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Electric and hybrid vehicle testing

BMWi3 performance assessment in realistic use scenarios

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Electric and hybrid vehicle testing: BMWi3 performance assessment in realistic use scenarios

A plug-in electric vehicle with range extender was tested at ambient temperatures varying between -30°C and 50°C. The objective was to assess energy efficiency variability depending on use conditions.
The test campaign was performed in the framework of the transatlantic collaboration between the United States' Department of Energy (Argonne National Laboratory) and the European Commission's Joint Research Centre.

Contents

Foreword

The EU-US Energy Council and the Transatlantic Economic Council (TEC) recognized e-mobility as a common growth sector [1]. The TEC endorsed in 2011 a comprehensive Work Plan [2] prioritising short- and medium-term objectives to foster transatlantic cooperation on e-mobility and smart electricity systems. The plan addressed the development of harmonized regulation, cooperation among regulators, EV-smart grid interoperability and communication methods, research on charging and energy storage.

On this ground, the US Department of Energy (DoE) and European Commission (EC) signed a Letter of Intent (LoI) in November 2011. The intent was to establish two complementary Electric Vehicles and Smart Grids Interoperability Centres (IOCs), to promote harmonization of EV-grid connectivity and communication standards, technology advancement and test procedures between US and EU. The two centres were based one in the United States at the DoE Argonne National Laboratory (ANL) in Chicago and the other one in Europe at the Ispra and Petten sites of the Joint Research Centre (JRC).

The US IOC was inaugurated in July 2013 to foster legislative and technological harmonization in e-mobility, with focus on helping bridge the gaps in standards, communication protocols and verification procedures that support electric vehicle (EV)-grid connectivity.

The EU IOC was inaugurated in October 2015 (**Figure 1**) to address interoperability of EVs, charging devices (or supply equipment, EVSE), smart grid interactions, safety aspects and performance of vehicle batteries.

The present report addresses a joint test campaign partially carried out at the EU Interoperability Centre for Electric Vehicles and Smart Grids, in collaboration with the DoE ANL.

Figure 1. The Vice-President of the European Commission for Energy Union, Maroš Šefčovič, and the Associate Deputy Secretary of the U.S. Department of Energy, John MacWilliams, at the launch of the EU IOC.

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Executive summary

Electrified vehicles (EVs) are characterized by relatively high energy efficiency, influenced by a wide range of factors (e.g. accessory use and ambient temperature). Assessing energy efficiency variability with respect to real-world operations is extremely important for characterising EVs, as it directly affects the attainable electric driving range and thus achievable emissions reduction. In turn, it determines the market competitiveness of this alternative drive-train technology: limited driving range (stoking customers' "range anxiety") and long recharging times are among the main inhibitors to the braod diffusion of EVs. The present report summarizes results from a joint experimental campaign carried out in the framework of the transatlantic collaboration between the US DoE Argonne National Laboratory (ANL) and the EC Joint Research Centre (JRC). An extensively instrumented plug-in EV with range extender (REEV) was tested against EU and US legislative cycles, at ambient temperatures varying between -30°C and 50°C. The aim of the study was to assess the impact of varying ambient conditions on vehicle energy efficiency and achievable driving range

Policy context

The EU-US Energy Council and the Transatlantic Economic Council (TEC) recognized e-mobility as a common growth sector. The TEC endorsed in 2011 a comprehensive Work Plan prioritizing short- and medium-term objective to foster transatlantic cooperation on e-mobility and smart electricity systems. On this ground, the US Department of Energy (DoE) and European Commission (EC) signed a Letter of Intent (LoI) in November 2011, to establish two complementary Electric Vehicles and Smart Grids Interoperability Centres (IOCs), to promote harmonization of EV-grid connectivity and communication standards, technology advancement and test procedures between US and EU.

Within this framework, the presented energy efficiency analyses were oriented to support the development of updated testing procedures and standards - aimed at evaluating the environmental benefits brought by the electrification of road transport in a methodologically sound way.

Key conclusions

Presented data provided good replicability between the dedicated transatlantic laboratories and valuable information on vehicle and vehicle-components energy use across the considered operative testing ranges.

Results demonstrated that ambient temperature strongly affects vehicle energy use over the considered test cycles and a similar variation trend is observed across tested temperatures: over all driving cycles, maximum energy consumption is reached at -30 °C, while minimum is touched at 23°C. As a consequence, the attained driving range was significantly reduced at cold temperatures (between 40% and 70% of the compared standard testing conditions). The energy consumption increase due to the use of cabin heating, together with battery performance deterioration at negative temperatures were found to be the main causes for driving range reduction. It is worth stressing that information about EVs performance degradation at cold temperature is not available to customers.

Related and future JRC work

Results of the same testing campaign, including is testing, were presented in two prior conference papers, referenced in the present report. Further analysis will investigate how varying ambient temperatures affect the vehicle fuel economy during charge sustaining operations (i.e. after the internal combustion engine, ICE, starts).

Future studies will focus on plug-in hybrid electric vehicles (PHEVs) with a different hybridization level, in order to compare the impact of extreme temperatures on vehicle energy consumption.

1 Introduction

Climate change, air quality in urban areas and energy security are the driving factors moving our society towards decarbonisation of transport. Indeed, the transport sector in EU was responsible in 2010 [3] for:

- nearly one fifth (22%) of global CO2 emissions, with 15% share coming from road transport;
- high concentrations of air pollutants above EU standards in many EU cities;
- almost a third (32%) of total EU energy consumption, with road transport segment dominating the scene with very high energy needs (82%) and very low energy efficiencies (around 30%).

Transport is also the only sector which emissions were growing in the EU (by 19%) when comparing 2013 values to the baseline year 1990 [4]. In addition to that, passenger car transport is expected to further grow over the next decades [5].

Europe's answer to these challenges is an irreversible shift to low-emission mobility in terms of carbon and air pollutants [6]. Ambitious targets set by the current CO2 reduction policy framework [7]-[10] implies that electric vehicles (EVs) will play a major role in reducing the climate impact of transport as well as local air pollution. Furthermore, the electrification of the road vehicles fleet will also increase energy security by reducing the dependency on fossil fuel.

Predicted future scenarios [3] foresee a relatively modest EVs market penetration in the next future (between 1.5% and 7% of global car sales in 2020) and a more consistent diffusion in the long term (40 to 95% for 2050). Therefore, pre-normative research assessing EVs performance in terms of emissions and energy efficiency, as well as their compatibility with current and future infrastructure, becomes more and more crucial to support political decisions and suitable update of current legislation.

The present report addresses an experimental campaign focused on two-axis chassis dynamometer testing of a plug-in hybrid electric vehicle (PHEV). A BMW i3 REx (range extender version), equipped with more than 400 recorded channels, was tested at both the ANL’s Advanced Powertrain Research Facility (APRF), and at the JRC's Vehicle electric Laboratory, VeLA 8. After providing a description of the testing facility and equipment, experimental results for the vehicle performance in terms of energy and fuel efficiency are presented and discussed.

2 The EU Interoperability Centre for EVs and Smart Grids

The Directorate for Energy, Transport and Climate of the European Commission's Joint Research Centre is actively contributing to EC pre-normative research in the field of pollutant emissions from road vehicles since late 1990s. JRC scientific support to the EC policy makers in this area is strongly based on test performed at the Vehicle Emissions Laboratories (VELAs), which allow testing all kind of conventional vehicles and engines. Research has so far mainly focussed on conventional vehicles to contribute to the development of the latest European emission standards for road and off-road vehicles [11].

According to DoE-EC LoI, JRC embarked on a strategic programme to foster standardization in e-mobility through the establishment of the European Interoperability Centre for Electric Vehicles and Smart Grids (**Figure 2**). The new JRC IOC comprises facilities for vehicles and components testing, as well as grid infrastructure testing laboratories, located in two different JRC sites:

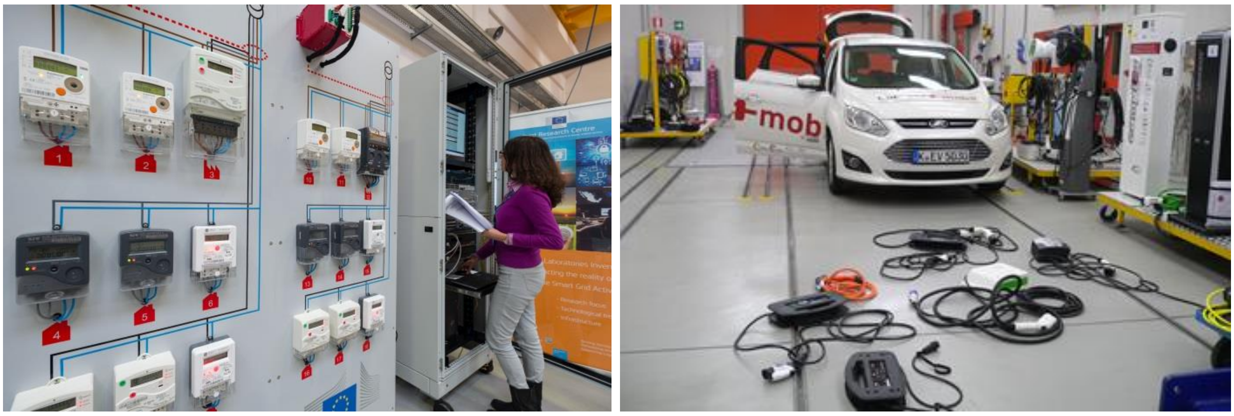
- Ispra (Italy) based facilities:
    - VeLA 8, climatic chamber for efficiency and emissions testing (**Figure 3a**)
    - VeLA 9, semi-anechoic chamber for electromagnetic compatibility testing (**Figure 3b**)
    - Smart Grid Interoperability Laboratory (**Figure 3c**)
    - EV-EVSE interoperability testing equipment (**Figure 3d**)
    - PeMS, portable measurement system for on-road electric vehicles testing (**Figure 4**)
- Petten (The Netherlands) based facilities:
    - BESTEST, Battery Energy Storage Testing for Safe Electrification of Transport
    - Smart Grid and Smart Home Laboratory

Figure 2. The EU Interoperability Centre for Electric Vehicles and Smart Grids at JRC Ispra.

Figure 3. EU IOC, Ispra based facilities.

(a) V*e*LA8

(b) V*e*LA9



(c) Smart Grid Lab

(d) EV-EVSE interoperability

Figure 4. EU IOC, e-PEMS testing at Ispra.

2.1 VeLA 8 testing facility

VeLA 8 is an automotive dynamic testing facility for hybrid and full- electric vehicles, enabling the JRC to record and analyse vehicle performance and exhaust emissions for legislative and potential future drive-cycles, at different temperatures. The facility (**Figure 5**) is designed to perform tests on full-electric and hybrid vehicles with different fuels (gasoline, diesel fuel, LPG, natural gas, hydrogen etc.).

A 4WD chassis dynamometer with adjustable wheelbase length is embedded into VeLA 8 cell. The powerful roller bench (300 kW per axle) can achieve full road-simulation for speeds up to 260km/h and accelerations up to ±10m/s$^{2.}$ A precision vehicle-speed coupled blower allows reproducing on-road operative condition and vehicle cooling through relative air speed. Varying the wheelbase length from a minimum of 1800 mm to a maximum of 4600 mm, the test cell can accommodate a wide range of vehicle categories (**Figure 6**), ranging from light duty passenger cars to light-medium duty vehicles such as city delivery vans and mini-buses. Four independent breaking motors and rollers - one for each wheel - are controlled by the system ensuring full synchronization and allowing the system to simulate real driving manoeuvres. In addition, the assisted braking can be disabled during deceleration phases in order to properly measure regenerative braking by the vehicle.

Figure 5. 3D rendering of VeLA 8 infrastructure.

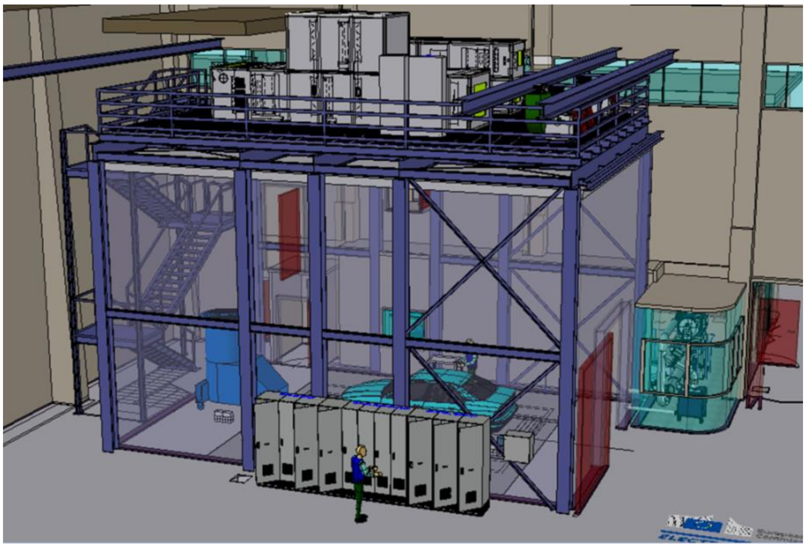


Figure 6. The BMWi3 tested into VeLA8 climatic chamber.

VeLA 8 emissions measurement system was also customized in order to allow reliable hybrid vehicle testing during the phases when the combustion engine is switched off. Tailpipe pressure control avoids sucking intake air through the engine inlet valve when the vehicle shifts from the thermal engine mode to the pure electric mode, so that similarly to real world operations, the exhaust gas after-treatment system is not artificially cooled down.

A wide-range temperature control is of particular importance to electric and hybrid vehicle efficiency testing, and the climatic test cell of VeLA 8 allows reaching and maintaining temperatures in the range -30/+50°C for more than one hour, at controlled humidity. This feature also allows for testing physical and communication interoperability between electric vehicles and charging devices at different temperatures, as recently done in the framework of the Interoperability (InterOp) Project [12].

3 Experimental Equipment

3.1 Tested vehicle

A 2014 BMW i3 Rex (US market version) was chosen as a research plug-in hybrid electric vehicle, due to its unique architecture. Indeed, it is equipped with a Permanent Magnet Synchronous AC electric motor (power output 125 kW, maximum torque 250 Nm) offering a high level of electrification, coupled with a downsized internal combustion engine (two-cylinder, 649cc) for extended range driving. The powertrain of the BMW i3 is a series hybrid, as the ICE drives an electric generator which provides power to the vehicle high voltage bus upon state of charge (SOC) decreasing below certain limit values.

The main vehicle characteristics are summarized in Table I, while the vehicle architecture is sketched in Figure 2

The main vehicle characteristics are summarized in Table 1 and the vehicle architecture is sketched in **Figure 7**.

The BMW i3 allows the driver to influence the EV's energy consumption through three different drive modes: Comfort, Eco Pro, or Eco Pro+ mode (see Table 2).

All tests discussed within this work were performed with the vehicle in the default comfort driving mode, with a variable speed fan simulating the driven vehicle speed.

Table 1. Vehicle architecture overview [13].

Architecture	Series hybrid
Propulsion	Permanent Magnet Synchronous AC
Range Extender	two-cylinder, 649cc 28kW @ 5000rpm
Max. Power	125 kW
Max. Torque	250 Nm
Mass (unladen)	1195 kg
Battery	Li-Ion 18.1kWh (usable), 355.2V

Figure 7. BMW i3 architecture and high-voltage current layout (Courtesy of ANL).

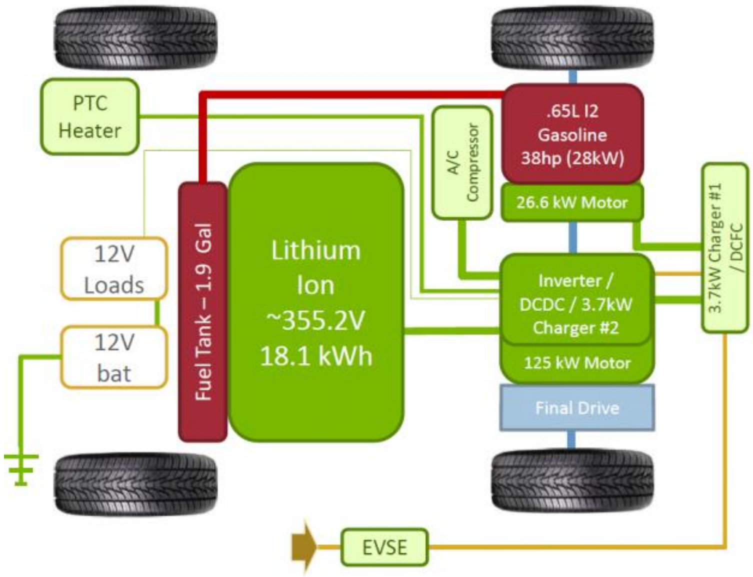


Table 2. Vehicle driving modes.

COMFORT	- Standard operation
ECO PRO	- variation in pedal mapping - limit heat output or heating cycle for exterior mirror, rear window and seat heating - climate control is set to be fuel-efficient. - speed is limited to a set maximum value between 80-130 km/h
ECO PRO+	- variation in pedal mapping - deactivation of cooling and heating - low beams are dimmed - max speed is set at 90km/h

3.2 On-board instrumentation

The 2014 BMW i3 Rex was purchased by ANL and extensively instrumented. The vehicle instrumentation was directed to capture fuel and electric energy use at both vehicle system- and component-level, whilst capturing the input parameters that influence the EV's operating conditions. Instrumentation was multifaceted, consisting of both invasive and non-invasive methods [14][15].

More than 400 signals acquired from the roller bench, emission analysis benches, vehicle CAN (Controller Area Network), power analysers and installed probes were recorded through customized data acquisition panels and software (Table 3). All instrumentation equipment was selected to match temperature working conditions in the range explored by the experimental campaign.

Table 3. On-board measurement locations.

Facility Baseline	- dynamometer (speed & tractive effort, …) - test cell (temperature, pressure, humidity,..)
High Voltage (HV) current Measurements	- DC- HV Battery Net - DC- A/C compressor - DC- PTC heater - DC- Range Extender - DC- Charger (each charger) - AC- EVSE wall supply - AC- Charger (each charger)
Low Voltage Instrumentation	- DC: DCDC output [1] DC: 12V Battery
Coolant System Measurements	- Power electronic/ Rex / Cabin heating loops - Flow (6 locations) - Temperature (20 locations)

Additional Temperature Measurements	- Cabin (7 locations) - Engine oil (2 locations) - Catalyst (pre/mid/post) - Engine bay - Radiator outlet
CAN: Diagnostics and Broadcast	- Diagnostic messages - Broadcast CAN

4 Test procedure

4.1 Drive cycles

The BMWi3 was tested against a modified version of the SAE J1634 Multi Cycle Test (MCT) [16], the New European Drive Cycle (NEDC) [17]-[20], and the World Harmonised Light Vehicle Test Procedure (WLTP) [21].

The MCT (**Figure 8**) was developed to provide a full depletion of the vehicle's HV battery within reasonable testing time, while offering a range of powertrain loading and driven vehicle speeds. It includes the US EPA cycles UDDS, HWFET, US06, and depending on the overall duration of the testing (varying with temperature) it also includes depletions sections at 105 km/h. When the vehicle was unable to complete the drive cycles within the test, the end of test criteria was determined as the starting of the range extending engine.

Figure 8. Modified MCT (UDDS, HWY and US06 drive cycles, with depletion events at 105km/h).

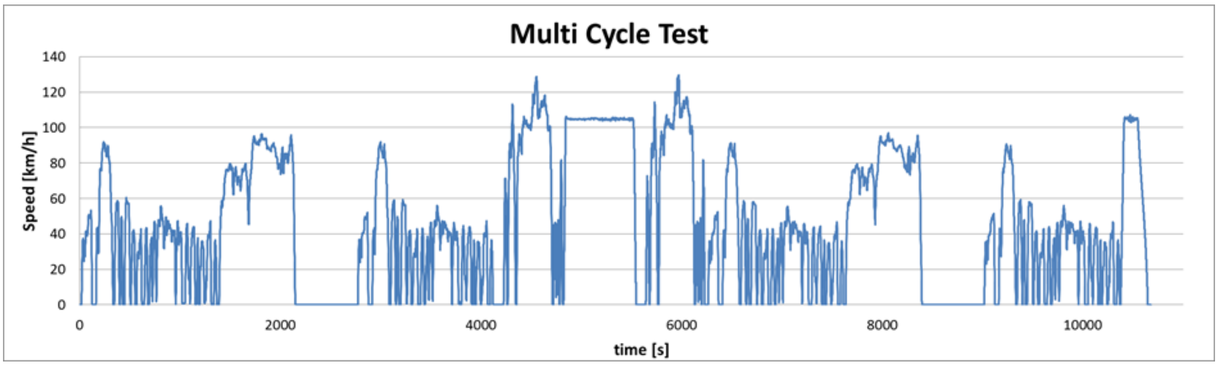
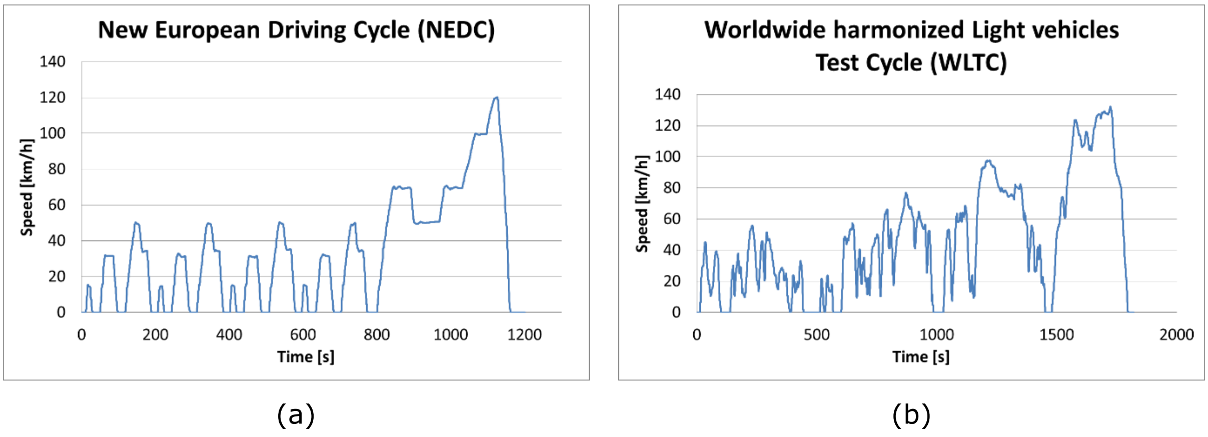


Figure 9. Speed vs. time profiles for NEDC (a) and WLTC (b).



The NEDC (**Figure 9**a) was adopted according to applicable EU legislation, at the time of the testing, for type approval of light passenger and commercial vehicles, which also applied for emissions and energy efficiency measurements of EVs [19][20].The charge depleting (CD) test procedure to determine the range and energy consumption of electrified vehicles foresees the repetition of the NEDC cycle. The *end-of-test* is reached at one of the following criteria: (1) when the vehicle is not able anymore to meet the target curve at 50 km/h, or (2) when an indication from the standard on-board instrumentation is given to the driver to stop the vehicle, or (3) when the fuel consuming engine starts up [20].

The BMWi3 was also tested according to the new WLTP [21] the new, more realistic, test procedure for measuring CO_2 emissions, fuel or energy consumption and electric range from light-duty vehicles (passenger cars and light commercial vans) introduced as from last September 1st. The end-of-test criterion was applied according to the procedure specifications [21].

4.2 Test Matrix

A joint test matrix was established for complementary testing at ANL and JRC facilities. The aim was to assess the vehicle energy use variation across EU and US legislative cycles, at ambient temperatures in the range -30°C/+50°C, providing a comparison with data at standard test temperatures. Overall ANL and JRC results were presented in two prior papers [14][15]; the present report will focus on the experimental activity carried out in VeLA 8 facility (see Table 4).

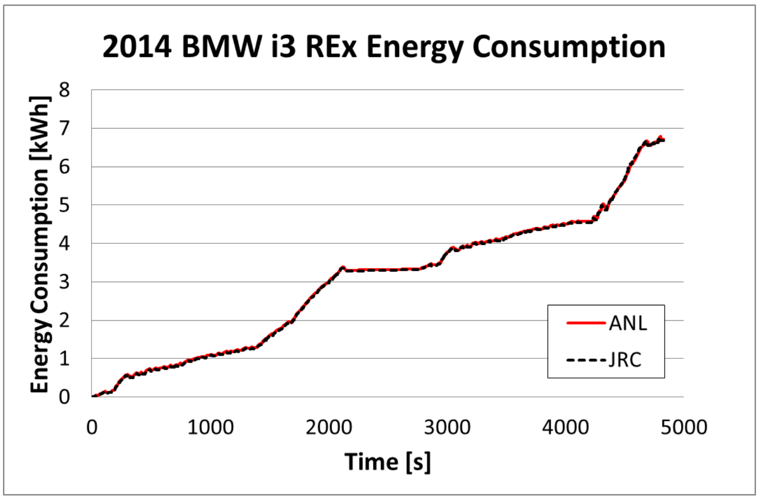
Table 4. Tests performed in VeLA 8

T [°C]	HVAC [ON/OFF]	Driving Mode
-30 23 50	ON OFF ON	COMFORT
23	OFF	COMFORT
-30 -7 -7 23 50	ON ON OFF OFF ON	COMFORT

4.3 Cross-Lab comparison

The initial test campaign was conducted at ANL's APRF test facility, and then the vehicle was shipped fully instrumented from Chicago to JRC premises in Italy. Preliminary test runs were performed at VeLA8 in order to verify consistent operation of the vehicle and instrumentation following transport between the two facilities. The evaluation was done through two steps: (1) the verification of the vehicle loading and operational behaviour during dynamometer coast downs; (2) the completion of standard and custom drive cycles in which the vehicle operation and energy use were compared. During the coast down tests, the vehicle operation and corresponding vehicle losses compared well, and the vehicle energy consumption on comparative drive cycles varied between the two facilities by less than 1% (**Figure 10**).

Figure 10. Energy use compared across the correlation drive cycle.



5 Presentation and discussion of results

Previous studies have already demonstrated that electrified vehicles performance is significantly affected by low ambient temperature [22][23]. This is due to increased drag and friction in moving components, lower efficiency and decreased power capabilities of the battery, and to the associated accessories use (most notably, cabin conditioning). The present study reports about results on energy use variability at extreme temperatures ranging from - 30°C to 50°C, while capturing comparative data at standard temperatures.

5.1 Energy efficiency for CD operation

5.1.1 US legislative cycles

This paragraph presents energy consumption results over the modified MCT. The test was repeated under 4 different temperature conditions: namely -30°C, 23°C and 50°C. Vehicle soaking at the set temperature for variable duration (12 – 48 hours) was performed prior to each test, and proper instrumentation was applied in order to ensure that thermal stability of vehicle and its components was reached. All tests were performed with same settings of the vehicle's climate control system and without vehicle cabin temperature pre-conditioning - except for test at 23°C, which was performed with climate control off.

Test results displaying vehicle energy consumption over the MCT are reported in **Table 5** and in the following figures without taking into account the recharge efficiency losses.

Table 5. Energy use across temperatures for MCT

Ambient Temperature	Charge Depleting Useable Battery Energy (UBE)	Percent of Manufacturer Stated Useable Battery Energy (18,100 Wh)
-30°C	16439	90.8%
23°C	17743	98.0%
50°C	17481	96.6%

Figure 11. Vehicle energy use as a function of the varying temperatures for MCT.

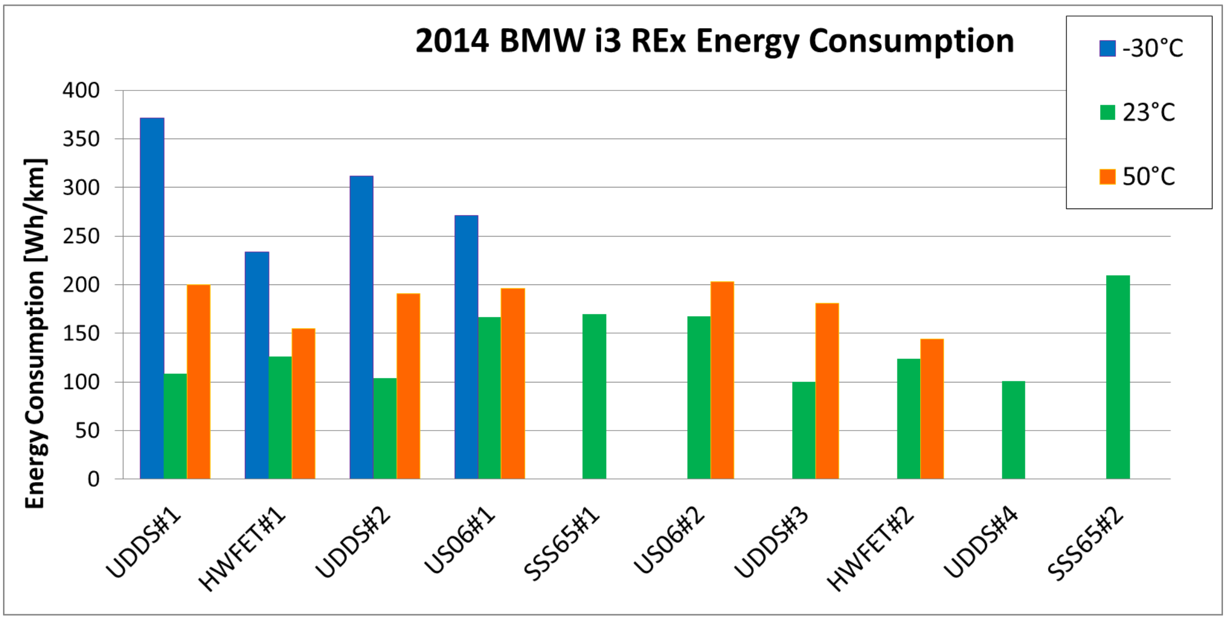


Table 5 summarises the useable battery energy for the cycles within the MCT at different temperatures, compared to the stated useable battery capacity by the manufacturer [24]. As can be noticed, extreme ambient temperatures affect the available battery energy during charge-depleting operation, with more significant impact at negative temperature.

In addition to impacting the useable battery energy, ambient temperature also affect the energy consumption of the vehicle while in operation, as can be observed from **Figure 11** showing the specific energy consumption of the vehicle over all cycles within the MCT.

The first four cycles were completed at all test temperatures, then testing continued until start of the range extending engine (end of test criterion). Please note that the -30°C final cycles are not displayed, as only a partial cycle was completed prior to the engine start; also, according to the test procedure, steady state driving was not performed at 50°C and -30°C.

As a result, the variation in ambient temperature caused an increase in the distance-specific energy consumption at both higher and lower temperature than 23°C, with more significant variations found at cold temperature (+120% at -30°C). The distance-specific energy consumption increased significantly on the initial cold-start driving cycle: ≅ 250% at -30°C and 89% at 50°C. Accordingly, the energy use share across the drive-cycles also changed varying the test ambient conditions, with a more evident "first-cycle effect" (higher energy consumption for UDDS#1 cold start compared to UDDS#2 hot start) at negative temperature, due to drag and friction increase in moving mechanical components.

Figure 12 presents a review of energy consumption distribution across the main vehicle components on a per-cycle basis, as each cycle within the MCT offers unique vehicle driving intensity, average speed, and range [14].

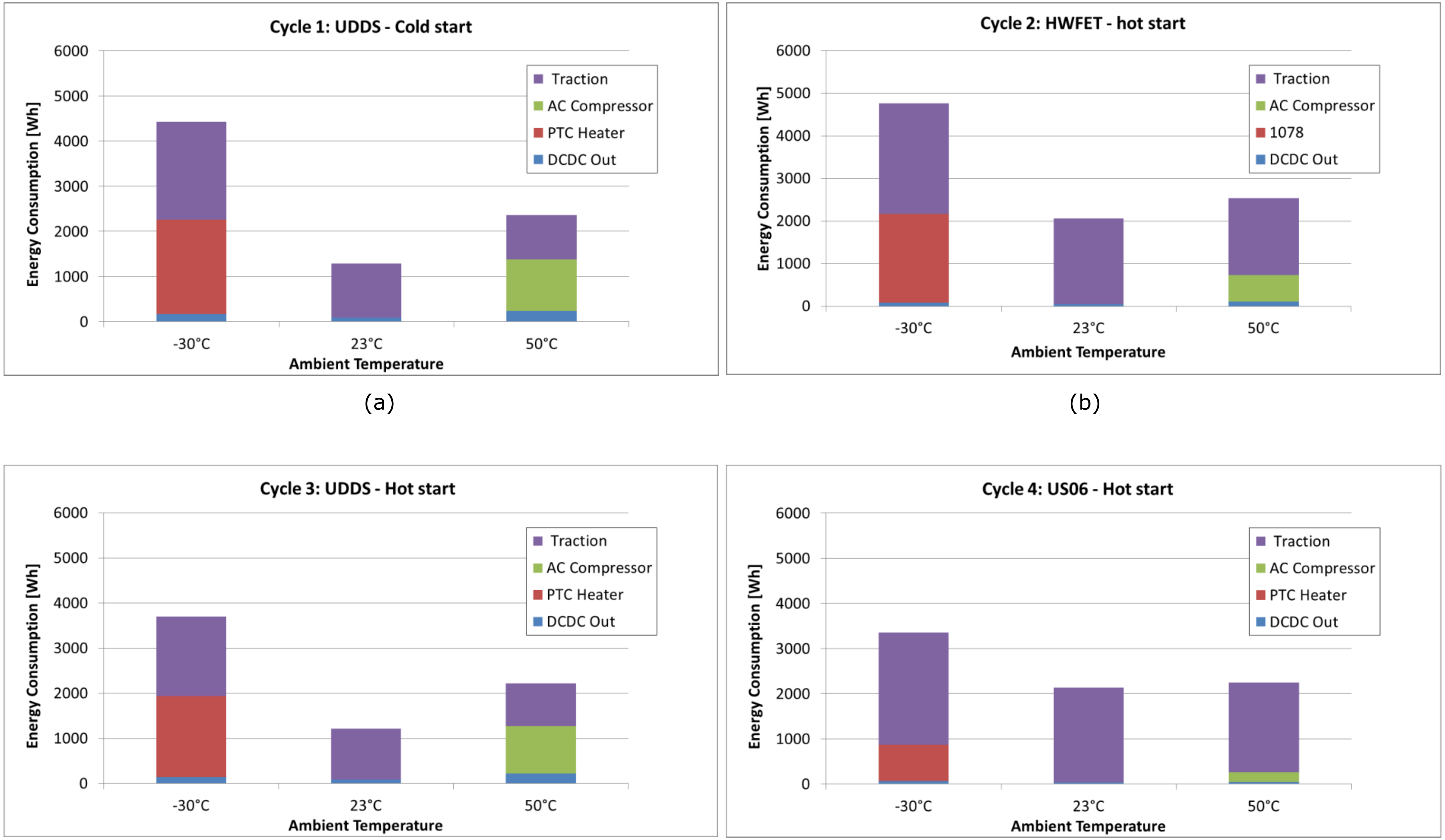
The first drive cycle of the MCT is the UDDS cycle, characterized by low speed and low energy driving, performed as a "cold start". All vehicle components are brought from ambient to operating temperature within this cycle, so that the energy use is higher respect to the following UDDS "hot start" cycle, in particular at cold temperature as energy is required to condition the vehicle cabin and powertrain components. Total energy use on this cycle at -30°C was greater than that of any other cycle performed, with a ~100% increase respect to the 23°C baseline. As can be observed from **Figure 12a**, both vehicle traction and cabin conditioning account for nearly half of the total energy used at extreme temperatures, with a minor energy share needed for power supply to the low voltage accessories through the DCDC inverter.

The second cycle completed, immediately after the first UDDS cycle, was the HWFET, which represents a higher speed, but low power cycle. Both the vehicle and its HVAC (Heating Ventilation and Air Conditioning system) system already reached normal operating conditions in the previous cycle, so that energy was not required for bringing the powertrain or the cabin to operating temperature. Indeed, the prior conditioning, higher average speed, and reduced cycle length led to a consistently higher percentage of total energy devoted to driving the vehicle **Figure 12b**.

Then, another UDDS cycle was performed following 10 min soak. As can be seen from **Figure 12c**, by comparing the hot and cold start UDDS, without the energy requirement for bringing the cabin and powertrain to operational temperature, the energy required for driving the vehicle reduced significantly (by ~20% at cold temperature).

The fourth cycle of the MCT was the aggressive US06 cycle which includes sections of higher speed and more aggressive driving behavior, during shorter test duration. As a consequence, the majority of energy use was devoted to vehicle traction (see **Figure 12d**) and a lower impact of ambient temperature was observed. While the difference between the highest and lowest energy use on the UDDS cold start cycle was 245%, the different on the US06 cycle was only 57%.

Figure 12. Energy Consumption by major component with respect to ambient temperature for the different drive cycles



(a)

(b)

(c)

(d)

5.1.2 EU legislative cycles

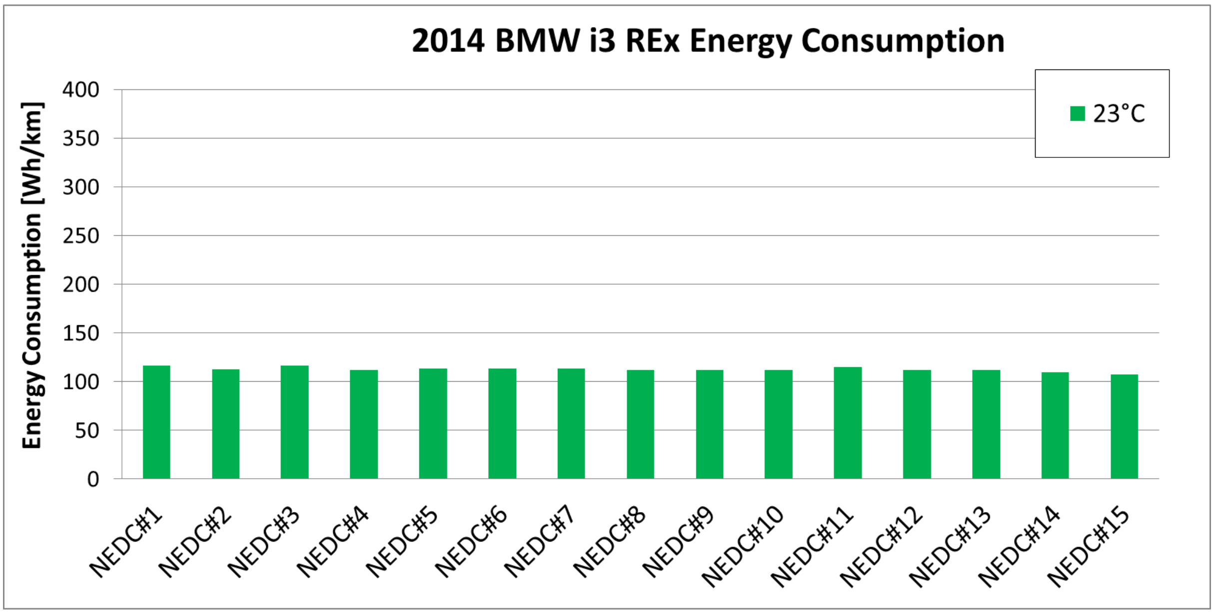
This paragraph presents energy consumption results over the NEDC and WLTP test procedures.

Energy consumption results for the NEDC at 23°C are presented in **Table 6** and in **Figure 13**. The NEDC cycle is characterized by low speed and low energy driving, similarly to the UDDS cycle, so that also energy needs are comparable. As the test was performed at reference ambient temperature, the "first-cycle effect" due to cold start was not significant. Due to the low energy consumed per NEDC cycle, a relatively high number of repetitions (15) were needed before reaching the end of test criteria with the start of the internal combustion engine. It is worth noting that, according to **Table 6**, the CD usable battery energy for that cycle was higher than the value stated by the manufacturer [24], probably due to the way the stated UBE was calculated (e.g. static value or charge depleting operation).

Table 6. Energy use across temperatures for NEDC

Ambient Temperature	Charge Depleting Useable Battery Energy (UBE)	Percent of Manufacturer Stated Useable Battery Energy (18,100 Wh)
23°C	18270	100.9%

Figure 13. Vehicle energy use at 23°C for NEDC.



The WLTP was repeated under 5 different temperature conditions: -30°C, -7°C with and without HVAC system activated, 23°C and 50°C. Vehicle preconditioning was performed prior to each test according to the legislative procedure requirements. All tests were performed with same settings of the vehicle's climate control system and without vehicle cabin temperature pre-conditioning - except for test at 23°C and one test at -7°C, which were performed with cabin climate control off.

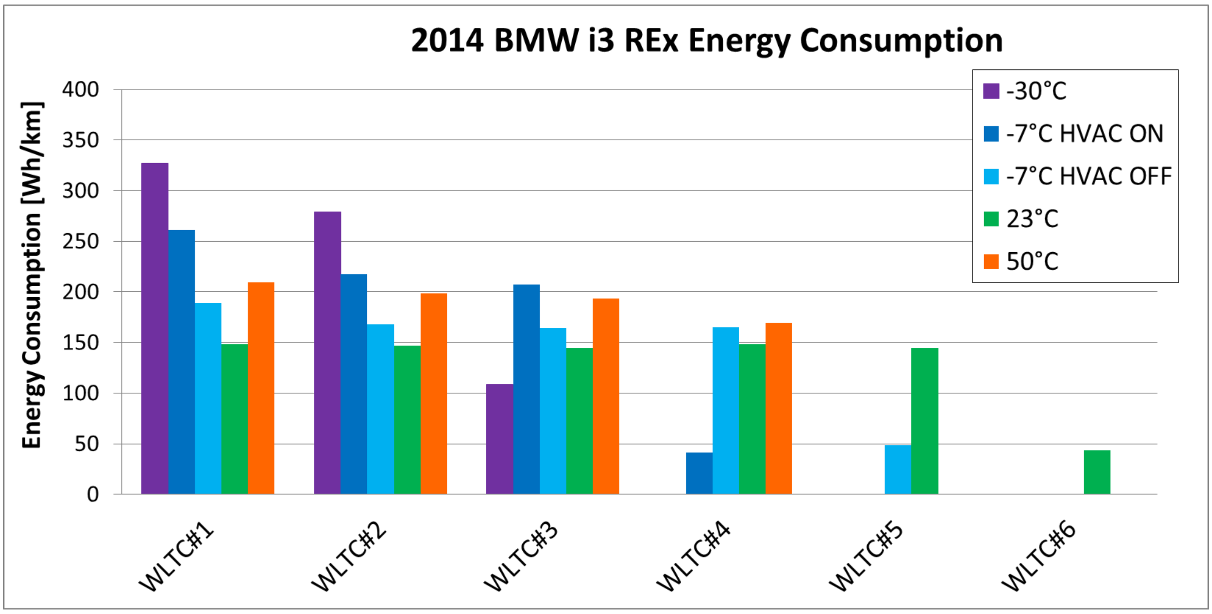
Table 7 summarises the useable battery energy for the cycles within the MCT at different temperatures, compared to the value stated by the manufacturer [24], and **Figure 14** presents the vehicle energy use as a function of the varying test temperatures.

Table 7 clearly shows the impact of varying ambient temperature on the battery performance, i.e. the available battery energy during charge-depleting operation, with larger variations at negative temperatures.

Table 7. Energy use across temperatures for WLTP

Ambient Temperature	Charge Depleting Useable Battery Energy (UBE)	Percent of Manufacturer Stated Useable Battery Energy (18,100 Wh)
-30°C	16562	91.5 %
-7°C (HVAC ON)	16844	93.1%
-7°C (HVAC OFF)	17057	94.2%
23°C	18016	99.5%
50°C	17887	98.8%

Figure 14. Vehicle energy use as a function of the varying temperatures for WLTP.



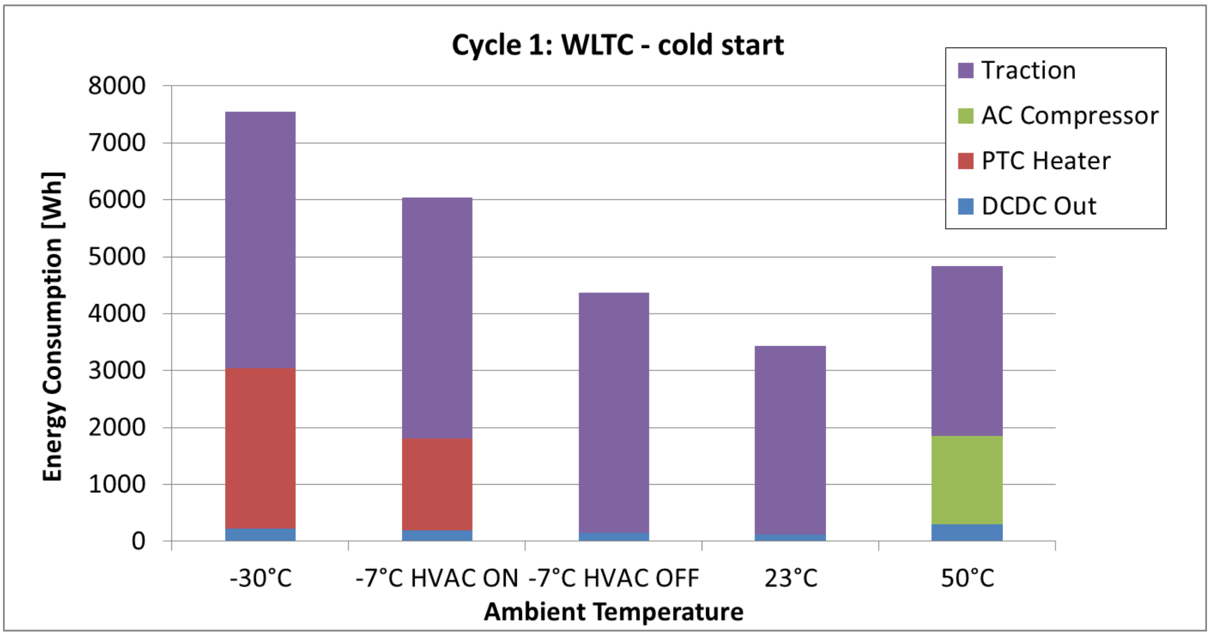
The WLTC features a more dynamic speed profile, a higher mileage and longer duration than NEDC [25].

As can be observed from **Figure 14**, different behaviour is encountered between cold and hot start, which is more significant at negative temperatures due to the higher energy demand for bringing at operational temperature the cabin and powertrain (energy consumption increased by 17% during cold start at -30°C).

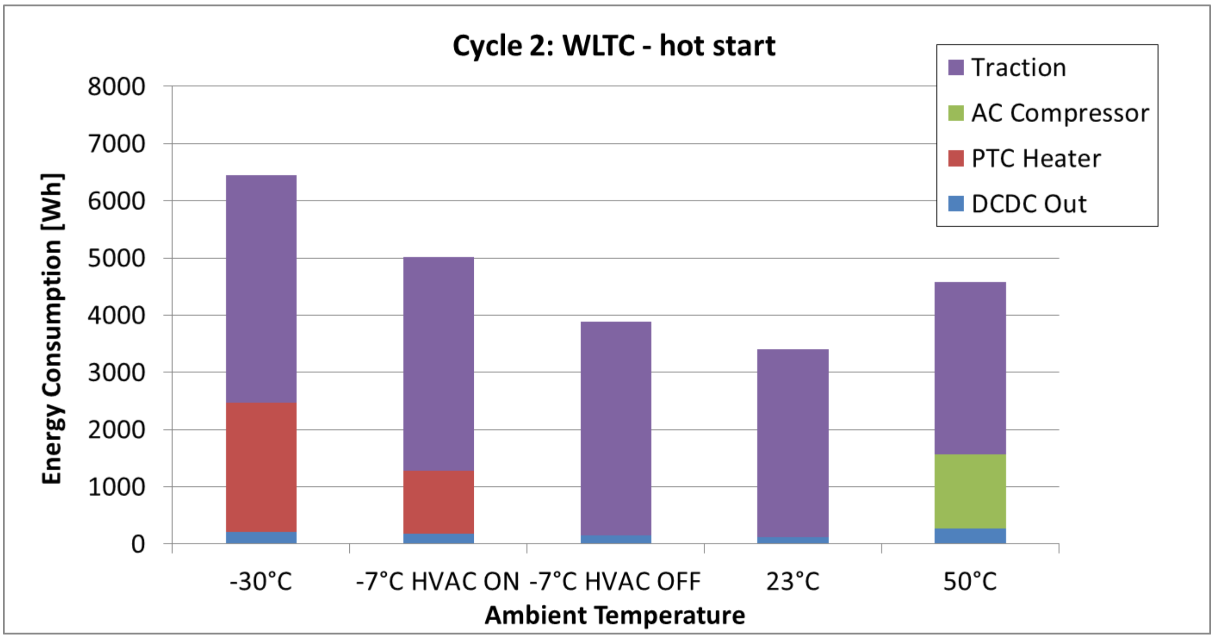
Comparing energy consumption results over WLTP at -7°C and at 23°C, both without cabin climate control, a 27% increase was found due uniquely to the cold temperature effect over mechanical parts (drag and friction increase in moving components) and battery performance. A further 38% energy use increase was then observed for the WLTP test at -7°C with the climate control activated, due to AC Compressor operation.

As confirmed when looking at **Figure 15**, energy share across vehicle components is generally characterized by a significant percentage of energy use by HVAC system at cold temperatures ("PTC heater", for the heating) as well as at 50°C ("AC compressor", for air conditioning). Minor percentage differences were observed between cold and hot start cycle (e.g. 2% decrease for PTC energy use at -30°C for the latter).

Figure 15. Energy Consumption by major component with respect to ambient temperature for WLTP.



(a)



(b)

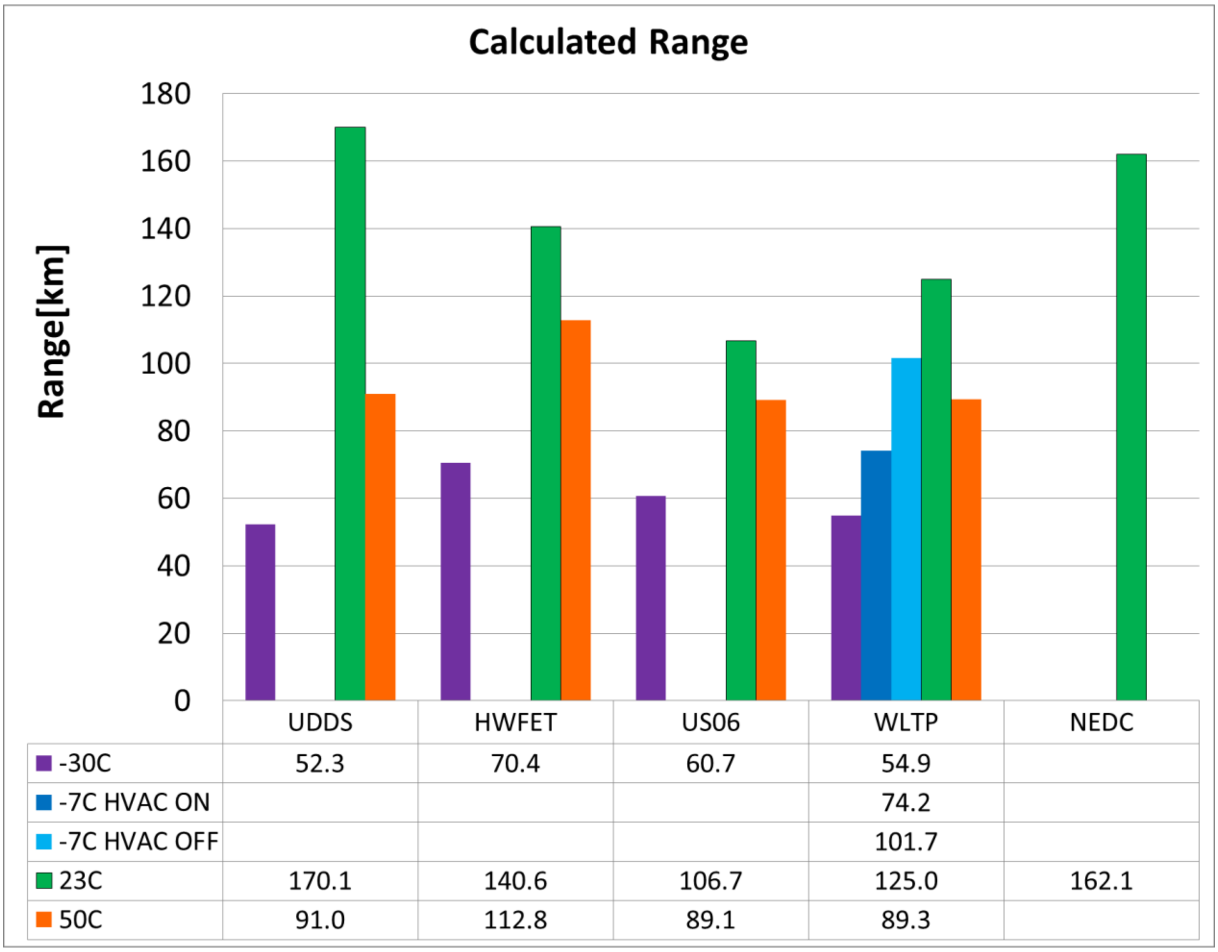
5.2 Driving range for CD operation

Figure 16 provides a summary of the achieved full-electric driving range (i.e. before the ICE starts) for tests on both EU and US legislative cycles. Cycle-specific results for MCT were calculated according to the J1634 standard. Vehicle range over the WLTP cycle was measured according to the legislative specifications.

As can be observed, the maximum driving range was achieved at 23°C for all cycles. Consistently with what observed for the energy consumption variations, the overall driving distance driven before the start of the REx (Range Extender) engine was also significantly affected by ambient temperature. The most significant range reductions were obtained at negative temperatures, ranging from 17% to 53% for tests at -7°C and from 50% to 70% for tests at -30°C, compared to results at 23°C. Still, while the achieved range differed significantly depending on the considered cycle at 23°C, such differences were drastically reduced at -30°C.

It is worth stressing that temperature effects were also rendered more realistic by simulating driving wind speeds onto the EV, which reproduced more realistic operation conditions for the battery and the e-drive train components.

Figure 16. Driving range as a function of varying ambient temperatures.



	UDDS	HWFET	US06	WLTP	NEDC
🟪 -30C	52.3	70.4	60.7	54.9	
🟦 -7C HVAC ON				74.2	
🟦 -7C HVAC OFF				101.7	
🟩 23C	170.1	140.6	106.7	125.0	162.1
🟧 50C	91.0	112.8	89.1	89.3	

6 Conclusions

The report presented experimental findings from a test campaign on a range-extended electric vehicle, carried out in the framework of the transatlantic collaboration between the US DoE ANL and the EC JRC. The aim of the study was to assess the impact of varying ambient conditions on vehicle energy efficiency and achievable driving range.

Tests were performed at ambient temperatures varying in the range -30°C/50°C, over US legislative cycles included in the MCT procedure, over the EU NEDC legislative cycle and according to the new WLTP test procedure. Efficiency analysis of the vehicle and of its components was presented, together with driving range data.

Experimental results demonstrated that ambient temperature strongly affects vehicle energy efficiency over the different test cycles. A similar variation trend was observed across tested temperatures: over all driving cycles, maximum energy consumption was reached at -30 °C, while minimum was touched at 23°C. As a consequence, the attained driving range was significantly reduced at cold temperatures (between 40% and 70% of the compared standard testing conditions). Also, cold temperatures emphasized the "first-cycle effect" (i.e. higher energy consumption for the first cold-start cycle) as more energy is required to condition the vehicle bringing cabin and powertrain components from ambient to operating temperature.

Efficiency analysis of vehicle components demonstrated that a significant percentage of energy was used by the HVAC system when activated, with a stronger impact for heating the cabin at negative temperatures (up to 50% of the total energy use).

A further effect of varying ambient temperature concerned the battery performance, i.e. the available battery energy during charge-depleting operation, which decreased significantly at negative temperatures (9% decrease at -30°C).

When the HV battery energy is depleted and a predefined minimum SOC is reached, the vehicle operates in the charge-sustaining mode and the ICE drives an electric generator recharging the HV Battery. Further analysis will investigate how varying ambient temperatures affect the vehicle fuel economy during charge sustaining operations.

Future studies will focus on PHEVs with a different hybridization level, in order to compare the impact of extreme temperatures on vehicle energy consumption.

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List of abbreviations and definitions

AC	Alternate Current
A/C	Air Conditioning
ANL	Argonne National Laboratory
APRF	Advanced Powertrain Research Facility
CAN	Controller Area Network
CD	Charge Depleting
CS	Charge Sustaining
DC	Direct Current
DoE	Department of Energy
EC	European Commission
EPA	Environmental Protection Agency
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
HEV	Hybrid Electric Vehicle
HV	High Voltage
HVAC	Heating Ventilation and Air Conditioning system
HWFET	Highway Fuel Economy Test
ICE	Internal Combustion Engine
IOC	Ineroperability Centre
JRC	Joint Research Centre
LoI	Letter of Intent
MCT	Multi Cycle Test
NEDC	New European Drive Cycle
P*e*MS	Portable *e*lectric Measurement System
PHEV	Plug-in Hybrid Electric Vehicle
PTC	Positive Temperature Coefficient
REEV	Range Extended Electric Vehicle
REx	Range Extender
SAE	Society of Automotive Engineers
SOC	State of Charge
TEC	Transatlantic Economic Council
UDDS	Urban Dynamometer Driving Schedule
US06	Supplemental Federal Test Procedure
VELA	Vehicle Emission LAboratory
V*e*LA 8	Vehicle *e*lectric Laboratory
WLTC	World Harmonised Light Vehicle Test Cycle
WLTP	World Harmonised Light Vehicle Test Procedure

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