Energy Consumption, Driving Range and Cabin Temperature Performances at Different Ambient Conditions in Support to the Design of a User-Centric Efficient Electric Vehicle: the QUIET Project

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ABSTRACT

The energy consumption and efficiency of Battery Electric Vehicles (BEVs) are key topics to determine the usability and potential of electric vehicles in real-world conditions. In this framework different aspects must be addressed, such as the representativeness of different test duty cycles versus real-driving, the impact of different environmental conditions as well as the energy demand of auxiliaries in different climate conditions.

In order to perform accurate tests on advance vehicle concepts such as BEV and hybrid electric vehicles (HEV) and to be able to investigate their energy efficiency, a hardware system to accurately and reliably measure parameters at several locations within the vehicles (i.e. performance of electric components, drive trains etc.) has been customised.

The test results will set the base of comparison for the development of an improved and energy efficient electric vehicle with increased driving range under real world driving conditions in support to the research and innovation action H2020 project QUIET (QUalifying and Implementing a user-centric designed and EfficienT electric vehicle).This is achieved by exploiting the synergies of a technology portfolio in the areas of user centric design with enhanced passenger comfort and safety, lightweight materials with enhanced thermal insulation properties, and optimised vehicle energy management.

The paper provides the reader with a detailed description of the test campaign, the measurement equipment and methods used for monitoring the energy consumption, current flows and voltages in selected measurement points in the vehicle and an overview of driving range and distance specific energy consumption results in different ambient conditions and with usage of auxiliaries' systems.

Keywords: electric vehicle, energy consumption, driving range, HVAC, cabin temperature, data logger

INTRODUCTION

The EU's greenhouse gases emission reduction policies and the goal to keep the global temperature increase below 2°C commit the EU to reduce emissions by at least 20% below 1990 levels by 2020, and by 80-95% by 2050. This calls for major changes for future mobility, as outlined by EC White Paper 2011 [1], by the Strategy and Action Plan for creating an Energy

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Union [2] and by the European strategy for low-emission mobility [3]. Determining the energy consumption and efficiency of Battery Electric Vehicles (BEVs) under different driving conditions is a key to understand the potential benefits of this technology in replacing conventional fuel vehicles. Despite all the recent progress of the automotive industry towards environmentally friendly solutions the electric passenger cars are not yet competitive with internal combustion engine (ICE) vehicle technology since the electric energy storage system cannot yet perform in term of driving range and costs as the fuel tank. Beyond these limitations, previous studies from the authors suggest that the driving range of the current generation of BEVs is not a strict limitation, and approximately one-fourth of the urban cars could be shifted from conventional fuel vehicles to BEVs [4], [5] without any negative impact due to the shorter driving range. This share increases to approximately half of the fleet by accepting a very limited modal-shift [6]. These studies are based on a large-scale anonymous activity datasets acquired on conventional fuel vehicles from private citizens [7], and highlight that the actual potential of BEVs might go far beyond the common expectations. However, they rely on the fine-tuning of numerical models and, therefore, an accurate experimental estimate of BEVs' energy consumption in real driving conditions remain of key importance.

A test campaign carried out on a B-segment BEV in support to the research and innovation action H2020 project QUIET (QUalifying and Implementing a user-centric designed and EfficienT electric vehicle) [8], [9] will be illustrated in this work. QUIET aims at developing an improved and energy efficient electric vehicle with increased driving range under real-world driving conditions. This will be achieved by exploiting the synergies of a technology portfolio in the areas of user centric design with enhanced passenger comfort and safety, lightweight materials with enhanced thermal insulation properties, and optimised vehicle energy management. A novel refrigerant for cooling, combined with an energy-saving heat pump operation for heating, advanced thermal storages based on phase change materials, power films for infrared radiative heating, and materials for enhanced thermal insulation of the cabin will be investigated to this purpose. Further focus will be on lightweight glasses and composites for windows and closures, as well as light metal aluminium or magnesium seat components. Optimised energy management strategies, such as pre-conditioning and zonal cooling/heating the passenger cabin and user-centric designed cooling/heating modules will further enhance the thermal performance of the vehicle. These strategies will be seamlessly implemented in an intelligent vehicle control unit enhanced by a novel Human Machine Interface (HMI), which, beyond being intuitive and user friendly, will also consider diverse users' needs, accounting for gender and ageing society aspects. The new developed technologies will be integrated and qualified in a B-segment electric vehicle validator, the performances of which were characterised with the test campaign illustrated in this work to identify improvement potentials and optimisation. The objective of QUIET is to reduce the energy needed for cooling and heating the cabin of an electric vehicle under different driving conditions, by at least 30 % compared to the baseline vehicle. Additionally, a weight reduction of about 20 % of vehicle components (e.g. doors, windshields, seats, heating and air conditioning) is also addressed. These efforts will lead to a minimum of 25 % driving range increase under both hot (+40 °C) and cold (-10 °C) weather conditions.

The paper will provide the reader with a detailed description of the test campaign, the measurement equipment and methods used for monitoring the energy consumption, current flows and voltages in selected measurement points in the vehicle. The selected measuring points were located at the battery, at the electric motor and at the heating, ventilation and air conditioning

(HVAC) system, heater and A/C compressor, together with several temperature sensors and thermal comfort measurement devices. Additionally, the electric current from the grid during the recharges have been monitored to be able to reconstruct the efficiency cascade from the grid to the wheel during the several testing conditions with and without the use of the auxiliaries system in support to the performance optimisation.

EXPERIMENTAL SET-UP

Test Vehicle and Measurement Points

The BEV adopted for this study is a 5-seat car, powered by a synchronous electric motor in front-wheel driving configuration. The tested vehicle is a 2013 year model with a total of 68,239 kilometres before starting the tests. The vehicle's main characteristics are summarised in Table 1, while its schematic representation is provided Figure 1. In normal driving mode, the electric motor (EM) is rated at 75 kW maximum power and 256 Nm maximum torque [10]. The actual vehicle test mass was 1620 kg, including additional tools and equipment. The vehicle is equipped with a 432-cells Lithium-Ion battery (Lithium titanium oxide anode), accounting for a 20 kWh nominal capacity and approximately 331 V nominal voltage [11]. The temperatures of the powertrain components are controlled by a water cooling system. The battery pack is not connected to this water cooling system but has an air cooling system. In normal operation, it relies on the natural air-flow around the battery modules. In the rare case that this is not sufficient, two battery fans are activated. The car is equipped with an automatic Heating, Ventilation and Air-Conditioning (HVAC) system, which controls air outlet temperature and fan speed. The HVAC system consists of a conventional heater/blower unit, supplemented by an electric A/C compressor and an electric coolant heater. Compressor and heater draw their electric power directly from the high voltage system of the car. The outlet temperature is continuously adjusted by mixing hot and cold air, whereas the air distribution is changed between four fixed distribution modes as illustrated in Figure 2 [12]. The location of the corresponding air outlets inside the vehicle is shown in Figure 3 [12]. All the sub-systems are inter-connected by several power lines. Grey circles in Figure 1 represent the measurement points on the vehicle used to monitor the energy flows. A detailed description of these measurement points is provided in Table 2.

Table 1 Test vehicle characteristics.

Architecture	BEV
Propulsion	Synchronous electric motor
Max. Power [kW]	75
Max. Torque [N·m]	256
Mass [kg]	1620
Battery	20 kWh – 432 Li-Ion cells 331 V (nominal voltage)

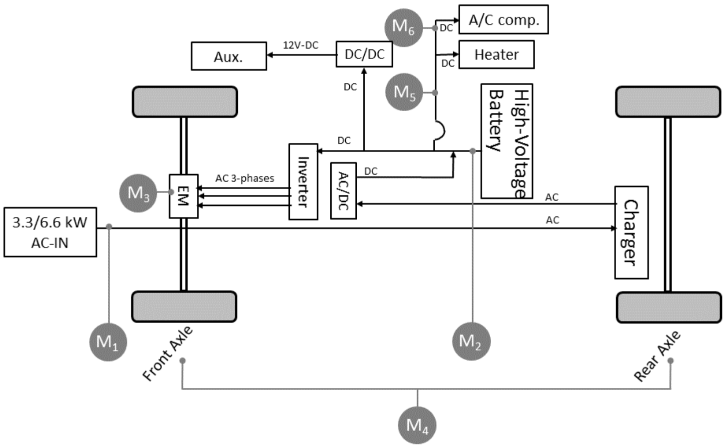

Figure 1. BEV schematic representation and measurement points (see Table 2).

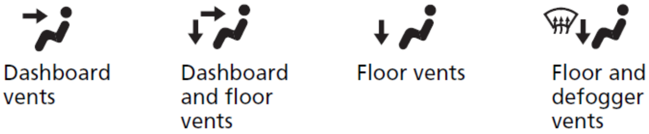

Figure 2 Air distribution modes [12]

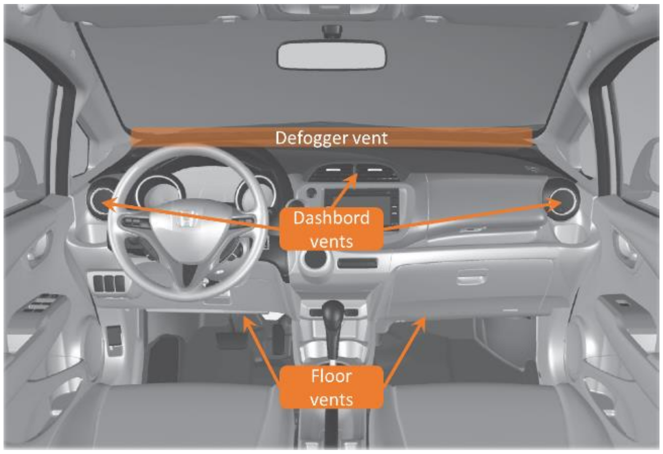

Figure 3 Air outlet locations [12]

Table 2 Measurement points summary (see Figure 1).

Measurement point label	Description
M_1	Energy from the grid to the high-voltage battery [Wh]; (acquired directly on the recharging station)
M_2	Current [A] and Voltage [V], from the high-voltage battery feeding the inverter, the low-voltage auxiliary systems and the heating and A/C systems → energy outflow from the battery to all subsystems [Wh]; (acquired both by CANbus, current clamp and voltage measurement)
M_3	Rotational speed [rpm] and torque [N·m] of the electric motor → mechanical energy of the electric motor [Wh]; (acquired by CANbus)
M_4	Energy at the wheel [Wh]; (acquired by the dyno)
M_5	Current [A] and Voltage [V], from the high-voltage battery to the heater → energy from the battery to the cabin heating system [Wh]; (acquired by current clamp)
M_6	Current [A] and Voltage [V], from the high-voltage battery to the A/C compressor → energy from the battery to the cabin cooling system [Wh]; (acquired by current clamp)

The measurement at the stage M_1 is acquired directly on the 3.3/6.6 kW AC recharging station, by monitoring the electric energy required to recharge the battery. The measurement at the stage M_2 is acquired in three ways, i.e. via the vehicle CANbus and via a current clamp directly mounted on the battery output power-line and voltage measurement by a derivation box. The measurement at the stage M_3 is acquired only via CANbus, whereas the measurement at the stage M_5 and M_6 is acquired only via current clamp.

The measurement equipment installed on the vehicle consists of current probes and voltage intake derivation box connected to a data logger. The data can be either stored on the internal memory of the power analyser or acquired in real-time by the laboratory data logger. The system has been configured for the present test campaign according to the measurement points described in Table 2. Cabin thermal acquisition, according to the specifications described in the European MAC draft test procedure [13], has been also configured as shown in Figure 4 and synchronised to all the other laboratory data. Additional temperature sensors and thermal comfort measurement devices have been installed for monitoring the vehicle energy management system in view of the new developed advance systems optimization. CANbus data acquisition was also active during the tests.

Three combinations of results will be presented: results from CAN current and CAN voltage measurements (Case 1), AC/DC clamp for current and measured voltage (Case 2), AC/DC clamp for current and CAN voltage measurements (Case 3).

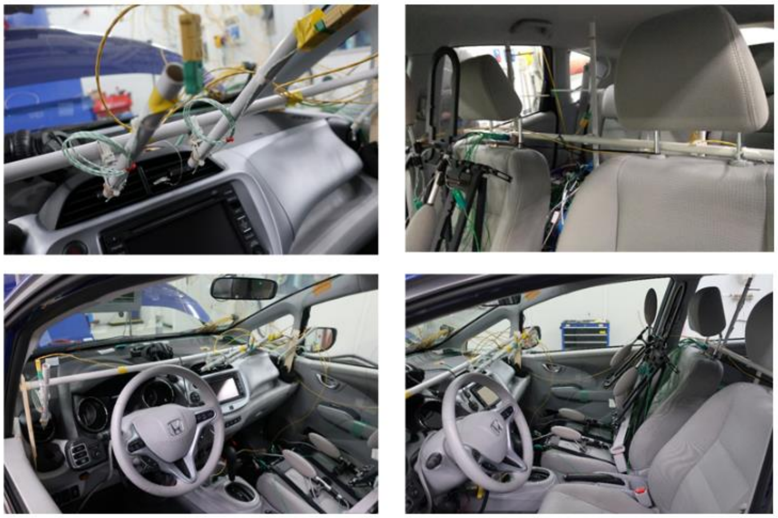

Figure 4 Cabin temperature sensors

The distance specific energy consumption and the driving range estimates were derived performing laboratory and on-road tests in different environmental and driving conditions with and without the usage of the HVAC system of the vehicle. The tests generated a set of data useful to calibrate the QUIET developed models in its several aspects of components optimisation and targeted efficiency. This work will focus only on laboratory tests.

The laboratory tests were performed in the Vehicle Emission Laboratories (VELA) of the Joint Research Centre of the European Commission in Ispra (Italy), precisely in theVeLA-8 facility, equipped with a 4x4 chassis dynamometer (independent roller benches) with a nominal power per axle of 300 kW that can achieve full road-simulation for speeds up to 260 km/h and accelerations up to ±10m/s2. This facility is designed to test passenger cars and light duty trucks, conventional fuel engine, full-electric and hybrid vehicles, at different ambient temperatures ranging from -30 ºC to +50 ºC. The inertia range varies from 250 up to 4,500 kg, while the wheelbase can be adapted from 1800 mm up to 4600 mm.VeLA-8 is equipped with an emission measurement system and with a driver aid system, to ensure consistent performance across all tests. The laboratory is equipped with a data logger for real-time acquisition of signals from the measurement devices available, among which is a precision power analyser used for the electrical components during this test campaign. A precision vehicle-speed coupled blower allows reproducing on-road operative condition and vehicle cooling through relative air speed. VeLA 8 emissions measurement system is also customised to allow reliable hybrid vehicle testing during the phases when the combustion engine is switched off. A more detailed description of the facility can be found in [14], [15].

Test Driving Cycles

Three test cycles have been adopted in the test campaign and their phases are shown in Figure 5: the World-wide harmonized Light-duty Test Cycle (WLTC), the Mobile Air Conditioning (MAC) cycle and the World-wide harmonized Light-duty Shorten Test Procedure (WLTP STP) [16], [17] [13].

The WLTC for Light Duty Vehicles (LDVs) [16], [17] is a test cycle characterized by four phases: low speed (589 seconds and 3.09 km), medium speed (433 seconds and 4.76 km), high

speed (455 seconds and 7.16 km) and extra-high speed (323 seconds and 8.25 km). These phases are designed to represent urban traffic, mixed conditions and highway conditions respectively. The Consecutive Cycle Test (CCT) where the WLTC cycle is repeatedly driven up to the complete charge depleting of the vehicle has been applied at both +23°C and -10°C with the HVAC system in operation to characterise the driving range and distance specific energy consumption of the vehicle in different ambient conditions. An assessment of the performance of the vehicle at +40°C with air conditioning in operation and additional on-road tests were carried out in a laboratory at the QUIET consortium member Honda R&D Europe (Deutschland) GmbH.
In order to determine the energy and fuel consumption of the HVAC system, the MAC cycle test procedure has been adopted [13]. This test prescribes a cycle made of three phases: the pre-conditioning phase (i.e. phase 1) plus two identical phases (i.e. phases 2 and 3), respectively with and without the HVAC system in operation. Phase 1 lasts for approximately 30 minutes at a constant speed of 90 km/h, while phases 2 and 3 last for approximately 16 minutes each, half driven at a constant speed of 50 km/h and half at 100 km/h. This test prescribes the minimum HVAC system mass flow rate (i.e. 230 kg/h), together with the monitoring of the cabin temperature in seven control points: four located on the dashboard and three behind the seats of the driver and the passenger (Figure 4). The test is carried out at the ambient temperature of +25 ºC, and the HVAC system of the vehicle must decrease the cabin temperature to a target value set below +15 ºC. The phase 1 is designed to stabilize the cabin temperature at this temperature, while phase 2 and phase 3 are designed to compare the energy or fuel consumption of the vehicle with and without the HVAC system in operation (cooling mode). During phase 2 the HVAC system must only maintain the cabin temperature around a steady-state value. A modified version of the MAC test procedure has been applied also at -10 ºC, with the HVAC system in heating mode, with the phase 1 shortened to 15 minutes of driving plus 15 minutes of idling (keeping the HVAC system in operation) in order to have enough energy in the battery to complete the phases 2 and 3, as shown in Figure 5.
The WLTP STP for pure electric vehicle driving range determination [16], [17] has also been applied to collect more data on the vehicle performance. The STP consists of two dynamic segments (DS1 and DS2 in Figure 5) combined with two constant speed segments (CSS_M and CSS_E in Figure 5). The dynamic segments DS1 and DS2 are used to calculate the energy consumption of the phase considered. The constant speed segments CSS_M and CSS_E are intended to reduce test duration by depleting the battery more rapidly than the CCT procedure. The test cycle is designed based on the vehicle characteristics. In this test campaign the STP defined for ambient temperature of 23 ºC has been applied also at -10 ºC to get insights on the limitation of this procedure at cold temperature.
Table 3 summaries the tests performed on the baseline vehicle. The vehicle is recharged after each driving range test using the 6.6 kW on-board AC charger. The recharging energy is recorded both at the mains and in the vehicle resulting in an average charging efficiency of approximately 92 % at 23 ºC and 91% at -10 ºC.

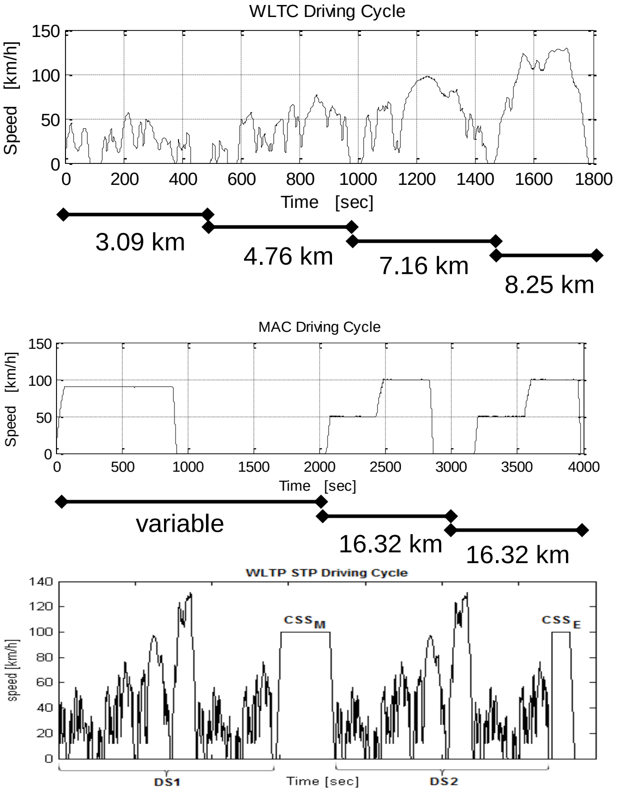

Figure 5 Driving cycles adopted: WLTC, MAC and WLTP STP.

Table 3 Laboratory and on-road driving tests.

Cycle	Ambient Temperature	HVAC	Test repetition number
WLTP CCT	23°C	off	3
WLTP CCT	-10°C	AUTO mode (heating)	3
WLTP CCT	40°C	AUTO mode (cooling)	1
WLTP STP	23°C	off	1
WLTP STP	-10°C	AUTO mode (heating)	2
MAC	25°C	AUTO mode (cooling)	1
MAC	-10°C	AUTO mode (heating)	1
On-road tests	ambient temperature	AUTO mode	several

RESULTS AND DISCUSSION

Energy consumption results

The WLTP CCT procedure [16], [17] has been applied to derive the distance specific energy consumption of the reference vehicle in different ambient conditions and without and with the HVAC system in operation. The WLTP test procedure has been developed to be carried out at +23 ºC. During this test campaign has been applied also at -10 ºC, to explore the impact of cold temperatures on the energy consumption with the HVAC system in operation in support to the QUIET project objectives, but to also explore the limitations and strong aspects of the procedure when applied at different ambient temperature. Each WLTP CCT test has been repeated three times for each ambient temperature, as reported in Table 3. The HVAC system was switched-on in heating mode at -10 ºC. It has been switched-on immediately before the test (i.e. without performing the cabin temperature pre-conditioning). Table 4 provides the energy consumption results calculated for each driving cycles of the CCT tests at the battery level (i.e. without considering the efficiency loss during the recharge) by the current and voltage at the battery outlet measured according to Case 1, Case 2 and Case 3, explained above (i.e. M_2 according to Table 2). Both the whole combined energy consumption and the WLTP K-weighted value from the start of the test up to the break-off criteria are reported.

In the WLTP [16], [17] the energy consumption is calculated applying a K-weighted according to the following equation (1):

$$EC_{DC,\,WLTC} = \sum_{j=1}^{n_{WLTC}} EC_{DC,WLTC,j} K_{WLTC,j} \tag{1}$$

where $EC_{DC,WLTC,j}$ is the electric energy consumption for the applicable WLTP test cycle j of the consecutive cycle Type 1 test procedure, in [Wh/km], calculated considering the electric energy change of all rechargeable electric energy storage systems (REESS) during the considered period j,

$$EC_{DC,WLTC,j} = \frac{\Delta E_{REESSj}}{dj} \tag{2}$$

$$\Delta E_{REESSj} = \sum_{i=1}^{n} \Delta E_{REESSj,i} \tag{3}$$

with n total number of REESS, and

$$\Delta E_{REESSj,i} = \frac{1}{3600} \int_{t_0}^{t_{end}} U(t)_{REESSji} I(t)_{REESSj,i} dt \tag{4}$$

$U(t)$: voltage of REESS$_i$ in period j,
$I(t)$: current REESS$_i$ during period j,
t_0: initial time of period j
t_{end}: final time period j

dj distance driven in the considered period j in [km] and n_{WLTC} the whole number of complete driven applicable WLTP test cycles. $K_{WLTC,j}$ is the weighting factor for the applicable WLTP test cycle j:

$$K_{WLTC,1} = \frac{\Delta E_{REESS,WLTC,1}}{UBE_{CCP}} \quad \text{and} \quad K_{WLTC,j} = \frac{1 - K_{WLTC,1}}{n_{WLTC} - 1} \quad \text{for } j = 2 \ldots n_{WLTC} \tag{5}$$

where $\Delta E_{REESS,WLTC,1}$ is the electric energy change of all the REESSs during the first applicable WLTP test cycle of the consecutive cycle Type 1 test procedure in [Wh].

The consumption values have been converted to an equivalent value expressed in litres of gasoline per 100 km (i.e. litres/100km, see values in parenthesis), by applying the conversion suggested by the Environmental Protection Agency (EPA, [18]) as per (6). The energy content of the gasoline fuel has been assumed equal to 8.90 kWh/litre (i.e. 115 kbtu/gallon),

$$Consumption \left[\frac{l}{100km}\right] = Consumption \left[\frac{Wh}{km}\right] . \frac{0.1123}{10} \tag{6}$$

The results given in Table 4 show that at +23 ºC and with the HVAC system switched-off the distance specific energy consumption varies between approximately 130 and 131 Wh/km. At cold temperature and with HVAC system operating in heating mode the distance specific energy consumption ranges from approximately 236 Wh/km to 240Wh/km. The HVAC system in heating mode (i.e. T_{Amb} = -10 ºC and HVAC ON) has an impact that can be quantified in approximately 70-80% increase of the energy consumption. The differences between the three measurement modes (case 1, 2 and 3) is approximate 3-5% at 23 ºC and 11-14% at -10 ºC. The energy consumption results are also graphically shown in Figure 6, in function of the ambient temperature, where it is immediately visible the effect of different ambient conditions and auxiliaries' load. By converting the energy consumption results to the equivalent gasoline consumption, a consumption ranging from 1.5 to 2.7 l/100 km (combined data) is derived, showing how BEVs are, in almost every condition, more energy efficient than conventional fuel cars, [19]. These values will increase if the effect of the energy losses during the recharge (i.e. from the grid to the battery) is included.

The energy recuperation ratio is also calculated both at the battery and at the EM level. At the battery level it is calculated by dividing the battery energy inflow by the battery energy outflow measured by current and voltage (see measurement point M_2), while, at the EM level, it is calculated by dividing the electric motor recuperated energy by the electric motor driving energy (see measurement point M_3). These ratios provide a quick estimate of the impact of the energy recuperation on the total energy consumption for each cycle and test conditions. The ratio at the battery level is lower than that at the EM level, accounting for the energy losses between the battery and the EM (i.e. power lines and inverter) and ranges from 9% to 24%. Moreover, the battery level recuperation at -10 ºC and with the HVAC system switched-on is significantly lower compared to other test conditions. This is probably due to the fact that the regenerated energy in this condition is not stored in the battery but directly used to feed the cabin heating system.

The distance specific energy consumption is given per the first cycle phases and combined cycle (without *K*-weighted of the WLTP procedure), for each test condition, in Table 5. The results are reported for the first cycle which includes the mechanical warm-up of the drivetrain (i.e. cold-start). This effect is very small (i.e. below 2% of the reported combined energy consumption results), and it has been included to represent the worst case scenario, in terms of energy consumption. Results for only the Case 1 measurement are reported.

Table 6 reports the distance specific energy consumption for the MAC test cycles, phases 1, 2 and 3 for the two ambient temperatures considered and the three measurement cases. The MAC test cabin temperature conditioning was performed according to [13], with the first phase of pre-conditioning. Only one test at 25 ºC and one test at -10 ºC were performed for the MAC cycle case. The recuperation ratios are not reported, being meaningless for driving phases driven at constant speed. Instead the ratio between the energy consumption from the phases 2 and 3 is reported, to highlight the influence of the HVAC system in operation on the energy consumption. Phase 1 (i.e. variable) is designed only to reach a steady-state cabin temperature. The results show that this impact is rather limited in cooling mode (i.e. approximately +12% of increase in the energy consumption, for +25 ºC ambient temperature), whereas a +71% increase is calculated for the HVAC system in heating mode. These results are in line with those from the driving cycles reported in Table 4, showing a significant increase of the energy consumption with cabin heating. The second-by-second cabin temperatures measured during the MAC tests are reported in Figure 7. The cabin temperature measurement points reported are: left, mid and right probe positions (corresponding to driver's head, between the driver's and the passenger's seat and behind the passenger's head) and left, mid and right duct positions (corresponding to the left, mid and right outlet of the HVAC system located on the dashboard). According to the MAC specifications, the thermocouples located on the dashboard are four: left, mid-left, mid-right and right outlets of the HVAC system. For simplicity the mid duct temperature reported here is the average between the mid-left and mid-right duct measurements. The thermocouples in the cabin show that the temperature stabilizes approximately after 10-15 minutes in cooling mode (reaching +10ºC less than the MAC target value of +15 ºC at the end of phase 1 for the ambient temperature equal to +25 ºC at the left duct and +20ºC in all the other monitoring points), whereas it takes approximately 20-25 minutes in heating mode.

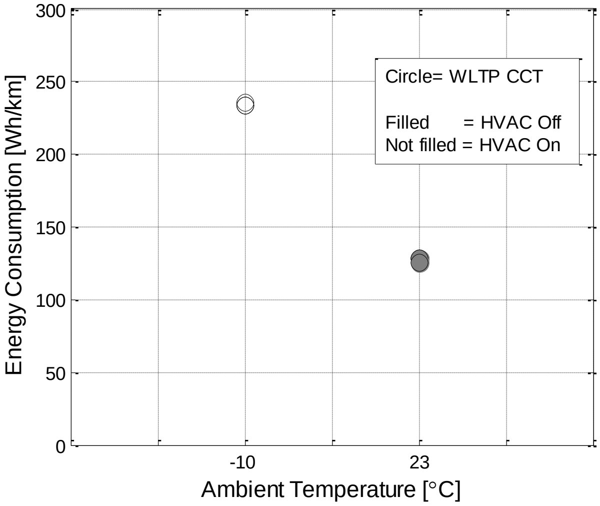

Figure 6. Energy consumption results at different ambient temperatures from the WLTP CCT tests (Case 1).

Table 4 Energy consumption results for the WLTP CCT tests at different temperatures. Results for the three measurement cases (Case 1 - CAN current and CAN voltage measurements, Case 2 - AC/DC clamp for current and measured voltage, Case 3 - AC/DC clamp for current and CAN voltage measurements).

		Test repetition #1			**Test repetition #2**			**Test repetition #3**		
		Case 1	**Case 2**	**Case 3**	**Case 1**	**Case 2**	**Case 3**	**Case 1**	**Case 2**	**Case 3**
		WLTC [Wh/km] (l/100 km)	**WLTC** [Wh/km] (l/100 km)	**WLTC** [Wh/km] (l/100 km)	**WLTC** [Wh/km] (l/100 km)	**WLTC** [Wh/km] (l/100 km)	**WLTC** [Wh/km] (l/100 km)	**WLTC** [Wh/km] (l/100 km)	**WLTC** [Wh/km] (l/100 km)	**WLTC** [Wh/km] (l/100 km)
$T_{Amb.}$ = +23 ºC HVAC OFF	Cycle 1 combined	131.3 (1.47)	127.6 (1.43)	128.7 (1.43)	130.6 (1.47)	124.5 (1.40)	125.5 (1.41)	132.3 (1.49)	125.8 (1.41)	126.9 (1.43)
	Cycle 2 combined	129.6 (1.46)	125.7 (1.41)	126.7 (1.41)	129.3 (1.45)	122.9 (1.38)	123.9 (1.39)	130.2 (1.46)	123.4 (1.39)	124.5 (1.40)
	Cycle 3 combined	129.4 (1.45)	126.3 (1.42)	127.4 (1.42)	129.4 (1.45)	124.1 (1.39)	125.2 (1.41)	128.9 (1.45)	124.0 (1.39)	125.1 (1.41)
	Cycle 4 combined	129.2 (1.45)	125.9 (1.41)	127.0 (1.41)	129.0 (1.45)	123.4 (1.39)	124.5 (1.40)	129.0 (1.45)	123.6 (1.39)	124.8 (1.40)
	Cycle 5 combined	130.7 (1.47)	127.2 (1.43)	128.5 (1.43)	131.6 (1.48)	125.4 (1.41)	126.6 (1.42)	130.5 (1.47)	125.5 (1.41)	126.7 (1.42)
	Cycle 6 combined	131.9 (1.48)	127.4 (1.43)	128.8 (1.43)	132.4 (1.49)	125.8 (1.41)	127.1 (1.43)	131.3 (1.48)	126.2 (1.42)	127.6 (1.43)
	Total from start up to break off criteria combined	128.6 (1.44)	124.6 (1.40)	125.9 (1.40)	128.6 (1.44)	-	-	125.9 (1.41)	120.2 (1.35)	121.4 (1.36)
	Total from start up to break off criteria WLTP K-weighted values	130.3 (1.46)	126.7 (1.42)	127.8 (1.44)	130.3 (1.46)	124.3 (1.40)	125.4 (1.41)	130.3 (1.46)	124.7 (1.40)	125.9 (1.41)
	Rec. Ratio (Battery)	24.3%	25.7%	25.5%	24.1%	-	-	24.2%	31.2%	25.9%
$T_{Amb.}$ = -10 ºC HVAC ON	Cycle 1 combined	257.5 (2.89)	253.0 (2.84)	-	257.6 (2.89)	279.0 (3.13)	287.0 (3.22)	258.9 (2.91	263.1 (2.96)	264.6 (2.97)
	Cycle 2 combined	222.1 (2.49)	217.5 (2.44)	-	222.2 (2.50)	255.1 (2.86)	261.2 (2.93)	227.6 (2.56)	231.7 (2.60)	233.2 (2.62)
	Total from start up to break off criteria combined	233.4 (2.62)	229.5 (2.58)	-	233.4 (2.62)	273.9 (3.08)	280.9 (3.15)	235.9 (2.65)	185.6 (2.08)	186.8 (2.10)
	Total from start up to break off criteria WLTP K-weighted values	236.4 (2.65)	-	-	236.6 (2.66)	264.1 (2.30)	270.9 (3.04)	240.5 (2.70)	248.4 (2.79)	249.9 (2.81)
	Rec. Ratio (Battery)	-	-	-	9.3%	-	-	8.9%	6.9%	6.9%

Table 5 Energy consumption phase specific results for the first WLTC cycle of the CCT tests at different temperatures. Results for the measurement Case 1.

		Test repetition #1	**Test repetition #2**	**Test repetition #3**
		Case 1	**Case 1**	**Case 1**
		WLTC [Wh/km] (l/100 km)	**WLTC** [Wh/km] (l/100 km)	**WLTC** [Wh/km] (l/100 km)
$T_{Amb.}$ = +23 ºC HVAC OFF 1st cycle	Phase 1	97.9 (1.10)	95.8 (1.10)	99.1 (1.11)
	Phase 2	98.3 (1.10)	97.5 (1.10)	99.1 (1.11)
	Phase 3	116.8 (1.31)	116.4 (1.31)	117.7 (1.32)
	Phase 4	175.9 (1.97)	175.6 (1.97)	177.0 (1.99)
	Combined	131.3 (1.47)	130.6 (1.47)	132.3 (1.49)
$T_{Amb.}$ = -10 ºC HVAC ON 1st cycle	Phase 1	413.1 (4.64)	414.3 (4.65)	396.1 (4.45)
	Phase 2	251.8 (2.83)	249.9 (2.81)	250.7 (2.82)
	Phase 3	212.5 (2.39)	214.1 (2.40)	219.0 (2.46)
	Phase 4	241.1 (2.71)	241.3 (2.71)	244.5 (2.75)
	Combined	257.5 (2.89)	257.6 (2.89)	258.9 (2.91

Table 6 Energy consumption results (MAC).

		Case 1	**Case 2**	**Case 3**
		MAC [Wh/km] (l/100 km)	**MAC** [Wh/km] (l/100 km)	**MAC** [Wh/km] (l/100 km)
$T_{Amb.}$ = +25 ºC	Phase 1 HVAC ON	143.3 (1.61)	116.8 (1.31)	117.1 (1.32)
	Phase 2 HVAC ON	140.9 (1.58)	107.3 (1.21)	107.6 (1.21)
	Phase 3 HVAC OFF	128.1 (1.44)	95.7 (1.07)	96.0 (1.08)
	Ratio	+10.0%	+12.1%	12.1%
$T_{Amb.}$ = -10 ºC	Phase 1 HVAC ON	301.7 (3.39)	298.0 (3.35)	298.9 (3.36)
	Phase 2 HVAC ON	237.3 (2.66)	233.1 (2.62)	234.0 (2.63)
	Phase 3 HVAC OFF	146.7 (1.65)	136.3 (1.53)	136.9 (1.54)
	Ratio	+61.7%	+71.0%	+71.0%

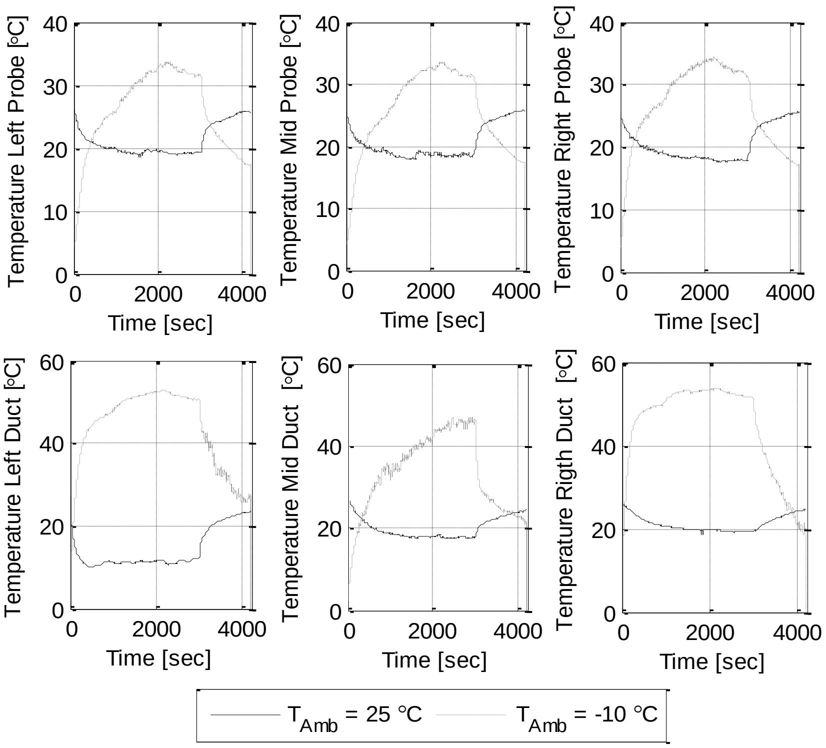

Figure 7. Thermocouples readings at the driver's head, between the driver's and the passenger's seat and behind the passenger's head (i.e. respectively left/mid/right probe positions) and at the left/mid/right duct outlets for the MAC driving cycle. Mid duct temperature is the average between the mid-left and mid-right duct measurements.

Driving range results

According to the WLTP driving range test [16], [17], the type approval driving cycle has to be driven in sequence at a temperature of +23 ºC and with the auxiliary systems switched-off. The driving range is then determined by the cumulative distance driven up to when the break-off criterion is reached, that is, when the vehicle is not capable to follow the duty cycle anymore for four consecutive seconds or more. The accelerator control shall be deactivated, the vehicle coasted-down and parked within 60 seconds.

The WLTP CCT pure electric range (PER) for a BEV is defined by:

$$PER_{WLTC} = \frac{UBE_{CCP}}{EC_{DC,WLTC}} \tag{7}$$

where UBE_{CCP} is the usable REESS energy determined from the beginning of the consecutive cycle Type1 test procedure until the brek-off criterion,

$$UBE_{CCP} = \sum_{j=1}^{k} \Delta E_{REESS,j} \tag{8}$$

with $\Delta E_{REESS,j}$ the electric energy change of all the REESSs during phase j of the consecutive cycle Type 1 test procedure in [Wh] and $EC_{DC,\,WLTC}$ defined by (1).

A way to estimate the driving range, when the estimated electric driving range is longer than 3 applicable WLTC, consists in the abbreviated Shorten Type 1 test procedure [16], [17], where the PER for a BEV is defined by:

$$PER_{WLTC} = \frac{UBE_{STP}}{EC_{DC,WLTC}} \tag{9}$$

where UBE_{STP} is the usable REESS energy determined from the beginning of the Shorten Type 1 test procedure until the break-off criterion,

$$UBE_{STP} = \Delta E_{REESS,DS1} + \Delta E_{REESS,DS2} + \Delta E_{REESS,CSS_M} + \Delta E_{REESS,CSS_E} \tag{10}$$

and $\Delta E_{REESS,\,DS1}$, $\Delta E_{REESS,\,DS2}$, $\Delta E_{REESS,\,CSS_M}$, $\Delta E_{REESS,\,CSS_E}$ are respectively the electric energy change of all the REESSs during the DS1, DS2, CSS_M, CSS_E phases of the Shorten Type 1 test procedure (Figure 5 c)) in [Wh], and

$$EC_{DC,\,WLTC} = \sum_{j=1}^{2} EC_{DC,WLTC,j} K_{WLTC,j} \tag{11}$$

where $EC_{DC,WLTC,j}$ is the electric energy consumption for the applicable WLTP test cycle DSj of the Shorten Type 1 test procedure in [Wh/km] and $K_{WLTC,j}$ is the weighting factor for the applicable WLTP test cycle of DSj of the Shorten Type 1 test procedure,

$$K_{WLTC,1} = \frac{\Delta E_{REESS,WLTC,1}}{UBE_{STP}} \quad \text{and} \quad K_{WLTC,2} = 1 - K_{WLTC,1} \quad . \tag{12}$$

$\Delta E_{REESS,WLTC,1}$ is the electric energy change of all the REESSs during the applicable WLTP test cycle from DS1 of the Shorten Type 1 test procedure in [Wh].

Table 7 reports the driving range test results calculated with the full-length WLTP CCT procedure and the WLTP STP. As reported above the WLTP procedures have been extended to cold temperatures. The *K*-weighting coefficient might be differently defined at cold temperature. For this reason the driving range reported in Table 7 for the -10 ºC is primarily the distance driven up to the break-off criterion. For completeness the *K*-weighted values are also reported between brackets. The STP cycle at -10 ºC presented some difficulties to be derived accordingly to the defined criteria in [16], [17] of break–off in the last phase, corresponding to a remaining energy <= 10% of the UBE, due to the usage of the HVAC system, but also of the powertrain behaviour at cold temperature. The results are reported for completeness despite this limitation. Some results for the measurements Case 2 and 3 are missing due to the loss of the data transmission to the power analyser.

During the CCT tests, the vehicle was able to drive 6 completed WLTC plus three phases of the seventh cycle at +23 ºC and 2 completed WLTC plus three phases of the third cycle at -10 ºC. The results show a driving range between 155 km and 156 km for CCT and 154 km using the STP at +23 ºC, slightly shorter as the procedure foreseen. At -10 ºC and with HVAC system operating in heating mode the driving range sets between 63 km and 68 km, depending on the battery temperature, approximately 59% shorter than the range at +23 ºC without HVAC system in operation.

Being the tested vehicle a single vehicle affected also by its driving history (e.g. aging of its battery), the driving range results reported in this section might not represent the driving range of this vehicle's model.

Table 7 Driving range test results for both the WLTP CCT and STP procedure at the different ambient temperatures

		Test repetition #1			**Test repetition #2**			**Test repetition #3**		
		Case 1	**Case 2**	**Case 3**	**Case 1**	**Case 2**	**Case 3**	**Case 1**	**Case 2**	**Case 3**
		Driving Range [km]			Driving Range [km]			Driving Range [km]		
$T_{Amb.}$ = +23 ºC HVAC OFF	WLTP CCT K-weighted	154.43	153.99	154.10	154.74	123.76	124.10	149.24	148.78	148.90
	WLTP STP K-weighted	153.50	-	154.94	-	-	-	-	-	-
$T_{Amb.}$ = -10 ºC HVAC ON	WLTP CCT up to break-off criterion (K-weighted)	63.98 (63.15)	63.98 (67.67)	63.98 (66.84)	63.93 (63.07)	63.93 (66.30)	63.93 (66.29)	62.83 (61.62)	-	-
	WLTP STP up to break-off criterion (K-weighted)	63.50 (65.79)	63.50 (55.27)	63.50 (65.36)	64.30 (68.48)	64.30 (56.54)	64.30 (68.55)	-	-	-

CONCLUSIONS

At +23 ºC and with the HVAC system switched-off, distance specific energy consumption results between approximately 130 and 131 Wh/km were achieved. This corresponds to a driving range between 155 km and 156 km for CCT and 154 km using the STP. At cold temperature and with HVAC system operating in heating mode the distance specific energy consumption ranges from approximately 236 Wh/km to 240Wh/km, resulting in a driving range between 63 km and 68 km, depending on the battery temperature. Comparing phase 2 (HVAC switched-off) and 3 (HVAC switched-on) of the MAC cycle an increase in distance specific energy consumption of approximately 12% for the test at 25 ºC and 71% for the test at -10 ºC due to the energy demand of the auxiliary systems is derived. These results are in line with those from the other driving cycles, showing a significant increase of the energy consumption with cabin heating in operation compared to cabin cooling. These tests suggest how BEV's energy consumption is significantly affected by ambient temperatures and auxiliaries' load. The accuracy of the results obtained for the energy consumption and driving ranges during all the tests were assured by using the customised data logger system that allows to accurately and reliably measure parameters at several locations within the vehicles without interfering with the operation of the components.

These results set the base for the final comparison with the user-centric designed validator and for the assessment of the objective of QUIET project to reduce the energy needed for cooling and heating the cabin of an electric vehicle under different driving conditions implementing advance and innovative technologies.

NOMENCLATURE

AC	Alternating Current
BEV	Battery EV
CCT	Consecutive Cycle Test
EM	Electric Motor
EV	Electric Vehicle
HMI	Human Machine Interface
HVAC	Heating, Ventilation and Air Conditioning
ICE	Internal Combustion Engine
MAC	Mobile Air-Conditioning
REESS	Rechargeable Electric Energy Storage System
SOC	State Of Charge
STP	Shorten Test Procedure
UBE	Usable Battery Energy
WLTC	World-wide harmonized Light vehicles Test Cycle

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