D1.1 C-segment requirements and specifications

nExt geNeration 1200V eLectric hIGH volTage powErtraiN

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Integration and testing of next generation post-800V electric powertrains

(2ZERO Partnership)

Coordinator: Hannes Lacher (AIT Austrian Institute of Technology GmbH)

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PROJECT ABSTRACT

ENLIGHTEN aims at developing, integrating and testing a next generation post 800V electric vehicle powertrain with an indicative voltage level of 1200V. It targets a high performing, cost-optimized and more sustainable drivetrain layout that is also backwards compatible to the existing charging infrastructure with 1000V or 500V respectively. Determining exactly how high the new voltage level should be, to enable expected advantages in a systemic and systematic way is also part of the project. A new voltage level affects the entire sphere of electric mobility, both horizontally (vehicle, charging infrastructure, users, manufacturers) and vertically (OEM, Tier1, Tier2, single component supplier), hence a deliberate decision is required. To accomplish this an advanced electrical system architecture is presented by the ENLIGHTEN consortium in this proposal on whose basis a specific electric vehicle drivetrain will finally be developed and demonstrated in a C-segment vehicle. The TRL5 delivered powertrain will consist of a dual voltage battery system and an integrated motor-inverter E-drive system, complemented by an intermediate DCDC converter, an AC and DC capable onboard charger and a power distribution. All power electronic devices will exploit low loss, ultra-fast switching gallium nitride (GaN) semiconductors for the highest efficiency and to minimize cooling demand and component size. The dual voltage battery can be switched dynamically from one battery voltage into the other while driving. Through these and other measures, the ENLIGHTEN system delivers significant advances over the 2024 State of the Art. The ENLIGHTEN consortium includes 2 automotive companies, 1 Tier1 supplier and 2 SMEs. Their expertise is leveraged by the partnership with 2 research institutions and 4 academia/universities, constituting an ideal setup for strengthening the competitiveness of the European automotive industry.

PARTNERS

Participant no.	Participant short name	Participant organisation name	Country
1. Coordinator	**AIT**	Austrian Institute of Technology GmbH	Austria
2.	**EAT**	Eaton	Czech Republic
3.	**POLITO**	Politecnico di Torino (Polito)	Italy
4.	**IFP**	IFP Énergies nouvelles	France
5.	**AU**	Aarhus University	Denmark
6.	**THI**	Technische Hochschule Ingolstadt	Germany
7.	**MAT**	Manifattura Automobili Torino	Italy
8.	**CGD**	Cambridge GaN Devices	United Kingdom
9.	**LT**	Leadtech	Italy
10.	**FMF**	FPT Motorenforschung AG	Switzerland
11.	**ETH**	Eidgenössische Technische Hochschule Zürich	Switzerland

LIST OF ABBREVIATIONS

Acronym / Short Name	Meaning
ADAC	Allgemeiner Deutscher Automobil-Club
BEV	Battery electric vehicle
CharIN	Charging Initiative
DC	Direct current
EV	Electric vehicle
ICE	Internal combustion engine
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
LFP	Lithium Iron Phosphate
LVD	Low Voltage Directive
NEDC	New European drive cycle
NMC	Nickel Manganese Cobalt
OEM	Original equipment manufacturer
SOC	State of charge
UNECE	United Nations Economic Commission for Europe
WLTC	Worldwide harmonized light-duty vehicles test cycle
WLTP	Worldwide harmonized light-duty vehicles test procedure

EXECUTIVE SUMMARY

The ENLIGHTEN project aims to accelerate the adoption of battery electric vehicles (BEVs) by developing high-voltage powertrains up to 1200V or above, surpassing the current 800V standard. This initiative is informed by a thorough benchmarking of C-segment EVs with a focus on 800V platforms (Section 1), which identified market trends, competitor performance in range and charging, and guided donor vehicle selection. High-voltage architectures are key for improved efficiency and faster charging.

Section 2 highlights the critical link between driving cycles (WLTC, highway) and user needs. While WLTC offers standard consumption data useful for comparisons, highway consumption is vital for BEV long-distance usability, more user oriented. The lack of specific public highway consumption data is noted as a concern for range anxiety.

User requirements analysis (Section 3) reveals key dissatisfactions in long-distance travel and regulatory aspects. Charging experience (speed, cost, availability) and range anxiety persist. Regulatory needs include greater transparency on BEV highway range, potentially requiring mandatory reporting of highway driving consumption.

Section 4 outlines relevant European standards and regulations for high-voltage systems, including the Low Voltage Directive (LVD) and standards like IEC 61851, IEC 62196, and IEC 60664. The CharIN initiative and Combined Charging System (CCS) are key for fast charging, with developments towards higher power and "boost current" highlighted.

This preliminary analysis of benchmarking, driving cycles, user needs, and regulations underpins ENLIGHTEN's goal to develop a 1200V powertrain optimized for efficiency, cost, and real-world usability, addressing current perceived limitations in the EV ecosystem.

1 BENCHMARKING AND STATE OF THE ART

Benchmarking is a fundamental tool in research and development activities, especially in fast-paced fields like electric mobility, enabling a detailed comparison of existing solutions. This helps identify the current best practices, assess performance gaps, and establish reference points useful to guide the development of future technologies. Within the ENLIGHTEN project, benchmarking provides a thorough assessment of the current state of the art of C-segment electric vehicles (EVs) and EVs in general, showing key areas for improvement in next generation high voltage powertrains.

One of the most significant advancements in EV technology in recent years has been the transition from 400V to 800V architectures, leading to substantial improvements in efficiency and charging speeds, with many automakers increasingly adopting these systems to minimize power losses and enable ultra-fast charging. However, the ENLIGHTEN project aims to push innovation further by exploring higher voltage architectures, up to 1200V, which should offer additional benefits.

Within the ENLIGHTEN project, benchmarking serves to analyse in-depth market and technology, providing insights into the strengths and limitations of existing C-segment EVs. Additionally, it enables a comprehensive performance evaluation, focusing on critical attributes such as battery capacity, range, charging speed, and vehicle efficiency. Regulatory compliance is also a key factor, ensuring that technological advancements align with European automotive standards and sustainability objectives. Moreover, benchmarking drives innovation, guiding improvements in power electronics, energy efficiency, and drivetrain architecture.

A thorough benchmarking analysis involves evaluating key parameters related to both powertrain performance and user-related aspects. Peak power (kW) determines vehicle performance and acceleration capabilities, while the battery cell configuration in series and parallel provides insight into energy distribution. The rated battery voltage (Vdc) is particularly relevant as manufacturers transition to higher-voltage architectures to enhance charging speeds and reduce energy losses.

Battery composition is another critical factor, as cell chemistry influences energy density, thermal stability, and longevity. Additionally, the battery cell form factor (e.g., pouch, cylindrical, or prismatic) affects packaging efficiency and cooling performance. Charging performance is assessed based on maximum DC charging power (kW) and average DC charging power from 10% to 80% (kW), providing a realistic measure of fast-charging capability. The ratio of average to maximum DC charging power further indicates how effectively a vehicle maintains high charging rates over a session.

Battery capacity, particularly gross capacity measured in kWh, directly influences range under the WLTP cycle (km) and remains a key determinant of EV usability. Energy efficiency during the WLTP cycle (Wh/km) measures how effectively stored energy is converted into driving range. Charging time, particularly the duration required to charge from 10% to 80% (minutes), is also analysed as it represents a typical fast-charging scenario. Additionally, the WLTP range recharged per minute (km/min) serves as a comparative metric for real-world charging performance.

Finally, a cost analysis is included to evaluate the economic feasibility of vehicles, ensuring that technological advancements remain accessible to consumers. By benchmarking these characteristics, the ENLIGHTEN project aims to identify best practices and areas for improvement, ultimately contributing to the development of a 1200V high-voltage powertrain that is optimized for efficiency, cost, and real-world usability.

1.1 C-SEGMENT EV BENCHMARK

The C-segment, or compact car segment, is a key category in the global automotive market. It represents the third tier of the European passenger car classification, positioned between the smaller B-segment (subcompact cars) and the larger D-segment (midsize cars). Typically measuring between 4.1 and 4.6 meters in length, these vehicles offer a balance between size, practicality and purchase price. These characteristics, in addition to the shift of the market offer towards bigger vehicles, make them very popular both for urban and suburban environments, for single users as well as families.

Moreover, C-segment cars, thanks to the great flexibility offered by their overall dimensions, come in multiple body styles, including hatchbacks, sedans, station wagons, and increasingly, SUVs and crossovers. This results in a highly competitive segment, which drives manufacturers to focus on continuous technological improvements, bringing to this segment features only available on higher end cars up to a few years ago. In fact, beyond versatility, these vehicles often feature high-quality interior materials, finishes and a complete suite of advanced driver-assistance systems (ADAS). Many models often offer multiple powertrain options, including gasoline, diesel, hybrid, and fully electric variants.

In Europe, C-segment vehicles hold a substantial market share, due to the specific use conditions such as urban driving, high fuel prices and growing sensibility towards environmental pollution issues, and limited parking space. Compact cars represent a good compromise between these aspects and the contrasting needs of interior space and rear trunk volume. Well-known models such as the Volkswagen Golf, Toyota Corolla, Audi A3, and Peugeot 308 are the market leaders in this segment in Europe.

C-segment vehicles account for approximately 36.5% of European passenger car sales in 2024, with C-segment SUVs (C-SUVs) emerging as the most popular category at 22.6% market share. As the industry shifts toward sustainability, C-segment EVs are at the forefront of innovation. Manufacturers are investing in longer ranges, faster charging, and improved battery efficiency to enhance EV competitiveness in this segment.

C-segment EVs must meet several key consumer expectations, including:

- Adequate driving range: Typically between 350 and 550 km (WLTP) to support urban and suburban mobility.
- Fast-charging capability: Many models support 100 kW or higher DC fast charging, allowing recharging in under 30 minutes.
- Practicality and space efficiency: Vehicles must retain ample cargo space and interior comfort despite battery integration.

The adoption of C-segment EVs in Europe is accelerating, driven by government incentives, stricter CO_2 regulations, and expanding charging infrastructure. In 2024, this segment accounted for over a third of all electric vehicle sales in Europe, with seven of the ten best-selling battery electric vehicles (BEVs) belonging to this segment.

The benchmarking dataset includes 78 EV models from 26 automotive brands, covering hatchbacks, crossovers, and compact SUVs. It provides a comprehensive view of the current C-segment EV market, incorporating insights from European, American, and Asian manufacturers, including both established and emerging brands.

MODEL	Peak Power [kW]	Battery Cells Series	Battery Cells Parallels	Rated Voltage [V]	Cells Chemistry	Cells Form Factor	Max Charging Power [kW]	Average Charging Power 10-80% [kW]	Average charging power/Max charging power	Battery Capacity [kWh]	WLTP Range [km]	WLTP Efficiency [Wh/km]	Charging Time 10-80% [min]	Range per minute WLTP 10-80% [km/min]	Price IT [€]
Alfa Romeo Junior	115	102	1	377	NMC 811	N/A	100	72.4	0.72	54	410	123.9	29.48	9.7	39500
Audi Q4 e-tron 40	150	N/A	N/A	N/A	NMC	Pouch	165	88.2	0.53	63	412	143.2	28.1	10.3	49990
Audi Q4 e-tron 45	210	96	3	352	NMC	Pouch	175	118.1	0.67	82	544	140.8	27.22	14	57800
Audi Q4 e-tron 55	250	96	3	352	NMC	Pouch	175	118.1	0.67	82	525	145.9	27.22	13.5	67250
BMW iX1 20	150	N/A	N/A	286	NMC 811	N/A	130	80.8	0.62	66.5	475	136.2	33.63	9.9	47990
BMW iX1 30	230	N/A	N/A	286	NMC 811	N/A	130	80.8	0.62	66.5	440	147	33.63	9.2	58800
BMW iX2 20	150	N/A	N/A	286	NMC 811	N/A	130	80.8	0.62	66.5	449	144.1	33.63	9.3	49500
BMW iX2 30	230	N/A	N/A	286	NMC 811	N/A	130	80.8	0.62	66.5	449	144.1	33.63	9.3	60400
BYD Atto3	150	126	1	403	LFP	Prismatic	88	70.2	0.80	62	420	138.1	34.67	8.5	38790
BYD Dolphin	150	126	1	403	LFP	Prismatic	88	61.4	0.70	62	427	145.2	42.42	7	33790
Citroën C3 Aircross	83	N/A	N/A	N/A	LFP	N/A	100	71.9	0.72	45	306	143.8	25.7	8.3	26790
Citroën ë-C4 156CV Plus	115	102	1	377	NMC 811	N/A	100	73.3	0.73	54	402	126.4	29.1	9.7	38900
Citroën ë-C4 X 156CV Plus	115	102	1	377	NMC 811	N/A	100	73.3	0.73	54	402	126.4	29.1	9.7	36900
Citroën ë-C4 X You	100	108	2	400	N/A	N/A	100	N/A	N/A	50	360	129	N/A	N/A	35000
Citroën ë-C4 You	100	108	2	400	N/A	N/A	100	N/A	N/A	50	354	131	N/A	N/A	35350
Cupra Born e-Boost	170	96	3	352	NMC	Pouch	175	88.2	0.50	82	548	140.5	36.68	10.5	46450
Cupra Born Impulse+	170	108	2	397	NMC	Pouch	165	69.8	0.42	63	424	136.8	34.88	8.5	42100
Cupra Born VZ	240	96	3	352	NMC	Pouch	185	91.6	0.50	84	570	138.6	36.22	11	52550
DS3 E-Tense	115	102	1	377	NMC 811	N/A	100	72.4	0.72	54	402	126.4	29.48	9.5	41650

Fiat 600	115	102	1	377	NMC 811	N/A	100	73.3	0.73	54	409	124.2	29.1	9.8	35950
Ford Explorer 52kWh	124	96	2	352	NMC	N/A	145	69.8	0.48	55	380	136.8	31.27	8.5	41500
Ford Explorer 77kWh	210	96	3	352	NMC	N/A	145	118.1	0.81	82	602	127.9	27.37	15.4	49000
Ford Explorer 79kWh AWD	250	96	3	352	NMC	N/A	185	130.4	0.70	84	566	139.6	25.45	15.6	52500
Ford Puma	124	N/A	N/A	N/A	NMC	N/A	100	75.3	0.75	46	376	116	24.3	10.8	32950
Honda e:Ny1	150	N/A	N/A	370	N/A	N/A	80	59.4	0.74	68.8	412	150.2	43.77	6.6	54700
Hyundai Kona Electric 48.6kWh	100	N/A	N/A	269	NMC	Pouch	100	72.8	0.73	51	377	128.4	27.9	9.5	38300
Hyundai Kona Electric 64.8kWh	150	N/A	N/A	399	NMC	Pouch	105	71	0.68	68.5	514	127.2	38.68	9.3	41300
Kia EV3 58.3kWh	150	N/A	N/A	369	NMC	N/A	100	N/A	N/A	58.3	436	126.1	N/A	N/A	35950
Kia EV3 81.4kWh	150	N/A	N/A	343	NMC	N/A	135	105.3	0.78	81.4	600	130	31.1	13.5	39950
Kia Niro EV	150	96	1	358	NMC	Pouch	80	60	0.75	68	463	140	45.35	7.1	40950
Lexus UX	150	96	1	355	N/A	N/A	50	29.4	0.59	72.8	450	142.2	91.5	3.4	58000
Lynk&Co 02	200	N/A	N/A	N/A	NMC	N/A	150	85.2	0.57	69	445	148.3	32.52	9.6	35495
Mercedes-Benz EQA 250+	140	N/A	N/A	N/A	NMC	Pouch	100	80.4	0.80	73.9	560	125.9	36.8	10.6	56630
Mercedes-Benz EQA 300	168	100	3	367	NMC	Pouch	110	93.8	0.85	69.7	438	151.8	29.77	10.3	58210
Mercedes-Benz EQA 350	215	100	3	367	N/A	N/A	110	93.8	0.85	69.7	438	151.8	29.77	10.3	60950
MG 4 Comfort	150	104	1	N/A	NMC	Prismatic	142	94.3	0.66	64	435	141.8	27.47	11.1	34790
MG 4 Standard	125	104	1	N/A	LFP	Pouch	87	59.2	0.68	51	350	145.1	36.02	6.8	30790
MG 4 Trophy Extended Range	180	N/A	N/A	N/A	NMC	Prismatic	144	94.3	0.65	77	520	143.1	33.12	11	40290
MG 4 XPower AWD	320	104	1	N/A	NMC	Prismatic	165	94.3	0.57	64	435	141.8	27.47	11.1	41290
MG ZS 51kWh	130	N/A	N/A	N/A	N/A	N/A	75	67.2	0.90	51.1	320	153.1	30.63	7.3	34490
MG ZS 72kWh	115	N/A	N/A	N/A	NMC	N/A	95	67.2	0.71	72.6	440	155.2	42.7	7.2	39290

Mini Countryman Cooper E	150	N/A	N/A	286	NMC	N/A	130	N/A	N/A	66.5	462	140	N/A	N/A	38700
Mini Countryman Cooper SE	230	N/A	N/A	286	NMC	N/A	130	80.8	0.62	66.5	440	147	33.63	9.2	44900
Nissan Ariya 63kWh Engage	160	96	3	353	NMC 811	Prismatic	130	84.2	0.65	66	403	156.3	31.4	9	42500
Nissan Ariya 87kWh Advance	178	96	4	352	NMC 811	Prismatic	130	105	0.81	91	533	163.2	34.8	10.7	55350
Nissan Leaf e+	160	96	3	350	NMC 532	N/A	46	N/A	N/A	62	385	153	N/A	N/A	37600
Omoda 5	150	N/A	N/A	N/A	LFP	N/A	80	63.8	0.80	64	430	139.5	39.52	7.6	36490
Opel Astra Electric	115	102	1	377	NMC 811	N/A	100	72.4	0.72	54	413	123	29.48	9.8	39900
Opel Frontera	84	N/A	N/A	N/A	LFP	N/A	100	71.9	0.72	45	306	143.8	25.7	8.3	29900
Opel Grandland Electric 73kWh Edition	157	96	1	N/A	NMC	Prismatic	160	72.4	0.45	77	525	139	42.37	8.7	40950
Opel Grandland Electric 82kWh Edition	157	N/A	N/A	N/A	NMC	Prismatic	160	N/A	N/A	86	583	141	N/A	N/A	44450
Opel Mokka BEV	115	102	1	377	NMC 811	N/A	100	72.4	0.72	54	406	125.1	29.48	9.6	36700
Peugeot e-2008 136CV	100	108	2	400	N/A	N/A	100	N/A	N/A	50	340	136	N/A	N/A	38000
Peugeot e-2008 156CV	115	102	1	377	NMC 811	N/A	100	72.4	0.72	54	406	125.1	29.48	9.6	39000
Peugeot e-3008	157	96	1	N/A	NMC	Prismatic	160	72.4	0.45	77	527	138.5	42.37	8.7	41980
Peugeot e-3008 Long Range	170	N/A	N/A	N/A	NMC	Prismatic	160	72.4	0.45	101	700	140	56.87	8.6	48980
Peugeot e-308	115	102	1	377	NMC 811	N/A	100	72.4	0.72	54	410	123.9	29.48	9.7	39650
Renault 4 E-Tech 40kWh	90	93	1	N/A	NMC	N/A	80	N/A	N/A	43	322	124	N/A	N/A	29900
Renault 4 E-Tech 52 kWh	110	92	2	N/A	NMC	N/A	100	N/A	N/A	55	409	127	N/A	N/A	32900
Renault Mégane E-Tech EV60 Evolution	96	96	3	352	NMC	Pouch	130	N/A	N/A	65	480	125	N/A	N/A	38050
Renault Mégane E-Tech EV60 Techno	160	96	3	352	NMC	Pouch	130	66.6	0.51	65	450	133.3	37.85	8.3	40550
Renault Scenic E-Tech Evolution Comfort Range	125	96	2	N/A	NMC	Pouch	130	105	0.81	65	450	133.3	24	13.1	40050
Renault Scenic E-Tech Techno Long Range	160	96	3	N/A	NMC	Pouch	150	95.7	0.64	92	625	139.2	38.17	11.5	47250

Skoda Elroq 50	125	96	2	352	NMC	Pouch	145	69.8	0.48	55	375	138.7	31.27	8.4	34500
Skoda Elroq 60	150	108	2	397	NMC	Pouch	165	69.8	0.42	63	390	151.3	35.48	7.7	38500
Skoda Elroq 85	210	96	3	352	NMC	Pouch	175	91.6	0.52	82	560	137.5	35.3	11.1	43500
Smart #1 Pro	200	N/A	N/A	N/A	NMC	N/A	150	85.2	0.57	66	440	140.9	30.55	10.1	39545
Smart #1 Pure	200	N/A	N/A	N/A	LFP	N/A	130	N/A	N/A	49	310	152	N/A	N/A	37045
Smart #3 Pro	200	N/A	N/A	N/A	LFP	N/A	130	N/A	N/A	49	325	145	N/A	N/A	40545
Smart #3 Pro+	200	N/A	N/A	N/A	NMC	N/A	150	85.2	0.57	66	415	149.4	30.55	9.7	45545
Volkswagen ID.3 GTX	210	96	3	352	NMC	Pouch	185	121.6	0.66	84	600	131.7	27.27	15.4	49600
Volkswagen ID.3 GTX Performance	240	96	3	352	NMC	Pouch	185	121.6	0.66	84	601	131.4	27.27	15.4	51400
Volkswagen ID.3 Pro	150	108	2	397	NMC	Pouch	165	69.8	0.42	63	427	135.8	34.88	8.6	40990
Volkswagen ID.3 Pro S	150	96	3	352	NMC	Pouch	175	91.6	0.52	82	553	139.2	35.3	11	42490
Volkswagen ID.3 Pure	125	96	2	352	NMC	Pouch	145	N/A	N/A	55	388	134	N/A	N/A	36490
Volkswagen ID.4 GTX	250	96	3	352	NMC	Pouch	175	91.6	0.52	82	515	149.5	35.3	10.2	54990
Volkswagen ID.4 Pro	210	96	3	352	NMC	Pouch	175	114.6	0.65	82	529	145.6	28.22	13.1	47990
Volkswagen ID.4 Pure	125	96	2	352	NMC	Pouch	145	69.8	0.48	55	363	143.3	31.27	8.1	39490
Volkswagen ID.5 GTX	250	96	3	352	NMC	Pouch	175	91.6	0.52	82	533	144.5	35.3	11	58280
Volkswagen ID.5 Pro	210	96	3	352	NMC	Pouch	175	91.6	0.52	82	556	138.5	35.3	11	51280
Volkswagen ID.5 Pure	125	96	2	352	NMC	Pouch	145	69.8	0.48	55	370	140.5	31.27	8.3	46280
Volvo EC40 Single Motor Core	175	N/A	N/A	N/A	NMC	N/A	180	85.2	0.47	70	478	138.1	32.52	10.3	53300
Volvo EC40 Single Motor Extended Range Core	185	108	3	400	NMC	Pouch	205	116	0.57	82	581	136	28.58	14.2	56100
Volvo EX30 Single Motor Core	200	N/A	N/A	N/A	LFP	N/A	135	85.2	0.63	51	344	142.4	24.15	10	37350
Volvo EX30 Single Motor Extended Range Core	200	N/A	N/A	N/A	NMC	Pouch	150	91	0.61	69	476	134.5	29.53	11.3	42600

Volvo EX40 Single Motor Core	175	N/A	N/A	N/A	NMC	N/A	180	85.2	0.47	70	467	141.3	32.52	10.1	51350
Volvo EX40 Single Motor Extended Range Core	185	108	3	400	NMC	Pouch	205	116	0.57	82	572	138.1	28.58	14	34150

Table 1 C-segment EV benchmarking

The peak power of C-segment EVs varies significantly across the dataset, reflecting differences in vehicle positioning, powertrain configurations, and market strategies. The average peak power is approximately 160 kW, with values ranging from 83 kW to 320 kW. This indicates that while most vehicles in this segment are designed to provide a balance between efficiency and performance, certain high-powered variants do exist.

Around 70% of the vehicles fall within a 100 kW to 180 kW range, which is typical for single-motor configurations aimed at urban and highway driving. Higher power outputs, exceeding 200 kW, are found in about 20% of the models and are generally associated with dual-motor configurations and all-wheel-drive systems, enhancing acceleration and dynamic performance. These models are often positioned as premium or performance-oriented variants.

Lower-power models, typically below 120 kW, make up about 10% of the dataset and prioritize efficiency and affordability, catering to urban commuters. On the other hand, vehicles at the higher end of the power spectrum are designed for customers seeking greater acceleration, high-speed capability, and enhanced driving dynamics. The variation in power outputs also reflects differences in battery capacity, motor technology, and vehicle weight.

The battery pack configuration across the dataset reflects variations in vehicle design, performance needs, and efficiency strategies. The nominal voltage of the battery pack is determined by the number of battery cells in series, while the total battery capacity is influenced by the number of cells in parallel.

The battery voltage in C-segment EVs generally ranges between 350V and 400V, with an average of approximately 360V. Most vehicles (around 75% of the total) use 96 to 108 cells in series, resulting in voltages around 352V to 400V, which is typical for 400V-class architectures. A small number of models, approximately 10%, have slightly lower values, around 270V to 350V.

Regarding battery size, vehicles with a higher number of parallel cells tend to have larger capacity battery packs, offering extended range at the expense of weight and cost. Models with one or two parallel cells make up about 60% of the dataset and generally fall into the mid-range battery category, while those with three or more parallel cells indicate higher capacity configurations, present in around 25% of the vehicles considered, often exceeding 75 kWh.

The presence of 400V architectures only indicates that C-segment EVs have yet to adopt the newer 800V systems, which are currently limited to higher-end and performance-oriented models. However, as battery technology advances and 800V charging infrastructure expands, it is likely that future iterations of C-segment EVs will begin incorporating higher-voltage powertrains to enable faster charging and improved efficiency.

Battery chemistry is a crucial factor in the performance, cost, and longevity of electric vehicles. In the analysed dataset, approximately 70% of C-segment EVs use Nickel Manganese Cobalt (NMC) batteries, while around 20% incorporate Lithium Iron Phosphate (LFP) chemistry. The choice of chemistry reflects trade-offs between energy density, cost, thermal stability, and lifespan.

Nickel Manganese Cobalt (NMC) batteries are widely used in the EV industry due to their high energy density, which enables longer range while keeping battery size and weight manageable. Different formulations exist, such as NMC 811 (80% nickel, 10% manganese and 10% cobalt), which contains a higher percentage of nickel, reducing cobalt dependency while increasing energy density. However, NMC batteries tend to be more expensive due to material costs, and they require active thermal management systems to maintain stability and prolong their lifespan.

Lithium Iron Phosphate (LFP) batteries offer greater thermal stability and longer cycle life, making them more resistant to degradation over time. They also reduce reliance on expensive and supply-constrained materials like cobalt and nickel, lowering production costs. However, LFP chemistry has a lower energy density, which typically results in a shorter range compared to NMC batteries of the same size. Recent improvements in cell-to-pack integration have helped offset this disadvantage, making LFP an increasingly attractive option for cost-effective and durable EVs.

The dataset reveals that NMC chemistry dominates the C-segment, particularly in vehicles focused on longer range and higher performance. The presence of NMC 811 variants in several models suggests a push toward higher nickel content, which enhances energy density but requires careful thermal regulation. Some older NMC variants, such as NMC 532, are still in use, particularly in models that have been on the market for a longer time.

LFP batteries are primarily found in cost-sensitive models, including entry-level EVs, where durability and affordability are prioritized over maximum range. Their adoption aligns with trends observed in other segments, where automakers are shifting to LFP for standard-range vehicles while reserving NMC for long-range and high-performance variants.

Overall, the data reflects a dual approach in battery chemistry selection, with NMC batteries dominating higher-end and longer-range models, while LFP is emerging as a viable alternative for budget-friendly EVs. As battery technology continues to evolve, improvements in LFP energy density and NMC cost efficiency could lead to further optimization in the C-segment EV market.

Battery cell form factor plays a crucial role in determining the energy density, thermal management, and overall packaging efficiency of an EV. The dataset shows that pouch cells dominate the C-segment, appearing in over 60% of analysed models, while prismatic cells are used in about 25% of the vehicles. The three main form factors used in modern EVs, are pouch, prismatic and cylindrical, each having distinct characteristics.

Pouch cells are widely used due to their lightweight design and flexibility in pack integration. They allow for higher energy density per unit volume, making them an efficient choice for space-constrained vehicle architectures. However, they require external structural support and are more susceptible to swelling over time, which can impact long-term durability.

Prismatic cells offer better structural integrity and are easier to package in a uniform battery pack design. Their rigid casing improves safety and heat dissipation, reducing the risk of thermal runaway. However, they are less space-efficient than pouch cells and tend to be heavier.

Cylindrical cells are not present in the analysed dataset but are sometimes used in high-performance EVs due to their robust design and efficient cooling properties. They are less common in the C-segment because of packaging constraints and space efficiency limitations.

The predominance of pouch and prismatic cells in C-segment vehicles indicates that manufacturers prioritize energy density, thermal management, and pack flexibility over absolute durability. As battery technology advances, the industry may shift toward structural battery integration, further optimizing weight distribution and energy efficiency in future EV designs.

Battery capacity plays a crucial role in determining an EV’s range. The dataset reveals that battery capacities in C-segment EVs range from 43 kWh to 101 kWh, with an average of approximately 66 kWh. Around 65% of the analysed models feature battery capacities between 50 kWh and 80 kWh, while larger packs above 80 kWh are present in about 20% of the dataset, mainly in long-range variants. A small percentage of vehicles, particularly entry-level models, utilize smaller battery packs below 50 kWh, prioritizing cost efficiency and urban mobility.

WLTP range varies significantly, spanning from 306 km to 700 km, with an average of 454 km across the dataset. Around 60% of the vehicles achieve a range between 400 km and 550 km, balancing battery size, energy consumption, and aerodynamics. Vehicles with the longest ranges, exceeding 600 km, generally feature battery capacities above 80 kWh. On the other hand, models with sub-350 km ranges, comprising approximately 10% of the dataset, typically use smaller battery packs and are designed for city commuting rather than long-distance travel.

Energy efficiency, measured in Wh/km under the WLTP cycle, provides insights into how effectively a vehicle converts battery energy into real-world range. The dataset shows efficiency values ranging from 116 Wh/km to 163 Wh/km, with an average of 138 Wh/km. The most efficient models, consuming below 125 Wh/km, make up about 20% of the dataset, often featuring aerodynamic optimizations, lightweight construction, and energy-efficient drivetrains. Conversely, less efficient vehicles consuming over 150 Wh/km, accounting for roughly 15% of the dataset, tend to have higher power outputs, all-wheel-drive configurations, and increased vehicle weight.

Besides drivetrain efficiency and battery technology, vehicle-specific characteristics such as shape, aerodynamics, and weight significantly influence overall energy consumption. Sleek, aerodynamically optimized designs with low drag coefficients (Cd) contribute to improved efficiency, while heavier vehicles, particularly SUVs, tend to exhibit higher energy consumption.

These findings highlight the trade-off between battery capacity and range, where larger battery packs enable longer range but increase vehicle weight. As battery technology and vehicle efficiency continue to improve, manufacturers will aim to optimize this balance, ensuring that future C-segment EVs deliver maximum range with minimal energy consumption.

Charging performance is a critical factor influencing the practicality of EVs, particularly for long-distance travel. The dataset reveals that maximum DC charging power varies from 46 kW to 205 kW, with an average of approximately 130 kW. Around 60% of vehicles support peak charging power between 100 kW and 175 kW, which is standard for most modern EVs. A smaller portion, approximately 20%, can charge above 180 kW, enabling significantly reduced charging times. On the lower end, vehicles with charging capabilities below 100 kW, making up around 15% of the dataset, often take longer to replenish their battery.

A more relevant metric for real-world charging performance is average charging power from 10% to 80% state of charge (SOC), which accounts for power tapering during the charging process. The dataset shows average charging power ranging from 29 kW to 130 kW, with an overall average of 84 kW. The ratio of average to maximum charging power provides insight into how effectively a vehicle maintains high charging rates. Most models have a ratio between 0.5 and 0.8, indicating that higher peak power ratings do not always translate to sustained fast charging. Vehicles with ratios closer to 0.8 tend to have more efficient thermal and battery management systems, preventing significant power drop-off during charging sessions.

Charging time from 10% to 80% varies significantly across models, ranging from 24 minutes to 92 minutes, with an average of 33 minutes. Roughly 50% of vehicles charge within 25 to 35 minutes, which aligns with expectations for modern EVs equipped with fast-charging capabilities. Models requiring more than 40 minutes, representing about 15% of the dataset, typically have either lower maximum charging power or larger battery capacities that take longer to recharge.

An important real-world metric is WLTP range added per minute of charging, which reflects how efficiently energy is transferred into usable driving distance. The dataset shows values ranging from 3.4 km/min to 15.6 km/min, with an average of 10 km/min. Around 25% of models achieve charging speeds above 12 km/min, making them highly suitable for long-distance travel. In contrast, vehicles below 7 km/min, comprising about 10% of the dataset, may require more frequent and prolonged charging stops.

The analysis highlights significant variations in charging performance across C-segment EVs, influenced by battery architecture, charging curve optimization, and thermal management efficiency. Future improvements in higher-voltage architectures, battery preconditioning, and fast-charging networks will be key to reducing charging times and enhancing user convenience.

Pricing is a key factor influencing consumer adoption of EVs. The dataset shows that C-segment EV prices in the Italian market range from €26,790 to €67,250, with an average of approximately €43,000. Around 50% of vehicles are priced between €35,000 and €45,000, aligning with the mid-range EV segment. Entry-level models, priced below €35,000, represent only 20% of the dataset, offering few accessible options for consumers. Meanwhile, premium and performance-oriented variants, exceeding €50,000, make up 25% of the market, often featuring larger battery packs, high-end powertrains, and advanced technology features.

Also, the brand of a vehicle plays a crucial role in pricing, as premium manufacturers tend to command higher prices due to brand positioning. Established European luxury brands typically fall in the upper price range, often exceeding €50,000, while Asian manufacturers and newer EV brands tend to offer more competitively priced alternatives. Additionally, automakers with strong electrification strategies benefit from platform-sharing and component standardization, allowing them to offer better-equipped vehicles at more competitive prices.

The analysis highlights a correlation between battery capacity, performance, and pricing, with larger battery packs and high-power drivetrains contributing to higher costs. However, certain models achieve competitive pricing by optimizing battery chemistry and production efficiency, particularly those utilizing LFP battery technology, which reduces reliance on expensive materials like cobalt and nickel.

As battery production costs decrease and government incentives continue to support EV adoption, pricing trends are expected to shift, making C-segment EVs more affordable over time. Increased competition from both traditional automakers and emerging EV brands is likely to further drive cost reductions and expand consumer choices in this segment.

1.2 800V EV BENCHMARK

The 800V electric vehicle architecture represents a significant advancement over traditional 400V systems, enabling faster charging, greater efficiency, and improved powertrain performance. This shift is particularly noticeable in premium and high-performance EVs, but it will gradually become more common in mainstream models as battery and power electronics technology continue to evolve. The move toward 800V systems is primarily driven by the need to reduce charging times, minimize energy losses, and optimize the overall efficiency of electric drivetrains.

One of the most significant advantages of 800V architecture is its ability to support ultra-fast charging. Compared to 400V systems, vehicles with 800V technology can accept higher power levels, often exceeding 270 kW, allowing them to recharge from 10% to 80% in as little as 15 to 20 minutes. This enhancement is crucial for long-distance travel, reducing downtime at charging stations and making EVs more practical for everyday use.

Beyond charging speed, 800V systems offer substantial efficiency improvements. Higher voltage reduces current flow, which minimizes electrical losses due to resistance. Because power loss is proportional to the square of the current, lowering the current significantly decreases energy dissipation as heat. This leads to improved overall efficiency, allowing EVs to extract more range per kilowatt-hour of battery capacity. Furthermore, the reduction in current enables the use of thinner and lighter wiring, contributing to weight savings that further enhance vehicle efficiency and dynamics.

Another key benefit of 800V technology is the potential for optimized powertrain performance. Higher voltage allows for more efficient inverters and motors, enabling increased power output with reduced losses. This leads to better acceleration, sustained high-speed performance, and overall improved vehicle dynamics. Many high-performance EVs leverage 800V systems to achieve superior driving characteristics and efficiency.

Despite these advantages, 800V architecture presents certain challenges. The development and manufacturing of 800V-compatible components, including inverters, battery management systems, and high-voltage cables, require specialized materials and engineering. As a result, the initial cost of producing 800V EVs is higher than that of 400V models, making them less accessible in budget-friendly vehicle segments. While prices are expected to decrease as production scales up, cost remains a barrier to widespread adoption.

Another limitation is the availability of charging infrastructure. Although the number of 800V-compatible fast-charging stations is growing, a significant portion of existing DC fast chargers still operate at 400V. This means that in many locations, 800V EVs may not achieve their full charging potential. The continued expansion of high voltage charging networks will play a critical role in addressing this issue.

The durability and longevity of battery cells also need careful consideration. Higher voltage operation places greater electrical stress on batteries, potentially impacting long-term reliability and degradation rates. Current lithium-ion battery chemistries must be optimized for high-voltage cycles to maintain long-term performance and safety. Additionally, shifting to an 800V system requires a complete redesign of key powertrain components, including motors, inverters, and onboard chargers, which adds complexity to vehicle manufacturing and supply chain logistics.

Looking ahead, the adoption of 800V systems is expected to accelerate, particularly as advancements in semiconductor materials such as silicon carbide (SiC) improve the efficiency and cost-effectiveness of high-voltage power electronics.

As of today, due to the current limitations in cost, infrastructure, and manufacturing complexity, 800V technology is primarily applied to high-segment and high-priced vehicles. There are to date no C-segment EVs available on the market that utilize an 800V architecture. However, as technological advancements continue, the possibility of integrating 800V systems into more affordable segments in the future remains a strong focus for automakers and industry leaders.

The dataset includes 20 different EV models, with 40 overall configurations analysed, from 8 different brands, all featuring 800V architectures. These vehicles belong to the premium and high-performance segments and are exclusively from D-segment or above, reflecting the current market trend where 800V systems are implemented in larger, more expensive models. The dataset includes a mix of luxury sedans, SUVs, and high-performance sports cars, emphasizing the advantages of 800V technology in delivering higher efficiency, faster charging times, and improved power output.

The presence of legacy premium manufacturers alongside newcomers like Lucid and BYD demonstrates how both established and emerging brands are leveraging 800V technology to enhance charging speed, efficiency, and driving performance.

MODELLO	Peak Power [kW]	Battery Cells Series	Battery Cells Parallels	Rated Voltage [V]	Cells Chemistry	Cells Form Factor	Max Charging Power [kW]	Average Charging Power 10-80% [kW]	Average charging power/Max charging power	Battery Capacity [kWh]	WLTP Range [km]	WLTP Efficiency [Wh/km]	Charging Time 10-80% [min]	Range per minute WLTP 10-80% [km/min]	Price IT [€]
Audi A6 Avant e-tron	210	150	1	550	NMC 811	Prismatic	225	158.6	0.70	83	598	126.8	20.07	20.9	68000
Audi A6 Avant performance	270	180	1	662	NMC 811	Prismatic	270	191.7	0.71	100	720	131.8	20.78	24.2	77000
Audi A6 Avant quattro	315	180	1	662	NMC 811	Prismatic	270	191.7	0.71	100	685	138.5	20.78	23.1	82000
Audi A6 Sportback e-tron	210	150	1	550	NMC 811	Prismatic	225	158.6	0.70	83	672	112.8	20.07	23.4	65500
Audi A6 Sportback performance	270	180	1	662	NMC 811	Prismatic	270	191.7	0.71	100	756	125.5	20.78	25.5	74500
Audi A6 Sportback quattro	315	180	1	662	NMC 811	Prismatic	270	191.7	0.71	100	716	132.5	20.78	24.1	79500
Audi E-tron GT S	500	198	2	728	NMC 811	Pouch	320	259.5	0.81	105	609	159.3	15.68	27.2	128400
Audi Q6 e-tron 75.8kWh	215	150	1	550	NMC 811	Prismatic	225	158.6	0.70	83	533	142.2	20.07	18.6	67800
Audi Q6 e-tron 94.9kWh	240	180	1	662	NMC 811	Prismatic	270	191.7	0.71	100	641	148	20.78	21.6	73300
Audi Q6 e-tron 94.9kWh quattro	285	180	1	662	NMC 811	Prismatic	270	191.7	0.71	100	625	151.8	20.78	21	79500
Audi Q6 Sportback e-tron 75.8kWh	215	150	1	550	NMC 811	Prismatic	225	158.6	0.70	83	545	139.1	20.07	19	74800
Audi Q6 Sportback e-tron 94.9kWh	240	180	1	662	NMC 811	Prismatic	270	191.7	0.71	100	655	144.9	20.78	22	80300
Audi Q6 Sportback e-tron 94.9kWh quattro	285	180	1	662	NMC 811	Prismatic	270	191.7	0.71	100	636	149.2	20.78	21.4	86500
BYD Han	380	178	1	569	LFP	Prismatic	120	97.6	0.81	88	521	159.3	35.72	10.2	70940
BYD Seal Design	230	172	1	550	LFP	Prismatic	150	97.6	0.65	84	520	158.7	35.5	10.2	43600
BYD Sealion 7 82.5kWh	230	172	1	550	LFP	Prismatic	150	125.8	0.84	84	456	180.9	27.55	11.6	44175
BYD Sealion 7 91.3kWh	390	168	N/A	538	LFP	Prismatic	230	125.8	0.55	93	502	181.9	30.48	11.5	57390
Hyundai Ioniq 5 63kWh (GEN2)	125	144	2	523	NMC	Pouch	195	N/A	N/A	63	440	136	N/A	N/A	43700
Hyundai Ioniq 5 84kWh (GEN2)	168	192	2	697	NMC	Pouch	260	171.8	0.66	84	570	140	19.55	19.5	52400

Hyundai Ioniq 5 58kWh (GEN1)	125	144	2	523	NMC	Pouch	175	N/A	N/A	58	400	135	N/A	N/A	N/A
Hyundai Ioniq 5 77.4kWh (GEN1)	168	192	2	697	NMC	Pouch	230	187.6	0.82	77.4	507	146	16.57	21.4	N/A
Hyundai Ioniq 6 53.3kWh	111	132	2	480	NMC	Pouch	150	N/A	N/A	53	429	117	N/A	N/A	47850
Hyundai Ioniq 6 77.4kWh	168	192	2	697	NMC	Pouch	230	187.6	0.82	77.4	614	120.5	16.57	25.9	52300
Kia EV6 58kWh (GEN1)	125	144	2	523	NMC	Pouch	175	129.4	0.74	58	394	137.1	17.52	15.7	48950
Kia EV6 77.4kWh (GEN1)	168	192	2	697	NMC	Pouch	230	187.6	0.82	77.4	528	140.2	16.57	22.3	58450
Kia EV6 63kWh (GEN2)	125	144	2	523	NMC	Pouch	195	N/A	N/A	63	428	140	N/A	N/A	N/A
Kia EV6 84kWh (GEN2)	168	192	2	697	NMC	Pouch	260	171.8	0.66	84	582	137.5	19.55	20.8	N/A
Kia EV9	150	152	3	552	NMC	Pouch	230	168.9	0.73	99.8	563	174.1	24.37	16.2	76450
Lotus Eletre	450	N/A	N/A	709	N/A	N/A	350	224.8	0.64	111.9	600	181.7	20.35	20.6	99490
Lotus Emeya	450	N/A	N/A	705	N/A	N/A	350	298.2	0.85	102	610	163.9	14.08	30.3	111490
Lucid Air Pure	325	180	30	756	NMC	Cylindrical	300	147	0.49	94	747	112.4	24	21.8	85000
Lucid Air Grand Touring	611	220	30	924	NMC	Cylindrical	350	170.8	0.49	114	839	133	29.02	20.2	129900
Porsche Macan Electric	265	180	1	662	NMC 811	Prismatic	270	191.7	0.71	100	641	148	20.78	21.6	84626
Porsche Taycan	300	168	N/A	618	NMC 811	Pouch	270	191.4	0.71	89	590	139	18.05	26.3	105530
Porsche Taycan GTS	515	198	2	728	NMC 811	Pouch	320	259.5	0.81	105	628	154.5	15.68	28	153739
Porsche Taycan Cross Turismo 4	320	198	2	728	NMC 811	Pouch	320	259.5	0.81	105	613	158	15.68	27.4	118079
Porsche Taycan Sport Turismo	300	168	N/A	618	NMC 811	Pouch	270	191.4	0.71	89	565	146	18.33	22.5	106555
Porsche Taycan Sport Turismo GTS	515	198	2	728	NMC 811	Pouch	320	259.5	0.81	105	601	161.4	15.68	26.8	154753
Volvo ES90 Single Motor Core	245	N/A	N/A	N/A	NMC	N/A	300	N/A	N/A	92	650	135	N/A	N/A	75000
Volvo ES90 Twin Motor Ultra	330	N/A	N/A	N/A	NMC	N/A	350	202.2	0.58	106	700	145.7	21.18	23.1	92670

Table 2 800V EV benchmarking

The peak power of 800V EVs spans a broad range, showcasing variations in market positioning, drivetrain configurations, and performance objectives. The average peak power across the dataset is approximately 275 kW, with values ranging from 111 kW to 611 kW. This spread highlights the diversity within this segment, from efficient long-range models to high-performance variants designed for dynamic driving.

About 60% of the vehicles have power outputs between 200 kW and 350 kW, a range typical of premium sedans and SUVs focused on balanced performance, driving comfort, and efficiency. These models often feature single or dual-motor setups, delivering strong acceleration and stable highway cruising capabilities.

Vehicles with power ratings above 350 kW account for roughly 30% of the dataset, indicating a significant presence of performance-oriented models. These high-powered variants, commonly equipped with dual-motor or all-wheel-drive configurations, prioritize rapid acceleration, enhanced handling, and sustained high-speed performance.

At the top end of the spectrum, around 10% of the vehicles exceed 500 kW, entering supercar-level performance territory. These models incorporate advanced powertrain and cooling technologies, ensuring optimized power delivery and track-capable dynamics, appealing to enthusiasts and performance-focused buyers.

The power output distribution across the dataset reflects differences in vehicle design philosophies and brand strategies, illustrating how 800V architectures enable both high-efficiency long-range models and extreme-performance vehicles.

The battery configurations of the considered vehicles exhibit significant variation, reflecting differences in energy storage strategies, powertrain architectures, and brand-specific optimizations. Despite these differences, all vehicles in the dataset feature 800V-class battery systems, allowing for ultra-fast charging, improved efficiency, and enhanced performance.

The number of battery cells in series falls between 132 and 220, directly influencing the rated voltage, which ranges from approximately 480V to over 900V. While most vehicles operate between 600V and 800V, a single model reaches 924V; this particularly high voltage is indicative of cutting-edge energy management systems designed for maximum performance and ultra-fast charging.

The majority of vehicles employ single or dual parallel cell configurations. A few models adopt higher parallel setups, typically in ultra-high-performance vehicles, to maximize battery capacity especially when using cylindrical cells with a lower energy content.

The cell chemistry used in 800V electric vehicles varies between NMC and LFP, highlighting different approaches to energy density, cost, and performance optimization.

Most vehicles in the dataset utilize NMC-based chemistries, with a notable presence of NMC 811, which features a high nickel content to enhance energy density and efficiency. This composition is commonly found in performance-oriented and premium models, where higher range, fast charging, and power output are key priorities. Other NMC variants are also used across multiple models, balancing energy capacity and durability while maintaining strong performance characteristics.

A smaller subset of vehicles employs LFP batteries, known for their long cycle life, thermal stability, and cost-effectiveness. While LFP cells typically have a lower energy density compared to NMC counterparts, they offer advantages in terms of safety, affordability, and resistance to degradation. These characteristics make them well-suited for vehicles where longevity and cost efficiency are prioritized over maximum range and power density.

The presence of both NMC and LFP chemistries highlights the divergent strategies among manufacturers, with some favouring higher energy density for premium vehicles, while others emphasize durability and cost-effectiveness in specific configurations.

The cell form factor in 800V EVs varies between prismatic, pouch, and cylindrical cells, with each format offering distinct advantages in packaging, performance, and thermal management.

Approximately 55% of the dataset features prismatic cells, which are widely used due to their high volumetric efficiency and structural stability. This form factor is particularly suited for compact battery pack designs, allowing for better integration within vehicle architectures while ensuring durability and ease of thermal management.

Another common format, found in around 40% of analysed vehicles, is the pouch cell, which provides higher energy density and flexibility in design, enabling lighter and more compact battery configurations. However, pouch cells require additional structural reinforcement within the battery pack to prevent swelling and mechanical stress over time. These characteristics make them a preferred choice for performance-focused models where weight savings and energy output are prioritized.

A smaller selection of vehicles utilizes cylindrical cells, which are known for their robustness, scalability, and high-power output capabilities. This format is often associated with advanced battery architectures, as cylindrical cells allow for efficient thermal regulation and modular pack designs.

The battery capacity of 800V electric vehicles in the dataset varies significantly, ranging from 53 kWh to 114 kWh, with an average of approximately 90 kWh. This spread highlights the diversity in vehicle positioning, range expectations, and energy storage strategies.

Around 60% of the models are equipped with battery packs between 80 kWh and 105 kWh, aligning with the most common segment for premium and long-range EVs. Vehicles with battery capacities above 105 kWh, representing about 15% of the dataset, are typically high-end or performance-oriented models, where extended range and high-power output are key priorities. Conversely, vehicles below 70 kWh make up approximately 25% of the dataset, catering to consumers prioritizing affordability, efficiency, and urban driving.

Regarding the battery size, the WLTP range varies widely, from 394 km to 839 km, with an average of about 600 km. Over 50% of the models achieve a range between 500 km and 700 km, indicating that most 800V EVs prioritize long-distance usability. The few models exceeding 750 km, comprising 10% of the dataset, stand out as high-efficiency luxury sedans, leveraging aerodynamics, optimized drivetrains, and large battery packs to achieve exceptional mileage per charge.

When analysing WLTP efficiency, measured in Wh/km, values range from 112 Wh/km to 182 Wh/km, with an average of 145 Wh/km. Despite being larger, heavier, and more powerful than C-segment electric vehicles, the average efficiency remains comparable, demonstrating the benefits of 800V architectures, advanced thermal management, and optimized drivetrain technologies. Around 65% of vehicles achieve an efficiency between 125 Wh/km and 150 Wh/km, reflecting a balance between range and energy consumption. Models with efficiency below 120 Wh/km, accounting for about 10%, demonstrate exceptional aerodynamics and drivetrain optimization, while those exceeding 160 Wh/km tend to be larger SUVs or high-performance models, where weight, power demands, and all-wheel-drive configurations contribute to higher consumption levels.

These variations in battery capacity, range, and efficiency showcase the different design priorities and technological approaches adopted by manufacturers to cater to diverse market segments, driving needs, and consumer expectations.

The analysis of charging performance among 800V EVs highlights their significant advantages in fast-charging capabilities, particularly when compared to conventional 400V C-segment EVs. Peak charging power varies widely across models, ranging from 120 kW to 350 kW, with an average of approximately 250 kW. More than 65% of these vehicles support over 225 kW, and around 30% exceed 270 kW, showcasing their ability to handle high-power charging sessions efficiently. Sustained charging power between 10-80% state of charge (SOC) follows a similar trend, ranging from just under 100 kW to nearly 300 kW. The ratio of sustained-to-peak charging power remains high, typically between 0.65 and 0.85 compared to 0,5 – 0,8 for 400V vehicles (chapter 1.1). This means that most 800V vehicles can maintain over 65% of their peak charging capability throughout the session. However, a small percentage (less than 10%) exhibit a sharper drop-off, maintaining below 55% of their peak power.

Charging times from 10-80% vary significantly, with the fastest models completing this process in just over 14 minutes, while the slowest take more than 35 minutes. On average, these vehicles achieve this charge level in approximately 20 minutes, which is 20-40% quicker than typical C-segment EVs, which generally fall within the 25–35 minutes range. One of the most relevant performance metrics, WLTP range gained per minute of charging, spans from as low as 10 km/min to an exceptional 30 km/min, with an average of 21 km/min. This means that most 800V vehicles can recover between 200-300 km of range in just 10-15 minutes, making them particularly suitable for long-distance travel.

When compared to C-segment EVs, which generally exhibit peak charging power in the 100-175 kW range, sustained charging power of 80-120 kW, longer charging times, and a lower range recovery rate of around 10-18 km/min, the advantages of 800V architecture become clear. Despite being on average 20-30% larger, heavier, and more powerful, these vehicles compensate with superior charging performance.

Pricing for 800V vehicles varies significantly, reflecting differences in brand positioning, performance, and features. Entry-level models are available from approximately €43,000, while high-performance and luxury variants can exceed €150,000, with an average price across the segment around €82,000. Over 60% of the models fall within the €50,000-€90,000 range, making them competitive with high-end C-segment and D-segment EVs. While premium options command higher prices due to brand reputation, advanced battery technology, and superior performance, some models offer relatively accessible pricing while still benefiting from fast-charging capabilities.

1.3 DONOR VEHICLE SELECTION

The selection of a suitable donor vehicle was a critical decision within the ENLIGHTEN project, as it sets the foundation for integrating and validating the next-generation high-voltage powertrain architecture developed by the consortium. Following an extensive and multi-criteria benchmarking analysis of currently available BEVs, the Hyundai Ioniq 5 Gen1 with a 58 kWh battery was identified as the most appropriate candidate. Although the vehicle is officially classified as a D-segment crossover, it was selected due to its unique combination of technical compatibility, dimensional suitability, economic feasibility, and availability, all of which align with the overarching requirements and constraints of the ENLIGHTEN project.

Figure 1 Hyundai Ioniq 5

At the core of the ENLIGHTEN project is the design and prototyping of a novel 1200V dual-voltage electric powertrain, including an advanced energy storage system, high-efficiency GaN-based inverters and converters, and a next-generation electric drive unit. Unlike traditional retrofitting efforts, this project will not reuse or adapt any of the donor vehicle's original powertrain components. Instead, it requires a flexible and robust platform that can accommodate experimental subsystems, support high-voltage operation, and enable the testing of novel functionalities under controlled and real-world driving conditions. As such, the donor vehicle must be fully compatible with high-voltage infrastructure, offer adequate spatial integration volume, and provide modular access to thermal and electrical interfaces.

One of the defining selection criteria was the availability of an 800V-class electrical architecture. As the ENLIGHTEN project is inherently post-800V in scope, targeting a 1200V-class system, it was critical to choose a donor vehicle with a native 800V platform, such as to provide a more relevant reference architecture. This ensures that the ENLIGHTEN demonstrator is tested in a platform aligned with the current technological state of the art and allows the new 1200V system to be benchmarked against an 800V architecture. However, during the benchmarking phase, it became evident that no vehicles within the C-segment category currently support 800V operation, with all models limited to 400V-class architectures. Although these vehicles may offer dimensions aligned with the project's initial specifications, their lower voltage architecture makes them unsuitable as a technological reference for post-800V system validation.

In contrast, the Hyundai Ioniq 5 was one of the few vehicles on the market that offered native 800V, while remaining affordable and readily available. Although the vehicle's dimensions place it to some extent outside the conventional C-segment range, its platform configuration, interior layout, and underbody packaging are closely aligned with those of emerging C-SUVs, which are rapidly becoming dominant in the European EV market. This reflects an ongoing shift in consumer and manufacturer preferences, where functional C-segment vehicles are increasingly adopting the form factors and design philosophies of crossovers and midsize platforms. As such, the selection of the Ioniq 5 is not only justified by technical considerations but is also aligned with the anticipated evolution of the C-segment landscape, where higher voltage platforms are likely to become standard in EVs in the coming years.

From a system integration perspective, the 58 kWh variant of the Ioniq 5 offers several distinct advantages that align with the ENLIGHTEN project's experimental requirements. Although the 58 kWh battery pack features lower energy capacity than the 77,4 kWh version, the difference extends beyond cell count: the 58 kWh pack is physically smaller, effectively a shortened version of the 77,4 kWh pack, with one section of the casing absent. Despite this reduced size, both variants retain identical mechanical and electrical interfaces. This platform uniformity, with the possibility to swap the two battery versions, significantly simplifies integration and testing workflows.

The lower acquisition cost of the 58 kWh variant provides a financial margin that could be strategically reinvested into acquiring a second 77,4 kWh battery pack or, alternatively, just an empty 77,4 kWh battery casing. This approach would enable the consortium to conduct battery assembly and integration activities in parallel with vehicle-level testing, decoupling the hardware development timeline from on-road baseline definition. Such a dual-path setup would increase flexibility, minimize downtime, and facilitate iterative testing of battery prototypes without interfering with ongoing vehicle-based evaluations.

This compatibility and modularity allow the ENLIGHTEN consortium to utilize the larger 77,4 kWh battery casing as the structural base for the newly developed 1200V dual-voltage battery system. The additional internal volume of the 77,4 kWh casing provides greater design freedom to accommodate the project's custom designed battery.

Figure 2 58kWh vs 77,4kWh battery pack comparison

An equally important aspect of the donor vehicle selection was its economic accessibility and market presence in Europe. Many of the vehicles that support 800V operation belong to premium brands or high-end model lines, often exceeding €70,000 in their base configuration. These include models such as the Lucid Air, Porsche Taycan, and Audi e-tron GT, which—while technologically advanced—are economically and logistically impractical for research-oriented demonstrators. The Ioniq 5, particularly in its base 58 kWh configuration, presents itself as a more cost-effective solution, with prices significantly lower than premium alternatives. Moreover, the first generation of this model is widely available on the used vehicle market, often at price points around €35,000, providing substantial budgetary flexibility for acquisition, modification, and integration activities. This availability also ensures access to service documentation, repair tools, and spare parts, further reducing technical risk during the development process.

The vehicle’s classification as a D-segment model was considered acceptable given the broader project requirements and market context. Segment classification is increasingly fluid in the electric vehicle market, especially with the proliferation of SUVs and crossovers and with the increasing spread of larger vehicles in place of more compact ones. The Ioniq 5 fits this transitional category, and its size and spatial layout have been evaluated as the most comparable to an upper C-segment vehicle among the 800V EVs currently available on the European market for a reasonable price. From a systems engineering standpoint, the extra space could be beneficial when integrating high-voltage experimental subsystems to the vehicle.

In conclusion, the Hyundai Ioniq 5 Gen1 with 58kWh battery was selected as the ENLIGHTEN donor vehicle due to its unmatched combination of 800V electrical architecture, modular and scalable platform design, closest compatibility with C-segment expectations and dimensions, and availability at a competitive cost, both new and used. While it exceeds the strict dimensional limits of the C-segment, its alignment with the state-of-the-art EV powertrain architecture makes it the most appropriate and forward-looking choice for the project. This selection, prioritizing technological reference over strict segment classification, enables the ENLIGHTEN consortium to develop and validate a high-voltage, high-efficiency 1200V powertrain within a vehicle platform that reflects the technological trajectory of next-generation electric vehicles.

2 DRIVING CYCLES

As the superordinate goal of ENLIGHTEN is to facilitate and accelerate the transition to BEVs a strong connection between driving cycles and user requirements becomes obvious. For the buyer of an ICE the average real-world consumption was and is the only important metric. Highway consumption does not play a major role when the range is still greater than many hundreds of kilometres, and refuelling is a matter of minutes. The efficiency in everyday driving and short distances is so poor that the difference to highway consumption is passable. For BEV the battery capacity (~tank size) and the DC-charging time (~refuelling) come into play as significant metric of the whole user experience. Driving cycles are necessary for a (prospective) user to know what he can expect from an EV, as it is much more sensitive to different use cases, regarding range, charging but also electricity cost.

For ENLIGHTEN two major driving cycles have been identified. First the WLTC, because it is the well-established standard in Europe for vehicle energy consumption. It gives the user a comparable number of the total energy consumption of the vehicle under real driving conditions, while, it also has some shortcomings that will be explained further below. The second important "cycle" is the highway consumption. As BEV are much more sensitive to driving resistance and due to the laws of physics these rise to the second power of speed, the highway consumption, actually the highway range, is much more important than compared to ICE vehicles or hybrids.

2.1 WLTC

The Worldwide Harmonized Light vehicles Test Procedure (WLTP) is a global driving cycle standard for determining the levels of pollutants, CO2 emission standards and fuel consumption of conventional internal combustion engine (ICE) and hybrid automobiles, as well as the all-electric range of plug-in electric vehicles and BEVs. The WLTP was adopted by the Inland Transport Committee of the United Nations Economic Commission for Europe (UNECE) as Addenda No. 15 to the Global Registry (Global Technical Regulations) defined by the 1998 Agreement[1]. The standard is accepted by China, Japan, the United States and the European Union, among others. In Europe it replaced the previous and regional New European Driving Cycle (NEDC) as the new European vehicle homologation procedure. Its final version was released in 2015.

The new WLTP[2] procedure relies on the new driving cycles (WLTC – Worldwide harmonized Light-duty vehicles Test Cycles) to measure mean fuel consumption, CO2 emissions as well as emissions of pollutants by passenger cars and light commercial vehicles. WLTC is based on real-world driving data collected in the participating member states and weighted according to the relative share of each region in the total driving performance. During the development process, the driveability of the cycle was verified through a testing program. The cycle definition depends on the vehicles power-to-mass ratio and its maximum speed. WLTP also includes special provisions for testing Full Electric. The Worldwide Harmonized Light-Vehicles test cycle 3b for vehicles with a power-to-

[1] https://unece.org/text-1998-agreement

[2] Source: Entwicklung einer neuen, harmonisierten Testprozedur im Rahmen der Fahrzyklusentwicklung (WLTP) für Pkw und leichte Nutzfahrzeuge in der UNECE. Abschlussbericht. Umweltbundesamt Deutschland, 2019

empty weight ratio greater than 34 W/kg and a maximum speed (v-max) of ≥ 120 km/h is shown in Figure 3.

Class 3b:

The WLTC is divided into 4 different sub-parts, each one with a different maximum speed:

Low, up to 56.5 km/h

Medium, up to 76.6 km/h

High, up to 97.4 km/h

Extra-high, up to 131.3 km/h.

Table 2. WLTC Class 3b test cycle summary.

	Low	Medium	High	Extra high	Total
Duration, s	589	433	455	323	1,800
Stop duration, s	150	49	31	8	235
Distance, m	3,095	4,756	7,162	8,254	23,266
% of stops	26.5%	11.1%	6.8%	2.2%	13.4%
Maximum speed, km/h	56.5	76.6	97.4	131.3	131.3
Average speed without stops, km/h	25.3	44.5	60.7	94.0	53.5
Average speed with stops, km/h	18. 9	39.4	56.5	91.7	46.5
Minimum acceleration, m/s2	-1.5	-1.5	-1.5	-1.44	-1.5
Maximum acceleration, m/s2	1.161	1.611	1.666	1.055	1.666

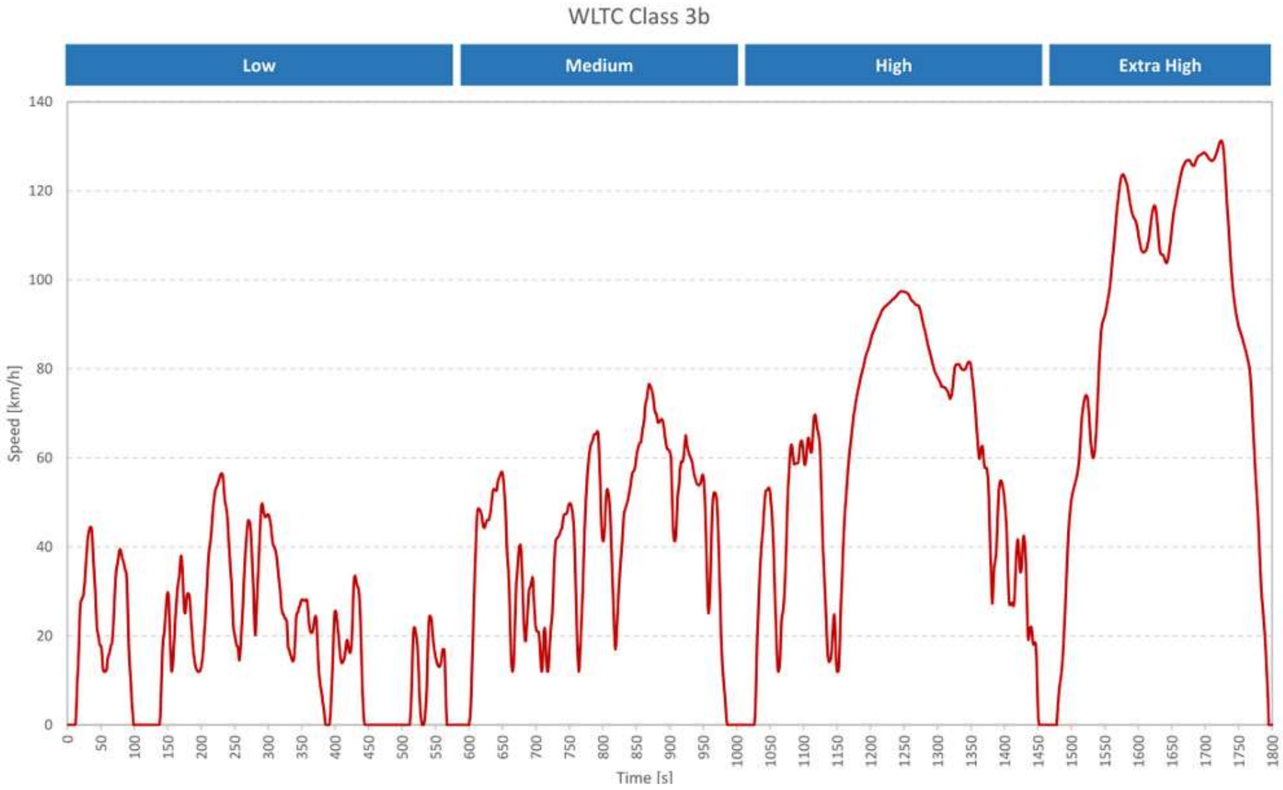

Figure 3 WLTC Class 3b speed over time profile.

2.2 HIGHWAY

It must not be overlooked that the WLTC driving consumption (Wh/km) that is published by all the OEMs always includes the charging losses, when charged via the onboard charger. After the vehicles complete the WLTC on a roller test bench, the vehicles are AC-charged to fully replenish the battery. The electric energy needed is measured on the AC lines. So, the WLTC consumption numbers do not only describe the pure driving losses but also the charging losses consisting of the onboard charger's and the battery's losses. The idea is to give the end-user a value for the consumption that includes the total energy needed for driving, as he also must pay for the charging losses. It is comparable to ICE vehicles, which do not have additional losses.

Even if the "extra-high speed" component describes realistic highway driving quite good, the value just for this part and without charging losses is not displayed separately. The OEMs have this information, but it is not accessible to the public nor to the scientific community in general. In practice all the different protagonists in the field like influencers, auto-journalism or the national automobile associations do their testing. There are two ways to gather serious and reproducible values for highway consumption by testing on the road, making a round trip on the highway or driving with different constant speeds. The roundtrip ends where it starts, thus it compensates for altitude differences and wind. Driving constant speeds also has to be done in both corrections for compensation. Sensible and comparable results can only be achieved if the temperatures are similar and if the wind is still or moderate. The roundtrip needs the same traffic conditions to achieve the same average speeds driven.

2.3 LONG DISTANCE TRAVELLING

Long distance travelling is very important as many of the concerns regarding transition from an ICE vehicle to a BEV refer to long distance travelling and the fear that is not feasible at all or that it takes much longer and is much more complicated than with combustion engine cars. For households with only one car or only one car large enough to go on holiday with the family it is obligatory that the user is confident that he can accomplish two or three long distance journeys a year with this car without a major effort.

The qualification of an electric car for long distance journeys is a combination of battery size, consumption at highway speeds and the capability of DC-fast charging. DC fast charging capability is normally expressed by the duration in minutes it takes to charge from 10% to 80% SOC. Usually, the duration that is given can be reached if the battery is in the right temperature window. Sophisticated electric cars precondition the battery for charging performance by heating up or cooling down the battery to bring it into the temperature window when reaching the charging station. Although the manufacturers publish the duration of DC fast charging, using the results of independent testing gives added value due to the different charging curves and as a confirmation of the OEM.

For a calculation of long-distance travelling, one can assume that the vehicle starts with 100% SOC and thereafter just charges to 80% during the trip, meaning a longer range can be assumed for the first section, compared to the ones following. For realistic long-distance journey evaluation, the testers often assume distances of 600 to 800km, an average speed of around 100 km/h and the need to have a certain remaining SOC at the destination.

3 END-USER REQUIREMENTS

An internet inquiry was conducted to find out what the end-user requirements are that cannot be fulfilled by the BEV ecosystem at the time of document creation. The research focused on pain-points that are in context to ENLIGHTEN ambitions. Two main points have been identified restraining electric vehicle adoption that are the subject of the project. Long distance travelling and regulatory aspects.

3.1 LONG DISTANCE TRAVELLING

For travelling distances that require charging stops, as it would be typically for holiday trips in summer and winter, there are multiple aspects that are not yet satisfying consumers and concern potential EV-buyers. Charging experience and range anxiety are probably the most important. Charging experience encompasses several aspects as speed, cost, conditions of payment, availability, distance between stations, to name just the most important. Numerous scientific publications and surveys can be found about EV charging[3][4], but very few are selective about charging regarding end user requirements for long distance travelling. Moreover, region is also of important, as Chinese travelling habits are not meaningful for European usage[5][6]. An ADAC survey of EV users in 2021[7] revealed several wishes for charging specifically on the highway:

- Expansion of charging infrastructure – More fast-charging stations for better availability.
- Simplified processes – Faster and more user-friendly charging procedures.
- More reliable charging stations – Fewer defective or non-operational chargers.
- Lower charging costs – 27% find prices unfair, 66% fear further price increases.
- More transparent pricing – Clear display of actual charging costs.
- Improved payment options – 67% want card payments directly at charging stations.
- Better signage & accessibility – One-third had trouble finding fast chargers.
- Blocking fees for occupied charging spots – Nearly 75% support a fee if EVs remain parked after charging.

As one can see, charging speed seems not to be among the most urging problems of EV-users, but it is for prospective EV-owners. Many of them refuse to accept an EV unless can expect charging speeds that align the consumer experience for long distance travelling to that of ICE vehicles and refuelling. What makes the difference, and this has been mentioned frequently by EV-testers is the question if the driver waits for the car or vice versa. 15 minutes or less seems to be widely accepted as a charging time for longer trips. Going to the toilet, having a coffee or simply stretching one's legs or having a quick look at the smartphone needs 10-15 minutes. The user does not have the feeling

[3] Mikkel Thorhauge, Jeppe Rich, Stefan E. Mabit (2024). Charging behaviour and range anxiety in long-distance EV travel: an adaptive choice design study.

[4] McKinsey Center for Future Mobility (2024). Exploring consumer sentiment on electric-vehicle charging.

[5] Weipeng Zhan, Yuan Liao, Junjun Deng, Zhenpo Wang, Sonia Yeh (2025) Large-scale empirical study of electric vehicle usage patterns and charging infrastructure needs.

[6] Jiyao Wang, Chunxi Huang,Dengbo He, Ran Tu (2023). Range anxiety among battery electric vehicle users: both distance and waiting time matter.

[7] https://presse.adac.de/meldungen/adac-ev/tests/schnellladen-noch-mit-verbesserungspotential.html

that he/she has to actively wait for the car and to pass the time, although the charging technically still takes significantly longer than refuelling.

This very subjective matter has been brought into a systematic approach by the P3 charging index[8]. “The P3 Charging Index investigates and analyses the long-distance suitability and charging behaviour of modern electric vehicles in order to assess how good the charging performance of current EVs really is. The aim is to answer the central question in a factual and data-driven manner: “How many kilometres of real range can an electric car charge in 20 minutes at a fast-charging station?” P3 is publishing the sixth edition of the P3 Charging Index in December 2024.” With the vehicles' consumption and charging curves, the number of kilometers recharged in 10 and 20 minutes of charging time can be displayed, allowing a concrete comparison of the fast-charging performance. The huge advantage of the index is that it incorporates the consumption into the equation. The drawback regarding its applicability regarding long distance travelling is, that it is calculated based on the so-called ADAC “Ecotest”, which is a mixed cycle and does not represent the consumption on the highway.

If the car receives a result of “1” it means, that it can recharge 300 kilometres of real-world range (ADAC Ecotest), if the result is higher than “1”, it means more than 300 kilometres. The results for the compact car class in 2019 show a far distance to reach this (see Figure 4). The best contender was the VW-ID3 (58 kWh) with 153km in 20 minutes (P3CI = 0,51). No 800V architecture was present in the class.

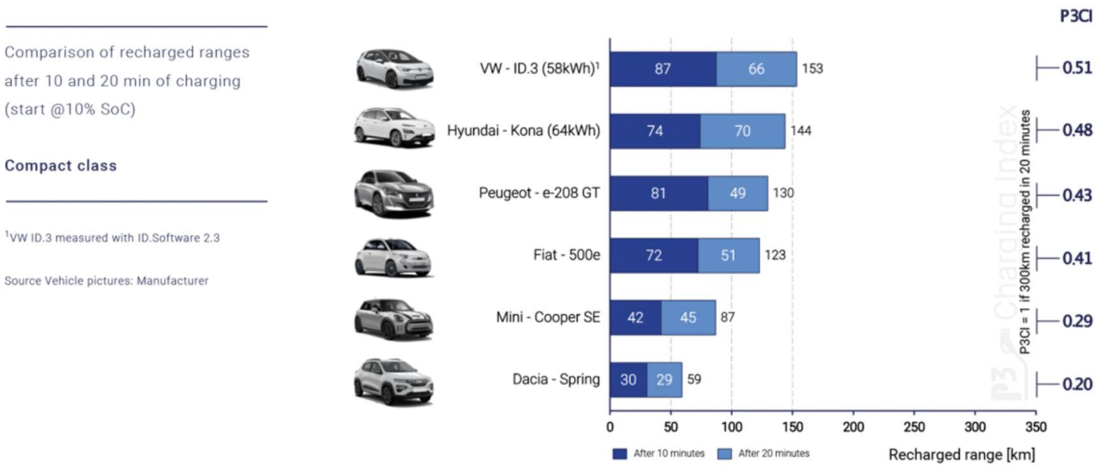

Figure 4: P3 Charging Index compact class results 2019
(source: https://www.p3-group.com/en/p3-charging-index)

The results of 2024 do not incorporate a compact class. They show that vehicles with 800V system voltage can already reach a score of “1” (KIA EV6) or even exceed it significantly, like the Hyundai Ioniq 6 2WD which has a recharged range of 346km (P3CI = 1,15). This vehicle recharges 234km in just 10 minutes (see Figure 5).

[8]https://www.p3-group.com/en/p3-updates/p3-charging-index-2024/

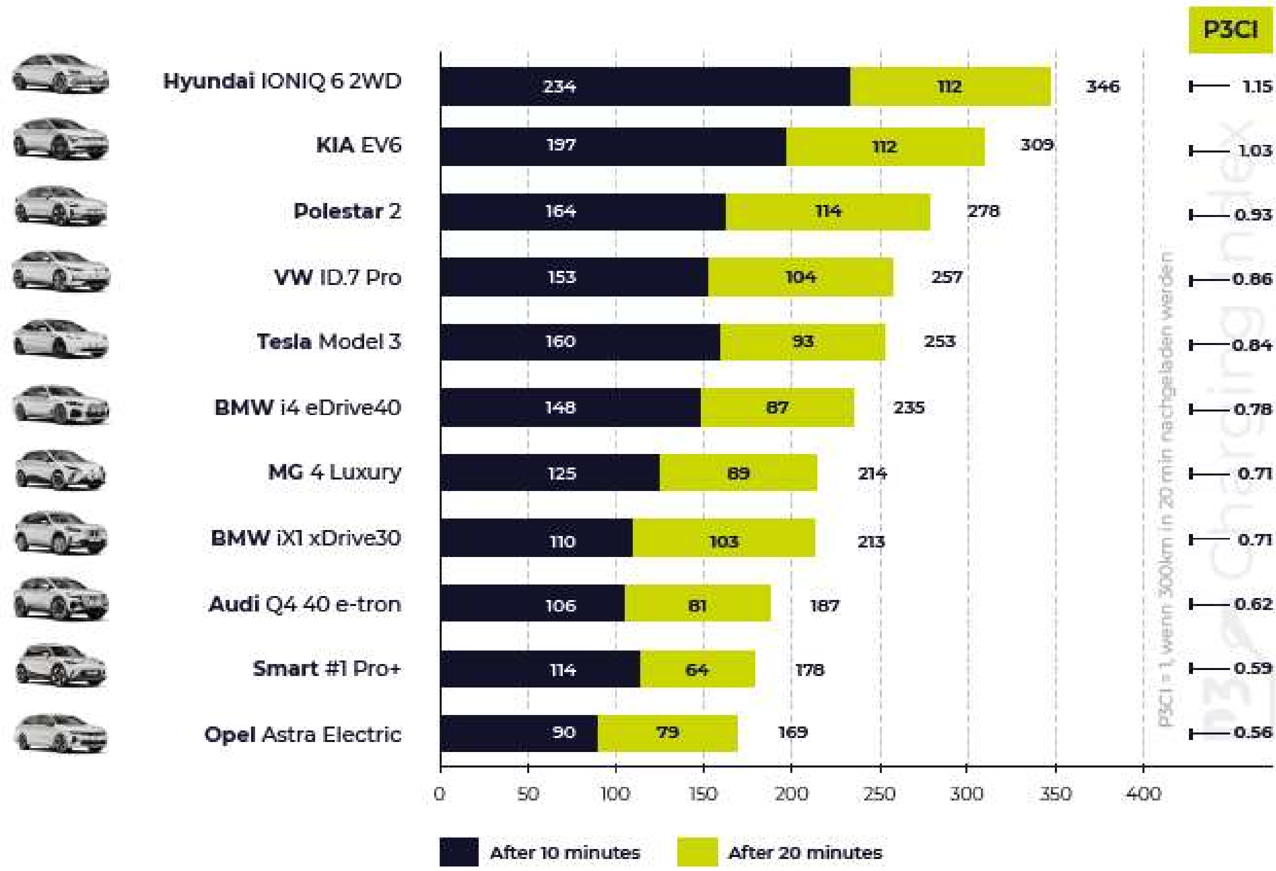

Figure 5: P3 Charging Index premium class results 2024
(source: https://www.p3-group.com/en/p3-charging-index)

For a broad acceptance of EVs for a long distance travelling, a long-term goal in the ENLIGHTEN consortium's position could be a recharged highway range of 300km in ten minutes, which can also be formulated as a charging speed of 1800km/h. Charging for 10 minutes every 300km means having a break of around 15 minutes every 2 – 3 hours of driving. This is in line automobile clubs who strongly recommended a break no later than every 3 hours[9]. It is going beyond the projects KPI of recharging from 20% to 80% in 10 minutes, which is uncoupled to the actual highway consumption of the car. Nevertheless, it is a reasonable intermediate step.

3.2 REGULATORY ASPECTS

From ENLIGHTENs recherch it came out that the end user is missing the information on which highway range a distinct electric vehicle will have and how it will behave on long distance trips. As stated in 2.2 the WLTC consumption does not allow a conclusion to the highway consumption. Due to the quadratic influence of the coefficient of drag (Cd) on consumption, a comparison of the range of two vehicles based on the WLTC is neither feasible. Also, charging losses are not relevant for the

[9] https://www.ots.at/presseaussendung/OTS_20020730_OTS0073/oeamtc-mehr-als-ein-drittel-der-urlauber-uebermuedet-unterwegs?utm_source=chatgpt.com, https://www.ots.at/presseaussendung/OTS_20060719_OTS0045/oeamtc-tagesetappen-mit-dem-auto-sollten-nicht-laenger-als-800-kilometer-sein-audio?utm_source=chatgpt.com

end user in this question. For that reason, and because buyers of electric cars have already complained because the highway range was significantly smaller than the WLTC value, some car brands offer calculation tools on their websites that allow users to calculate the autonomy for different constant speeds ambient temperatures, and cabin temperatures. So, these tools also include the air conditioning. These gadgets are on a voluntary basis, and comparability between different OEMs is disputable - this cannot replace a certified measurement by an official authority. What is needed from a regulatory standpoint is a compulsory indication of a distinct highway cycle (WLTC class 3, extra high) or the consumption for several constant speeds, without charging losses. This will give the consumer knowledge about a BEVs highway behaviour and the possibility to compare it between different models. As WLTC ranges of C-segment vehicles are already sufficient for a daily routine for many users, long distance travelling and highway range are becoming more and more important in the electric vehicle ecosystem.

4 STANDARDS AND REGULATIONS

Relevant standards and regulations regarding the higher voltage level of the ENLIGHTEN project will be listed below. The investigation has been limited to standards and regulations that are valid for Europe and not for other main passenger car markets like Norths America, China or Japan.

4.1 REGULATIONS

4.1.1 2006/95/EC Low Voltage Directive (LVD)

The low voltage directive[10] ensures that electrical equipment within certain voltage limits provides a high level of protection for European citizens, and benefits fully from the single market. It has been applicable since 20 April 2016. The low voltage directive covers health and safety risks on electrical equipment operating with an input or output voltage of between 50V and 1000 V for alternating current and 75V and 1500 V for direct current. It applies to a wide range of electrical equipment for both consumer and professional usage. It is available at the EUR-Lex[11] website from the European Union.

4.2 STANDARDS

4.2.1 IEC 61851 Standard for electric vehicle conductive charging systems

The IEC 61851 is an international standard for electric vehicle conductive charging systems. It is one of the International Electrotechnical Commission's groups of standards for electric road vehicles and electric industrial trucks.

IEC 61851 consists of the following parts, detailed in separate IEC 61851 standard documents:

- IEC 61851-1: General requirements
- IEC 61851-21-1: Electric vehicle on-board charger EMC requirements for conductive connection to AC/DC supply
- IEC 61851-21-2: Electric vehicle requirements for conductive connection to an AC/DC supply - EMC requirements for off board electric vehicle charging systems
- IEC 61851-23: DC electric vehicle charging station
- IEC 61851-24: Digital communication between a DC EV charging station and an electric vehicle for control of DC charging
- IEC 61851-25: DC EV supply equipment where protection relies on electrical separation

Independent of the detailed content of the single sub standards the important property for ENLIGHTEN is that the overall standard refers to a rated maximum voltage of up to 1 000 V AC or up to 1 500 V DC.

[10]https://single-market-economy.ec.europa.eu/sectors/electrical-and-electronic-engineering-industries-eei/low-voltage-directive-lvd_en

[11] https://eur-lex.europa.eu/eli/dir/2014/35/oj/eng

4.2.2 IEC 62196 Plugs, socket-outlets, vehicle connectors and vehicle inlets - Conductive charging of electric vehicles

IEC 62196 is the international standard for EV charging connectors and sockets, defining plug types, pin configurations, and power ratings for both AC and DC charging. It covers Type 1 (J1772), Type 2 (Mennekes) and CCS (Combined Charging System, see 4.2.7) for fast DC charging, ensuring compatibility and safety across EVs and charging stations. It also defines four different charging modes. In IEC 62196-1 the general scope of the standard is "intended for use in conductive charging systems which incorporate control means, with a rated operating voltage not exceeding 690Vac, 50-60Hz at a rated current not exceeding 250A or 1500Vdc at a rated current not exceeding 800A. In the IEC 62196-3 (2022-10)[12] these ratings are reduced according to the specific connectors. **For the European CCS connector (type 2) a maximum rated voltage of 1000Vdc and 400Adc is specified**. This may well be subject to change, as the Charging Interface Initiative e.V. (CharIN) is considering boost currents to further accelerate EV charging, see 4.2.8.

4.2.3 IEC 60664 Insulation coordination for equipment within low-voltage supply systems

This standard contains specifications for insulation coordination for equipment connected to low-voltage installations with a rated AC voltage of up to 1,000 V or a rated DC voltage of up to 1,500 V and frequencies up to 30 kHz (60664-1) or above 30kHz (60664-4). Higher voltages may occur in internal circuits of the equipment. This standard applies to equipment intended for use at altitudes of up to 2,000 meters above sea level (MSL) and provides guidance for use at higher altitudes. It includes requirements for Technical Committees to determine clearance distances, creepage distances, and criteria for solid insulation. It also includes procedures for electrical tests related to insulation coordination. Voltages higher than the levels given above are treated by the IEC60071. By the definition of the clearance distances, creepage distances, rated impulse voltage and criteria for solid insulation, this standard has very concrete implications on the ENLIGHTEN project.

4.2.4 ISO 17409 Electrically propelled road vehicles - Connection to an external electric power supply – Safety requirements

ISO 17409 specifies requirements and test procedures for conductive charging of EVs with AC or DC power from external electric power supply systems. It focuses on safety aspects, addressing both the vehicle and the charging equipment during normal operation and in the event of foreseeable misuse.

4.2.5 ISO 6469 Electrically propelled road vehicles – Safety specifications

ISO 6469 specifies safety specifications for the functional behaviour of electrically propelled road vehicles. It focuses on the design and layout of the electric drive system to ensure safe operation under both normal and fault conditions. Part one treats rechargeable energy storage system (RESS), part two vehicle operational safety means and protection against failures, and part three protection of persons against electric shock. ISO 6469-1:2019 chapter 5.4 contains specification for the isolation resistance, clearance and creepage distance that are directly related to the maximum working

[12] https://webstore.iec.ch/en/publication/59923

voltage of the RESS. ISO 6469-3 also states provisions regarding capacitive couplings. A maximum energy is specified, thus involving the working voltage.

4.2.6 CCS and CharIN Charging Interface Initiative

In the context of standards is important to name the CharIN[13] association. CharIN is a global industry alliance that promotes and develops the Combined Charging System (CCS) standards for EV charging. It was founded by leading automotive and charging infrastructure companies to establish CCS as the worldwide standard for fast charging. It strives to standardize and advance CCS for interoperability across different EV brands and charging networks. Its members include major automakers (e.g., BMW, Volkswagen, Tesla, Ford), charging station manufacturers, and energy providers. It has a global Presence and works with governments and industry bodies worldwide to push CCS adoption. For ENLIGHTEN relevant areas it is focusing on are High-power charging (HPC), megawatt charging system (MCS) for trucks and bidirectional charging (V2G).

Several CharIN topics are of special relevance for ENLIGHTEN:

4.2.7 CCS Standard

The Combined Charging System is a standardized charging system for plug-in electric vehicles, utilizing the Combo 1 (CCS1) and Combo 2 (CCS2) connectors. These connectors are based on the IEC 62196 Type 1 and Type 2 AC connectors, with two additional DC contacts to enable high-power fast charging. CCS chargers can deliver up to 500 kW of power (maximum 1000 V and 500 A). In response to the demand for even faster charging, 400 kW CCS chargers have been deployed by charging networks, and 990 kW CCS chargers have been successfully tested. Although the rated maximum current of the connector is 400A (see 4.2.2) currents of up to 500A are conducted temporarily. Tyco Electronics for example sells a CCS2 vehicle charge inlet[14] (108-94907) that can carry 500A for 12 minutes with a cooled connector.

The Combo 2 connector standard (sometimes incorrectly referred to as "CCS2") is based on the Type 2 connector pin layout but requires special vehicle inlets and connectors on the vehicle side. These vehicle inlets are designed to accept both standard Type 2 plugs and Combo 2 (CCS) connectors, allowing AC and DC charging using a single vehicle inlet. When using Combo 2 for DC charging, only the Protective Earth (PE) and the two signal contacts (CP, PP) from the original Type 2 connector are utilized. The main charging current flows through the two additional DC power contacts (DC+ and DC−). This setup follows IEC 62196 charging mode 4. According to IEC 61851-1, the charging cable and vehicle connector are permanently attached to the charging station and are plugged into the vehicle.

Pin configuration for Combo 2 DC charging:

- PE (Protective Earth) – Protective conductor, also known as ground or earth potential

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[13] https://www.charin.global/

[14] https://www.te.com/commerce/DocumentDelivery/DDEController?Action=showdoc&DocId=Specification+Or+Standard%7F108-94907%7FA%7Fpdf%7FEnglish%7FENG_SS_108-94907_A.pdf%7F2443730-2

* CP (Control Pilot) – Communication between the charging station and vehicle via an analog signal
* PP (Proximity Pilot) – Limits charging current based on resistance coding to prevent cable overload
* DC+ (Direct Current +) – Positive terminal for DC fast charging
* DC− (Direct Current −) – Negative terminal for DC fast charging

4.2.8 Other relevant CharIN specifications

Power classes:

CharIN specifies classes[15] to structure the power, current and voltage of DC charging, see Table 3. A power value is not given directly, it shall be provided by the manufacturer and is then validated by the CCS quality assurance program. There is also a denomination for the "old" charging stations that have a limited maximum voltage of around 500Vdc. They are called "legacy classes" (Table 4) and CharIN does not recommend the installation of new legacy charging stations beyond 2023. For ENLIGHTEN the legacy classes are important because of backwards compatibility.

[15] CharIN Position Paper: DC CCS Power Classes V7.2; 2021-12-09

Table 3 CharIN Minimum requirements for Power Classes

Power Class	Power*	U_{min} in [V]	U_{max} in [V]	I_{min} in [A]	I_{peak} in [A]	$I_{derated}$ in [A]	P_{ref} in [kW]	Duration I_{peak}	Name (EN)
LPC	*xx (kW)*	≤200	≥920		**<20**	*<20*	**<8**	*inf*	*Low-Power Charging*
DC	*xx (kW)*	≤200	≥920	≤1	**≥20**	*≥20*	**≥8**	*inf*	DC Charging
FC	*xxx (kW)*	≤200	≥920	≤1	**≥125**	*≥94*	**≥50**	≥ 30 min	Fast Charging
UFC	*xxx (kW)*	≤200	≥920	≤5	**≥250**	*≥188*	**≥100**	≥ 20 min	Ultra-Fast Charging
HPC	*xxx (kW)*	≤200	≥920	≤5	**≥500**	*≥375*	**≥150**	≥ 10 min	High-Power Charging
* P_{ref} values (provided by the manufacturer) shall be used (e.g.: HPC 300, FC 50). Validation will be done within CCS quality assurance program.									

Table 4 CharIN legacy classes

Power Class	Power*	U_{min} in [V]	U_{max} in [V]	I_{min} in [A]	I_{peak} in [A]	$I_{derated}$ in [A]	P_{ref} in [kW]	Duration I_{peak}	Name (EN)
DC_L	*xx (kW)*	≤200	≥500	≤1	**≥16**	≥16	**≥5 kW**	n.a.	DC Charging (legacy)
FC_L	*xxx (kW)*	≤200	≥500	≤1	**≥125**	≥93	**≥50 kW**	n.a.	Fast Charging (legacy)

Introduction of boost current for EV DC Charging:

There, CharIN proposes a "framework for utilizing short-term boost current to enhance EV fast-charging speeds while ensuring safety and interoperability. It defines key parameters such as Rated Boost Current, Boost Duration, and Cooling Down Duration to regulate thermal management and prevent overheating"[16]. **Fehler! Verweisquelle konnte nicht gefunden werden.** shows a table from the CharIN boost current white paper where notional charging currents of up to 1200Adc are proposed. In the pursuit of ENLIGHTEN to accelerate charging speeds, this is a relevant topic which has to be followed up.

[16] Charin_white_paper: Introduction of boost current for EV DC-Charging; 2025-02-04; Version 1.0

Table 5 Notional Boost Setups

	Boost Parameters at T_{amb} = 40°C			Measurement	Thermal management	
Boost Setup	***Δt_{RBC}***	***I_{RBC}***	***Δt_{RCD}***	***Intervention value***	***T_{Supply}***	***Flow Rate***
A	*5 min.*	1.000 A	*3 min.*	1,3 kΩ	30°C	1 l/min.
B	*5 min.*	1.200 A	*1 min.*	1,1 kΩ	10°C	1 l/min.
C	*6 min.*	900 A	*4 min.*	1,4 kΩ	30°C	1 l/min.
D	*10 min.*	1.000 A	*1 min.*	1,2 kΩ	10°C	5 l/min.

4.3 CHARGING ECOSYSTEM

For completeness an overview of all relevant charging standards and different types of EV charging connectors is given.

Table 6 Charging protocols, connectors and standards worldwide

Charging Plug-in technologies	In-use	In-use	In-use	In-use	In-use (Level 1)	In-use	In-use	In-use	In-use (Level 1)
Name	**Type 1 AC**	**Type 2 AC**	**CHAdeMO 2.0**	**GB/T**	**ChaoJi**	**CCS 1**	**CCS 2**	**NACS (Tesla)**	**MCS**
Plug design									
Max Power	**Up to 7kW**	**Up to 22kW**	**1000 V x 400 A = 400kW**	**950 V x 250 A = 237,5 kW**	**1500 V x 600 A =900 kW**	**1000 V x 500 A = 500kW**	**1000 V x 500 A = 500kW**	**410 V x 610 A = 250kW**	**1250 V x 3000 A =3,75 MW**
Communication protocol	**None**	**None**	**CAN (CHAdeMO)**	**CAN (GB/T-27930-2015)**	**CAN**	**PLC (ISO 15118)**	**PLC (ISO 15118)**	**CAN (SAE J2411)**	**CAN or Ethernet (ISO 15118)**
Location used	**USA**	**Europe**	**Global**	**China**	**China, Japan**	**USA**	**EU, South Korea, Australia**	**Global**	**USA, Europe**
Related standards	**SAE J1772-2017**	**IEC 61851**	**CHAdeMO (0.9,1.0,1.1, 1.2, 2.0)**	**IEC 61851**	**CHAdeMO 3.0**	**IEC 61851 / SAE J1772**	**IEC 61851 IEC 62196**		**IEC 61851 / SAE J3271**
Notes			**Liquid Cooled under development**		**Liquid Cooled variant possible**	**Liquid Cooled**	**Liquid Cooled**	**Liquid Cooled**	**Liquid Cooled**

5 CONCLUSIONS

The ENLIGHTEN project is strategically focused on accelerating the transition to battery electric vehicles by tackling key limitations identified through comprehensive benchmarking and analysis of user requirements. The benchmarking phase highlighted the advancements in 800V architectures and the performance characteristics of existing C-segment EVs, informing the project's ambitious goal of developing a next-generation 1200V dual-voltage powertrain. The selection of the Hyundai Ioniq 5 Gen1, with its native 800V electrical architecture and dimensional compatibility with the evolving C-SUV segment, provides a robust platform for the integration and validation of this innovative technology.

Analysis of end-user requirements underscored the critical need for improvements in long-distance travel capabilities, specifically addressing concerns related to charging speed, infrastructure availability, and range confidence. Furthermore, the regulatory landscape in Europe necessitates greater transparency regarding the real-world performance of EVs, particularly concerning highway driving range.

By pursuing the development of a 1200V powertrain, ENLIGHTEN aims to deliver significant advancements in charging efficiency and overall vehicle performance, directly addressing the identified user needs and pushing beyond the current state-of-the-art. The outcomes of this project are expected to contribute valuable insights and technological solutions that can pave the way for more efficient, user-friendly, and widely adopted electric vehicles in the future.