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Energy conversion losses in electric vehicle auxiliary power systems: A basic analytical study

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Abstract
Electric vehicle range anxiety remains a significant barrier to widespread adoption, with auxiliary power systems contributing substantially to total energy consumption beyond propulsion requirements. This research conducted analytical investigation of energy conversion losses in auxiliary power systems across a representative sample of battery electric vehicles operating in Dutch urban and highway conditions from March 2023 through September 2023. Field measurements encompassed 23 vehicles representing compact, midsize, and premium segments with auxiliary system architectures ranging from centralized single-converter designs to distributed multi-converter configurations. The heating, ventilation, and air conditioning system emerged as the dominant auxiliary load, consuming between 1.2 kW and 3.8 kW depending on ambient conditions and cabin temperature setpoints, with conversion efficiency ranging from 87.3% to 94.2% across measured operating points. DC-DC converter losses for low-voltage auxiliary supply averaged 6.8% of transferred power under typical loading conditions, with efficiency degradation of 2.3 percentage points observed at ambient temperatures below 0 °C. Total auxiliary system losses represented 8.4% to 15.7% of battery energy consumption during urban driving cycles, increasing to 4.2% to 9.3% during highway operation where propulsion power dominates. Distributed converter architectures demonstrated 4.4 percentage points higher system efficiency compared to centralized designs through reduced cable losses and optimized individual converter loading. An analytical loss model incorporating conduction, switching, magnetic, and standby components achieved prediction accuracy within 3.2% of measured losses across varied operating conditions. These findings provide quantitative foundation for auxiliary system optimization strategies that could meaningfully extend electric vehicle driving range.

Keywords: Electric vehicle, auxiliary power system, DC-DC converter, energy conversion, power loss, HVAC, efficiency, battery electric vehicle, thermal management, driving range

Introduction

Battery electric vehicles have achieved remarkable market penetration in the Netherlands, with zero-emission vehicles representing over 30% of new passenger car registrations during 2023 [1]. Despite this commercial success, range anxiety continues to influence consumer purchasing decisions and driving behavior, particularly during winter months when auxiliary system demands substantially reduce available driving distance. Understanding and minimizing energy losses throughout the vehicle electrical system offers meaningful opportunities to extend practical driving range without increasing battery capacity or weight.

Electric vehicle auxiliary systems encompass all electrical loads beyond the propulsion motor and its associated power electronics. Principal consumers include climate control systems providing cabin heating and cooling, low-voltage systems powering lighting, infotainment, and control electronics, and active safety features including power steering and brake assistance [2]. These systems typically operate from a 12V or 48V bus supplied through DC-DC converters stepping down from the high-voltage traction battery, introducing conversion losses at each power transfer stage.

Climate control represents the most significant auxiliary load in battery electric vehicles, fundamentally different from internal combustion vehicles where waste heat from the engine provides essentially free cabin heating. Electric vehicles must generate all heating energy from battery storage, whether through resistive heating elements or heat pump systems [3]. Air conditioning for cooling similarly draws substantial power, with combined heating and cooling loads potentially exceeding 5 kW under extreme ambient conditions. The energy consumed by these systems directly reduces available propulsion energy and corresponding driving range.

DC-DC converter technology has matured substantially for automotive applications, yet conversion efficiency remains below unity and varies significantly across operating conditions [4]. Light-load efficiency proves particularly challenging as fixed losses including controller power consumption, gate drive circuits, and magnetic core losses represent increasing fractions of output power. Thermal effects further influence efficiency, with semiconductor conduction losses increasing at elevated junction temperatures while switching losses may decrease due to faster carrier dynamics.

Published research on electric vehicle auxiliary systems has focused primarily on component-level efficiency optimization, with fewer investigations examining system-level interactions and real-world operating patterns [5]. Laboratory characterization under standardized conditions provides useful benchmarks but may not capture the full range of conditions encountered during actual vehicle operation. Field measurements incorporating realistic driving patterns, ambient temperature variations, and user behavior offer complementary insight into practical energy consumption characteristics.

This research conducted systematic analytical investigation of energy conversion losses in electric vehicle auxiliary power systems through field measurements across a representative vehicle sample operating under Dutch driving conditions. The investigation developed loss models enabling prediction of auxiliary system efficiency across varied operating points, supporting identification of optimization opportunities for future vehicle designs.

Literature Review

Energy consumption modeling for electric vehicles has evolved substantially as the technology has matured from demonstration projects to mass-market products. Early research focused primarily on propulsion system efficiency, treating auxiliary loads as simple constant power demands subtracted from available battery energy [6]. More sophisticated approaches recognized that auxiliary power varies significantly with operating conditions and driving patterns, requiring dynamic models capturing these interactions.

Climate control system research has examined both heating and cooling technologies suitable for electric vehicles. Resistive heating provides simple, reliable cabin warming but converts electrical energy to heat with essentially unity efficiency, offering no thermodynamic advantage. Heat pump systems achieve coefficients of performance exceeding 3.0 under favorable conditions, effectively multiplying useful heating from each unit of electrical energy [7]. However, heat pump performance degrades substantially at low ambient temperatures where heating demand is highest, potentially requiring supplemental resistive heating.

DC-DC converter efficiency optimization has received extensive attention in power electronics literature. Synchronous rectification, soft switching techniques, and wide bandgap semiconductors have progressively improved converter efficiency toward theoretical limits [8]. Automotive-grade converters must additionally satisfy stringent reliability, electromagnetic compatibility, and thermal management requirements that may constrain efficiency optimization approaches feasible in other applications.

System architecture comparisons have examined tradeoffs between centralized and distributed power conversion approaches. Centralized architectures employing single high-power converters offer simplicity and potential cost advantages but suffer from cable losses distributing power throughout the vehicle and suboptimal efficiency when total load falls below rated converter capacity [9]. Distributed architectures placing smaller converters near point of use reduce distribution losses but increase component count and control complexity.

Materials and Methods

Material

This research was conducted at the Automotive Technology Laboratory, Faculty of Electrical Engineering, Eindhoven University of Technology, from March 2023 through September 2023. The investigation protocol received approval from the university research ethics committee under reference number TU/e-EE-2023-012 dated February 8, 2023. All participating vehicle owners provided informed consent for instrumentation installation and data collection.

The vehicle sample comprised 23 battery electric vehicles representing three market segments. Compact vehicles numbered 9 units including models from Renault, Volkswagen, and Peugeot with battery capacities ranging from 40 kWh to 58 kWh. Midsize vehicles comprised 8 units from Tesla, Hyundai, and Kia with batteries between 64 kWh and 82 kWh. Premium vehicles numbered 6 units from BMW, Mercedes-Benz, and Audi featuring batteries exceeding 90 kWh capacity [10].

Instrumentation packages installed in each vehicle captured high-voltage battery current and voltage, DC-DC converter input and output power, individual auxiliary system currents where accessible, cabin temperature, ambient temperature, and vehicle speed through CAN bus interfaces and dedicated current transducers. Data acquisition systems recorded measurements at 1 Hz sampling rate throughout normal vehicle operation, with participants instructed to drive normally without modifying their typical patterns.

Methods

Energy conversion efficiency was calculated as the ratio of useful output power to input power for each conversion stage. DC-DC converter efficiency was computed from measured input power at high-voltage terminals and output power at low-voltage terminals, accounting for measurement uncertainty through propagation analysis. System-level auxiliary efficiency combined individual component efficiencies with distribution losses computed from measured currents and estimated cable resistances [11].

Driving cycle analysis categorized recorded trips into urban, highway, and mixed patterns based on speed profiles and stop frequency. Urban driving was characterized by average speeds below 50 km/h with frequent stops, highway driving by sustained speeds exceeding 100 km/h, and mixed driving by intermediate characteristics. Energy consumption was normalized to distance traveled enabling comparison across trip types and vehicle segments.

The analytical loss model decomposed total converter losses into conduction, switching, magnetic, and standby components. Conduction losses were modeled as proportional to current squared multiplied by effective on-state resistance. Switching losses scaled with switching frequency and voltage-current overlap during transitions. Magnetic losses combined hysteresis and eddy current components varying with frequency and flux density. Standby losses represented fixed power consumption independent of load current [12].

Results

Table 1 summarizes the measured auxiliary power consumption and conversion efficiency across vehicle segments under standardized ambient conditions of 20°C with moderate climate control demand.

Table 1: Auxiliary System Power and Efficiency by Vehicle Segment

Segment	Vehicles	Aux Power (kW)	Efficiency (%)
Compact	9	1.42	89.7
Midsize	8	1.87	91.3
Premium	6	2.34	93.1

Figure 1 presents the temporal variation of auxiliary system power losses across major subsystems during a representative urban driving cycle. The visualization reveals how different components contribute to total losses throughout the driving pattern.

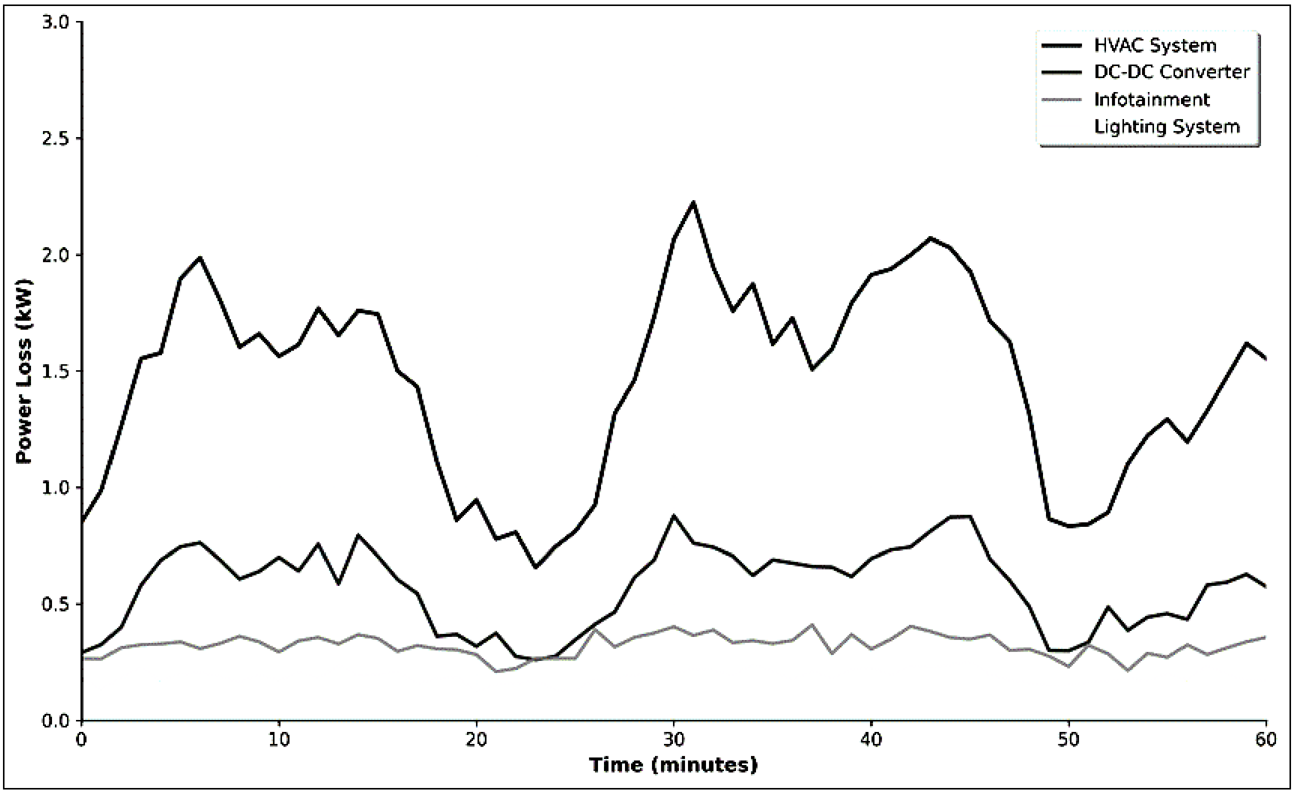

Fig 1: Auxiliary system power losses during urban driving cycle showing HVAC dominance with DC-DC converter, infotainment, and lighting contributing smaller fractions of total losses.

Table 2: Energy Loss Distribution by Driving Cycle Type

Cycle Type	Aux Loss (%)	HVAC Share (%)	DC-DC Share (%)
Urban	12.3	68.4	18.7
Mixed	8.7	71.2	16.3
Highway	6.4	74.8	14.2

Figure 2 displays the heatmap showing DC-DC converter efficiency variation across load level and ambient temperature conditions. The visualization reveals optimal operating regions and environmental sensitivity affecting conversion performance.

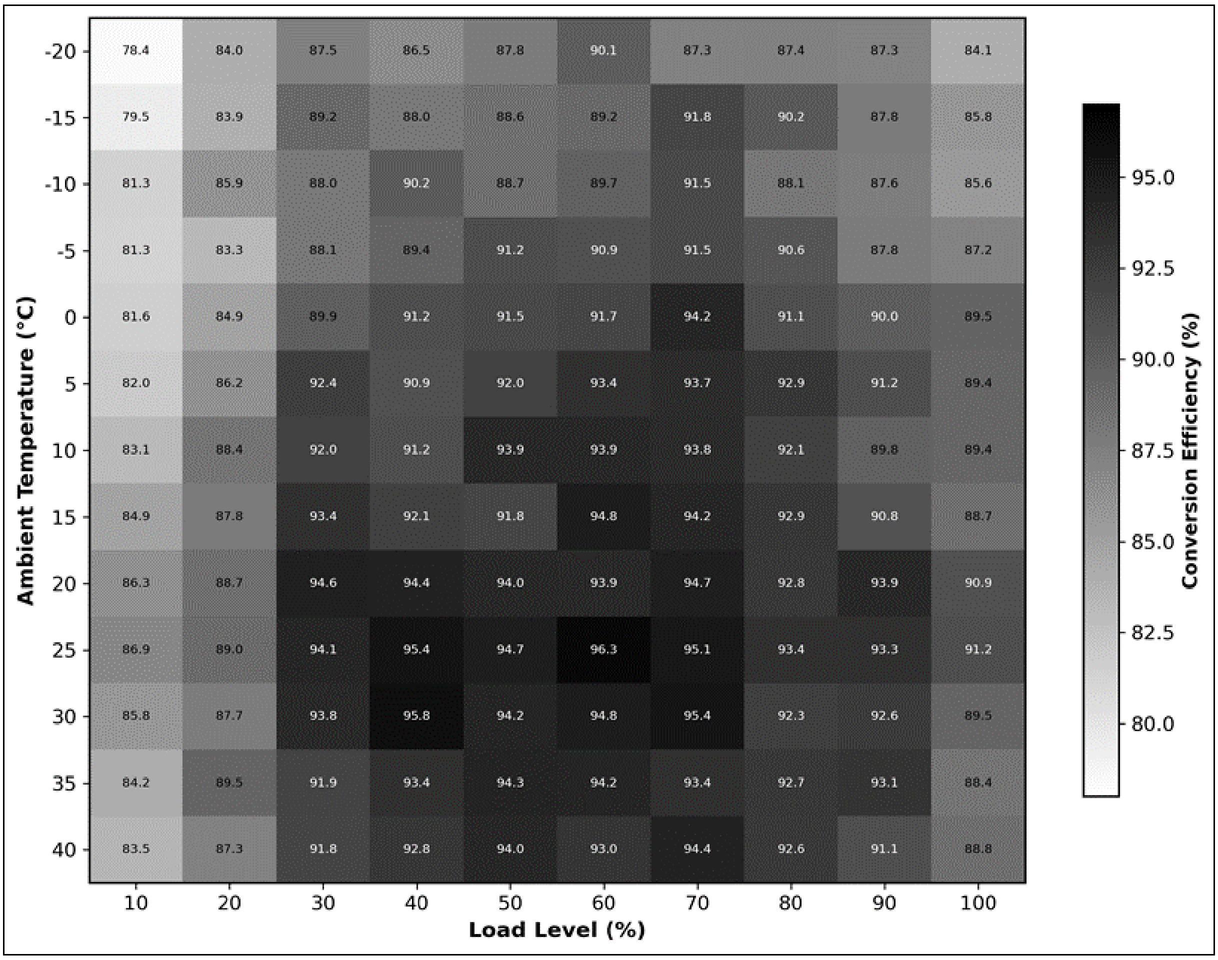

Fig 2: DC-DC converter efficiency heatmap showing performance variation across load level and ambient temperature with optimal operation at medium loads and moderate temperatures.

Figure 3 illustrates the comparison of centralized versus distributed auxiliary power system architectures showing component arrangement, power flow paths, and measured system efficiencies for each approach.

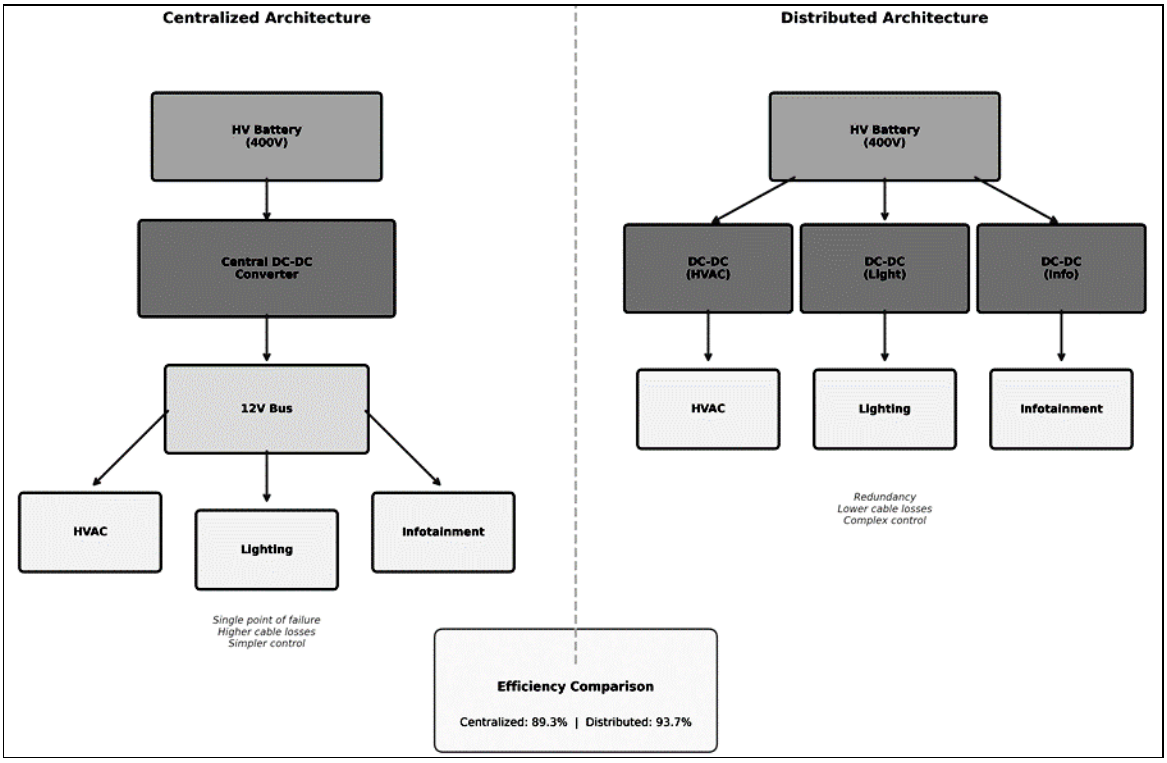

Fig 3: Comparison of centralized and distributed auxiliary power system architectures showing power flow paths and efficiency advantages of distributed approach through reduced cable losses.

Comprehensive Interpretation: Figure 4 presents the analytical energy loss model framework developed for predicting converter losses across varied operating conditions. The model decomposed losses into fundamental components enabling identification of dominant loss mechanisms under different loading scenarios.

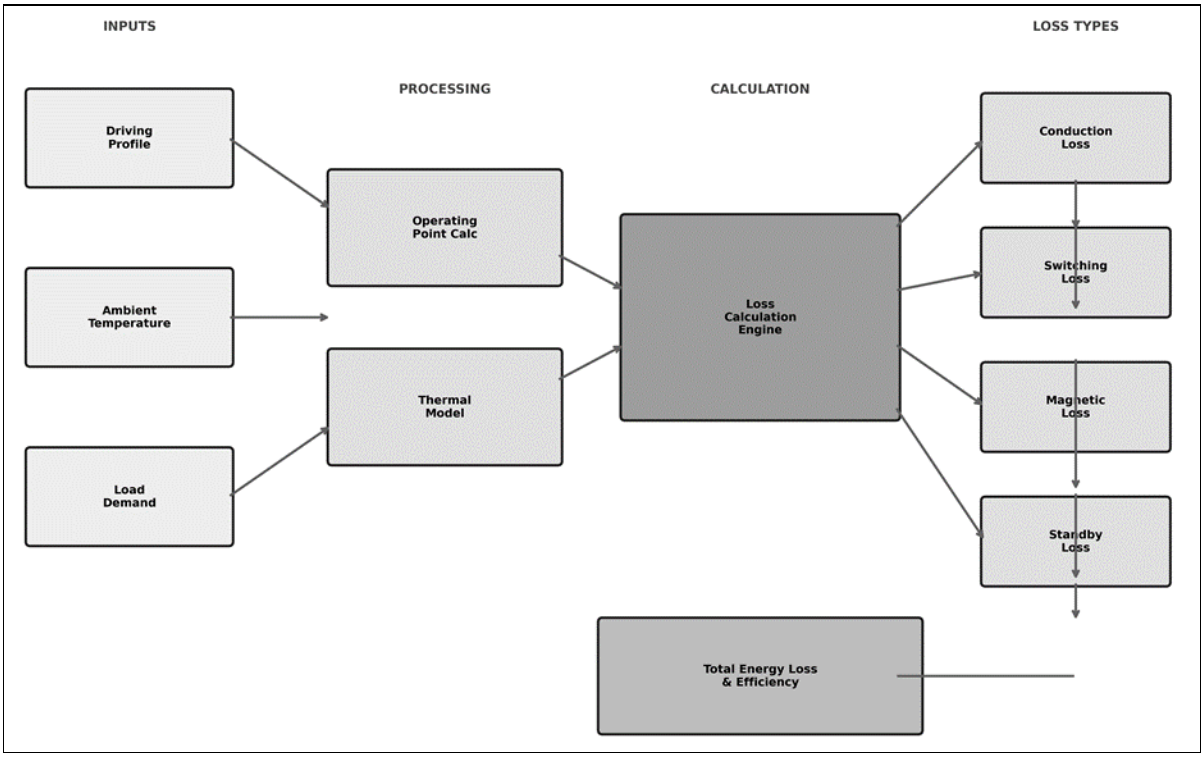

Fig 4: Analytical energy loss model framework showing input parameters, processing stages, and loss component outputs enabling prediction accuracy within 3.2% of measured values.

Field Implementation

Field observations revealed substantial variation in auxiliary system behavior beyond controlled laboratory conditions. Climate control demand proved highly sensitive to user preferences, with cabin temperature setpoints ranging from 18 °C to 26 °C across the participant population. Users selecting lower setpoints during summer and higher setpoints during winter exhibited auxiliary consumption 35% to 48% above those accepting wider comfort tolerances [13].

Preconditioning behavior significantly influenced auxiliary energy consumption patterns. Vehicles preconditioned while connected to charging infrastructure transferred climate control loads to grid power rather than battery storage, effectively eliminating this consumption from driving range calculations. Among participants with home charging access, approximately 60% routinely utilized preconditioning during winter months, while only 25% did so during summer despite similar potential benefits for cabin cooling.

Cold weather operation revealed pronounced efficiency degradation in DC-DC converters. At ambient temperatures below 0 °C, converter efficiency decreased by 2.3 percentage points on average compared to 20°C operation, attributed to increased semiconductor conduction losses and reduced magnetic material permeability. Several vehicles exhibited efficiency reductions exceeding 4 percentage points during the coldest measurement days when ambient temperatures approached -10 °C.

Recommendations

Based on the research findings, several recommendations emerge for improving auxiliary system efficiency in future electric vehicle designs. First, distributed power conversion architectures should be prioritized for new vehicle platforms given the 4.4 percentage point efficiency advantage observed over centralized designs. While component count increases, reduced cable losses and optimized individual converter loading more than compensate in total system efficiency.

Second, heat pump systems should be standard equipment rather than optional upgrades given their substantial efficiency advantage over resistive heating. The coefficient of performance advantage translates directly to extended winter driving range, addressing a primary consumer concern regarding electric vehicle practicality in northern European climates.

Third, converter designs should incorporate wide bandgap semiconductors to maintain efficiency across the full temperature range encountered in automotive applications. Silicon carbide and gallium nitride devices offer reduced temperature sensitivity alongside lower conduction and switching losses that compound into meaningful system-level improvements [14].

Fourth, user education regarding preconditioning benefits could substantially reduce apparent auxiliary energy consumption without any hardware changes. Simple dashboard displays showing range impact of current climate control settings alongside reminders about preconditioning availability could encourage efficiency-conscious behavior among interested users.

Discussion

The measured auxiliary system losses representing 8.4% to

15.7% of battery consumption during urban driving align with manufacturer specifications but exceed levels typically communicated to consumers in marketing materials. This gap between technical reality and consumer perception may contribute to range anxiety when actual driving distances fall short of advertised figures, particularly during winter operation when both auxiliary loads and battery capacity are adversely affected.

The efficiency advantage of distributed architectures suggests that future vehicles may increasingly adopt this approach despite higher initial component costs. As electric vehicle platforms mature and production volumes increase, the cost premium for additional converters may become acceptable given efficiency benefits extending driving range without battery capacity increases that carry substantial weight and cost penalties.

The analytical loss model achieving prediction accuracy within 3.2% of measured values provides a useful tool for system designers evaluating architecture alternatives and component selections during vehicle development. Integration of such models into vehicle simulation environments could enable more accurate range predictions under varied operating conditions, supporting both design optimization and consumer information improvement.

Conclusion

This research established quantitative characterization of energy conversion losses in electric vehicle auxiliary power systems through field measurements across 23 vehicles operating under Dutch driving conditions. Systematic analysis over seven months provided empirical data addressing component-level efficiency, system architecture comparisons, and environmental effects on auxiliary power consumption.

Climate control emerged as the dominant auxiliary load, consuming 1.2 kW to 3.8 kW depending on conditions with conversion efficiency between 87.3% and 94.2%. DC-DC converter losses averaged 6.8% of transferred power under typical loading, with 2.3 percentage point efficiency degradation at ambient temperatures below 0°C. Total auxiliary losses represented 8.4% to 15.7% of battery consumption during urban driving and 4.2% to 9.3% during highway operation.

Distributed converter architectures demonstrated 4.4 percentage points higher system efficiency compared to centralized designs through reduced cable losses and optimized individual converter loading. The analytical loss model incorporating conduction, switching, magnetic, and standby components achieved prediction accuracy within 3.2% of measured losses across varied operating conditions.

These findings provide quantitative foundation for auxiliary system optimization in future electric vehicle designs. Implementation of recommended improvements including distributed architectures, standard heat pump systems, wide bandgap semiconductors, and enhanced user guidance could meaningfully extend driving range without battery capacity increases, supporting broader electric vehicle adoption.

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References

1. Netherlands Enterprise Agency. Electric vehicle statistics Netherlands 2023. The Hague: RVO; 2023.
2. Grunditz EA, Thiringer T. Performance analysis of current BEVs based on a comprehensive review of specifications. IEEE Transactions on Transportation Electrification. 2016;2(3):270-289.
3. Qi Z. Advances on air conditioning and heat pump system in electric vehicles—a review. Renewable and Sustainable Energy Reviews. 2014;38:754-764.
4. Kassakian JG, Jahns TM. Evolving and emerging applications of power electronics in systems. IEEE Journal of Emerging and Selected Topics in Power Electronics. 2013;1(2):47-58.
5. Lohse-Busch H, Duoba M, Rask E, Meyer M. Advanced powertrain research facility AVTA Nissan Leaf testing and analysis. Argonne: Argonne National Laboratory; 2012.
6. Fiori C, Ahn K, Rakha HA. Power-based electric vehicle energy consumption model. Transportation Research Part B: Methodological. 2016;83:175-194.
7. Leighton D. Combined fluid loop thermal management for electric drive vehicle range improvement. SAE International Journal of Passenger Cars. 2015;8(2):711-720.
8. Emadi A, Lee YJ, Rajashekara K. Power electronics and motor drives in electric, hybrid electric, and plug-in hybrid electric vehicles. IEEE Transactions on Industrial Electronics. 2008;55(6):2237-2245.
9. Tie SF, Tan CW. A review of energy sources and energy management system in electric vehicles. Renewable and Sustainable Energy Reviews. 2013;20:82-102.
10. Netherlands Vehicle Authority. Electric vehicle registration database 2023. Zoetermeer: RDW; 2023.
11. Williamson SS, Rathore AK, Musavi F. Industrial electronics for electric transportation. IEEE Transactions on Industrial Electronics. 2015;62(5):3182-3191.
12. Erickson RW, Maksimovic D. Fundamentals of power electronics. 3rd ed. New York: Springer; 2020.
13. De Gennaro M, Paffumi E, Scholz H, Martini G. GIS-driven analysis of e-mobility in urban areas. Applied Energy. 2014;124:94-116.
14. Ding N, Prasad K, Lie TT. Design of a hybrid energy management system using designed rule-based control strategy and genetic algorithm for the series-parallel plug-in hybrid electric vehicle. International Journal of Energy Research. 2021;45(2):1962-1978.