPPC test

The next set of figures show the internal resistances for the cell as a function of SOC and temperature rates separately for charge and discharge pulses.

The discharge resistances are higher at lower SoC levels and the resistances decrease with increase in SoC level. The resistances are lower at low temperatures due to sluggish electrochemical reactions in cold weather. The resistances during discharge show similar trends, where lower SoC levels show maximum resistance.

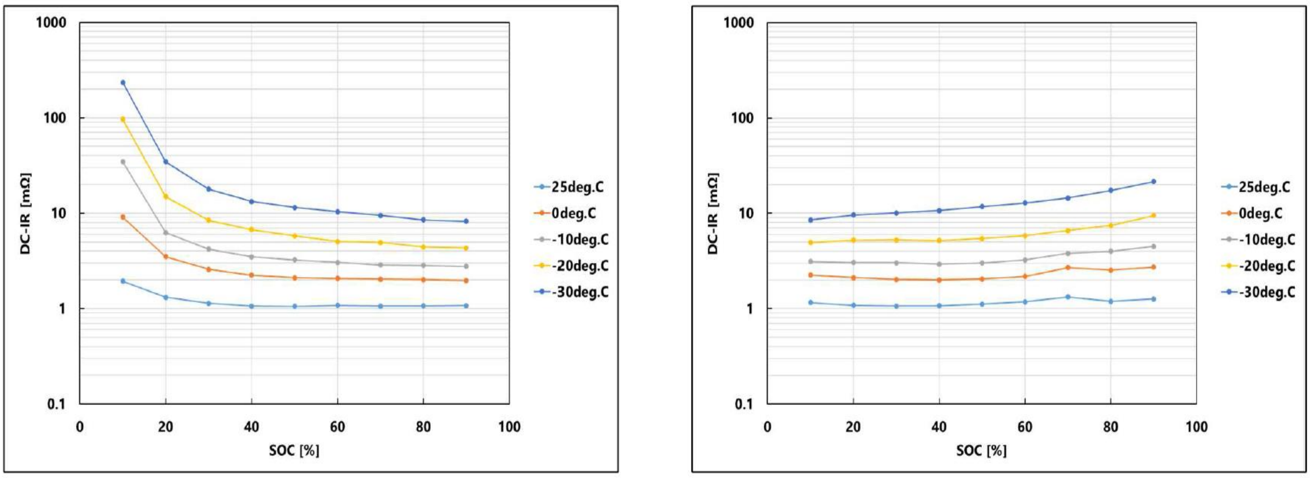

Figure 12. Internal resistance as a function of charging state, temperature and state of charge

3.1.5 Results from the validation tests

The WLTC profile used for validation is presented in Figure 13. The measured cell voltage response during this test will be compared to the simulated voltage of the cell in the next section for validation purpose for the case of 25ºC ambient temperature.

Figure 13. WLTC profile as function of temperature

3.1.6 Results from the EIS tests

3.2 Results from standard data collection for thermal modelling

3.2.1 Results from the heat capacity test

In Figure 14 the temperature rise in time of a pack comprised of cells with the same SOC level and an active planar resistance in between is shown. The mass of each cell is approximately of 417 gr. and the power supplied by the resistance is merely of 1.8 W. Different power values have been tried to obtain reliable mean values at different SOCs.

Figure 14. Results for standard heat capacity test

3.2.2 Results from the heat capacity test

In Figure 15 the temperature rise in time of a pack comprised of cells with the same SOC level and an active planar resistance in between is shown

=

Figure 15. Results for standard heat conductivity test

3.2.3 Results from the OCV thermal test capacity test

In Figure 16, the entropy variation due to the thermal cycle can be observed for the different SOC points of a G1 cell. After each temperature change a long time period of stabilization is maintained in order to obtain more data to adjust later in the evaluation of the entropic heat coefficient value for that SOC. OCV changes during the test due to temperature variation (main steps) and due to electric relaxation (secondary slope).

Figure 16. Results for the entropy

3.2.4 Results from the validation tests

The high-current profile used for validation is presented in Figure 13. The measured cell temperature response during this test will be compared to the simulated temperature of the cell in the next section for validation purpose for the case of 25ºC ambient temperature.

Figure 17. WLTC profile as function of temperature

4 Electro-thermal modelling of LTO cells

4.1 Description of the used methodology

4.2 Development of the electrical model

4.2.1 Description of the electrical model

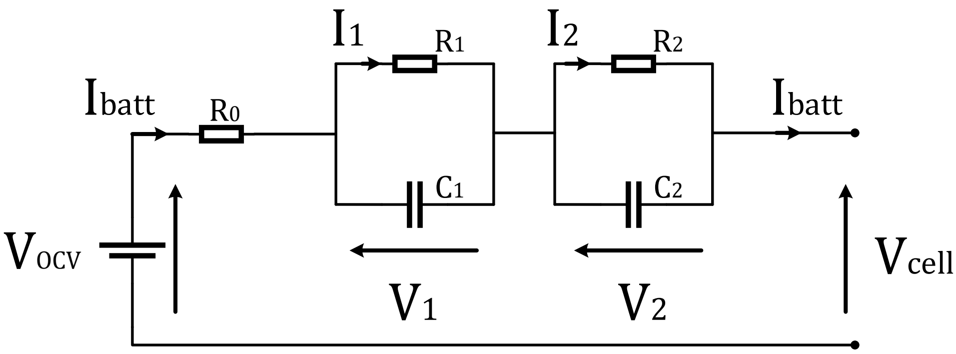

Figure 18: representation of the 2nd-order Thévenin model.

4.2.2 Results of the characterisation for electrical modelling

Figure 19 to Figure 23 show the electrical parameters for the 2nd order model (see next section) extracted from the HPPC test for one cell, tested at 25 degrees. The figures show the resistances and time constant for the cell as a function of SOC and current rates separately for charge and discharge pulses.

Figure 19. Ohmic resistance as a function of current rate and state of charge

Figure 20. Polarization resistance as a function of current rate and state of charge

Figure 21. Polarization resistance 2 as a function of current rate and state of charge

Figure 22. Time-constant as a function of current rate and state of charge

Figure 23. Time-constant 2 as a function of current rate and state of charge

The parameters are extracted and collected into organized lookup tables which are a function of the state of charge, cell temperature and C-rate.

4.2.3 Results of the validation for electrical modelling

4.3 Development of the 1D-thermal model

4.3.1 Description of the 1D-thermal model

$$\frac{dU}{dt} = Q_{gen} - Q_{loss} \text{ (2)}$$

The heat generation is then calculated from the resistance of the cell:

$$Q_{gen} = R_{th}.I^2 \text{(3)}$$

with Q_{gen} the heat generation (W) and I the battery current (A). It was chosen that the resistance would be non-dynamic for simplifications. The value was taken from the datasheet of Toshiba and Kokam: 0.5 m mΩ and 1.2 mΩ, respectively. In this context, we assume the charging resistance is equals to the discharging resistance, and the simulation results reflect both states. Moreover, to estimate the temperature, it was proposed to simulate the system in a transient state, for which the cell temperature evaluate in a non-linear system. The equation calculating the temperature is the following:

$$Q_{gen} = m.C_p.dT \text{(4)}$$

With m the mass of the cell, dT the temperature difference intrinsic to the system and C_p the specific heat capacity of the cell (J/(kg.K)). The value of C_p is commonly found for NMC cell in the literature: 1200 kg / (kJ.K) and 1500 kg / (kJ.K) for LTO.

Finally, regarding the boundary limits of the model, the heat transfer with the surroundings is determined by following the convection equation

$$Q_{loss} = A.h.(T - T_{amb}) \text{(5)}$$

with *A* the exposed area (m²) and *h* the convection transfer coefficient (W/(m².K)) In this investigation, the cell is cooled by natural convection, thus *h* equals 5 W/(m².K).

4.3.2 Results of the characterisation for thermal modelling

4.3.3 Results of the validation for thermal modelling

4.4 Development of the 3D-thermal model

4.4.1 Description of the 3D-thermal model

$$\frac{dU}{dt} = Q_{gen} - Q_{loss} \text{ (2)}$$

The heat generation is then calculated from the resistance of the cell:

$$Q_{gen} = R_{th}.I^2 \text{(3)}$$

with Q_{gen} the heat generation (W) and I the battery current (A). It was chosen that the resistance would be non-dynamic for simplifications. The value was taken from the datasheet of Toshiba and Kokam: 0.5 m mΩ and 1.2 mΩ, respectively. In this context, we assume the charging resistance is equals to the discharging resistance, and the simulation results reflect both states. Moreover, to estimate the temperature, it was proposed to simulate the system in a transient state, for which the cell temperature evaluate in a non-linear system. The equation calculating the temperature is the following:

$$Q_{gen} = m.C_p.dT \text{(4)}$$

With m the mass of the cell, dT the temperature difference intrinsic to the system and C_p the specific heat capacity of the cell (J/(kg.K)). The value of C_p is commonly found for NMC cell in the literature: 1200 kg / (kJ.K) and 1500 kg / (kJ.K) for LTO.

Finally, regarding the boundary limits of the model, the heat transfer with the surroundings is determined by following the convection equation

$$Q_{loss} = A.h.(T - T_{amb}) \text{(5)}$$

with *A* the exposed area (m^2) and *h* the convection transfer coefficient ($W/(m^2.K)$) In this investigation, the cell is cooled by natural convection, thus *h* equals 5 $W/(m^2.K)$.

4.4.2 Results of the characterisation for thermal modelling

4.4.3 Results of the validation for thermal modelling

5 Conclusion

There is potential for different options to design the battery pack of the PHEV and eBus with the LTO Toshiba cell. We propose to build a single unit with 144 cells in series and then rectify it with a factor of 8 to meet eBus battery pack requirements, respectively. The multiplication factor can be optimized in order to find best suited option for the packs. The single module meets the max size requirement of weight and volume factors, see Table 9 with the concluding remarks. Also, if the number of cells can be lowered, then LTO cells from Toshiba seem a promising candidate.

6 References

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