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Priority-Driven Energy Management System for PV-integrated Electric Refrigerator Trucks

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Executive Summary

In this paper, to address the challenge of fluctuating energy generation in photovoltaic (PV)-integrated vehicles due to weather variability and unpredictable driver behavior, a Priority-Driven Energy Management System (PDEMS) is proposed. The PDEMS employs a sequential priority-driven control algorithm that dynamically allocates available power among propulsion, refrigeration, and auxiliary systems based on predefined criticality levels. By continuously monitoring real-time system variables, such as battery state of charge, PV energy input, and subsystem demands, the system adjusts power distribution adaptively under different driving modes. This strategy enables real-time prioritization of critical components, ensuring efficient energy usage while maintaining operational reliability. Simulation results demonstrate that the PDEMS achieves a 5.5% increase in driving range compared to baseline allocation method. By effectively managing fluctuating energy availability and operational demands, the proposed approach enhances energy efficiency and reliability, making it particularly suitable for PV-integrated electric refrigerator trucks operating under variable conditions.

Keywords: Energy Management, Heavy Duty Electric Vehicles, Refrigerated Truck, photovoltaic truck.

1 Introduction

The integration of PV systems into electric vehicles (EVs) has emerged as a promising approach to improving energy efficiency and extending driving range. In particular, PV-assisted EVs are gaining attention for their ability to supplement battery power with renewable energy, making them a sustainable option for diverse transportation needs. Among these, electric refrigerator trucks have become a focal point for research due to their critical role in cold chain logistics, where the transportation of perishable goods like food and pharmaceuticals requires precise temperature control [1]. Advancements in drivetrain optimization and PV technology have demonstrated the potential for improved efficiency in these vehicles.

However, existing energy management strategies are predominantly focused on optimizing the powertrain, often overlooking the substantial and dynamic energy demands of refrigeration and HVAC systems [2].

Static power allocation methods, which distribute energy based on predetermined rules, have been commonly employed. While effective for steady-state conditions, these approaches fail to adapt to real-time variations in operational and environmental factors [3]. This limitation is particularly critical for PV-integrated electric refrigerator trucks, where energy demands fluctuate due to weather variability, driver behavior, and the competing requirements of multiple essential systems such as propulsion, refrigeration, and HVAC [4].

The unique challenges faced by PV-integrated electric refrigerator trucks are multifaceted. Solar energy generation is inherently variable, influenced by weather conditions such as sunlight intensity and cloud cover [5]. This variability complicates the balance between energy supply and demand. Moreover, refrigeration and HVAC systems alone can account for up to 30% of the vehicle's energy consumption during peak usage, significantly impacting overall efficiency and vehicle range [4].

Driver behavior further adds to the complexity, with changes in driving patterns and comfort requirements introducing unpredictable variations in energy needs [6]. Static energy allocation methods are ill-equipped to address these dynamic conditions, leading to suboptimal energy distribution, reduced operational reliability, and compromised cold chain integrity. As a result, there is a critical need for adaptive energy management strategies that can dynamically respond to real-time changes [7].

To address these challenges, a PDEMS is proposed as an innovative solution for managing energy distribution in PV-integrated electric refrigerator trucks. PDEMS dynamically adjusts power allocation across critical systems in real-time to prioritize energy distribution based on battery state of charge (SOC), environmental conditions, and driver-initiated demands.

By incorporating real-time data, PDEMS ensures optimal energy utilization, adapting to fluctuations in solar energy generation and changing operational requirements. This strategy not only enhances vehicle range and energy efficiency but also safeguards cold chain performance by ensuring refrigeration and HVAC systems receive adequate energy under varying conditions.

2 System Model and Problem Formulation

The refrigerator truck of ESCALATE [8] consists of several key subsystems. It utilizes a PV system, regeneration and a battery pack as primary energy sources. They support propulsion, refrigeration, and auxiliary loads. When regeneration power exceeds the immediate demand and battery charging capacity, the surplus power is directed to a resistor bank to prevent overcharging. The PV is located on the truck and trailer roofs (Figure. 1).

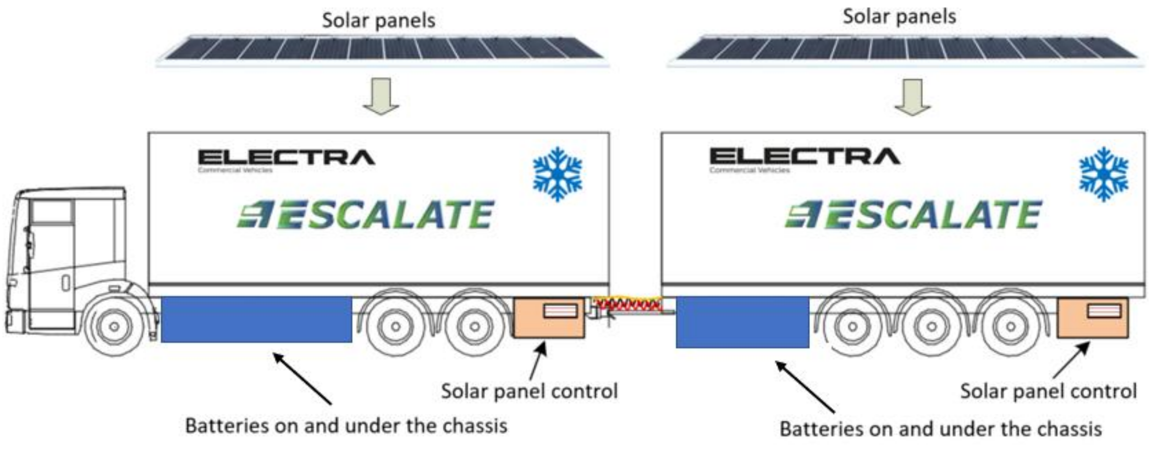

Figure 1: Schematic representation of ESCALATE ELECTRA’s truck

Each set of PV system, has 6 PV modules and 1 DCDC controller. An MPPT (Maximum Power Point Tracker) is used to stabilize the voltage. Bypass diodes are placed between modules to optimize PV performance under partial shading. The PV is modeled in MATLAB Simscape Electrical with the help of an equivalent circuit model embedded in the PV cell block using the 1-Diode approach [9]. A general system description can be seen in equation (1). Most of these parameters are variable, except R_s, R_{sh} and the cell I_{sc}. Certain parameters in the PV model are directly extracted from the ESCALATE project partner's datasheets, while others are calibrated to ensure that the simulated power output precisely matches the expected performance specified in the datasheets. The PV cell block uses the irradiance ($W/m2$) as input.

$$I = I_{sc} - I_s \left[\exp\left(\frac{\mathrm{V+I}R_s}{V_T}\right) - 1\right] - \left(\frac{\mathrm{V+I}R_s}{R_{sh}}\right) \quad (1)$$

where I is module current (A), I_{sc} is short circuit current (A), I_s is current in a diode (A), V is voltage (V), V_T is thermal voltage (V), R_s is series resistor (Ω), R_{sh} is parallel resistor (Ω).

The Trailer Refrigeration Unit (TRU) model developed in this study integrates a vapor compression refrigeration system, an insulated cargo body, a door-opening disturbance mechanism, and a thermal cargo model. The refrigeration system delivering a cooling capacity of 8.6 kW at an ambient temperature of 30 $°C$ and a return air temperature of 0 $°C$. Variable-speed inverter control allows adjustment of the compressor rotational speed to regulate cooling output. The insulated truck body, representing a 42.8 m^3 air volume, is modeled with simplified single-layer thermal walls whose total thermal resistance R_{tot} and equivalent conductivity k_{tot} are computed from material properties. Convection coefficients are set at 5 $W/m^2 \cdot K$ for the interior and 25– 40 $W/m^2 \cdot K$ for the exterior. The thermal dynamics of the compartment are governed by a first-order energy balance:

$$C_{box}\frac{dT_{box}}{dt} = \frac{T_{amb}(t) - T_{box}(t)}{R_{box}(t)} - \dot{Q}_{cool}(t) \quad (2)$$

where C_{box} is the thermal capacitance, R_{box} is the wall resistance, and $\dot{Q}_{cool}(t)$ is the refrigeration power output. Door-openings are simulated by temporarily increasing conduction and convection coefficients, representing realistic thermal disturbances during loading and unloading.

Truck's electric drive system is responsible for vehicle propulsion, ensuring efficient and reliable movement. The refrigeration system maintains the cargo at the required temperature to preserve goods during transport. Auxiliary systems, such as lighting, HVAC, and driver comfort features, enhance operational efficiency and safety.

Together, these components dynamically balance energy usage, optimizing power distribution among propulsion, refrigeration, and auxiliary needs to improve efficiency and sustainability.

The truck's motion is analyzed based on its longitudinal dynamics, represented by equation (3)

$$m\frac{dv}{dt} = F_{tr} - F_r - F_w - F_g \quad (3)$$

where, m denotes the vehicle's mass, $\frac{\mathrm{dv}}{\mathrm{dt}}$ represents the longitudinal acceleration, F_{tr} is the traction force, $F_r = C_r mgcos\theta$ is the rolling resistance, C_r is rolling resistance coefficient, $F_w = 0.5A\rho C_d \mathrm{v}^2$ is the aerodynamic drag where C_d is air resistance coefficient, and $F_g = mgsin\theta$ is the grading resistance. The parameters for the vehicle are provided in Table 1.

Table 1: Vehicle Parameters

Subsystem	Parameter	Value
Vehicle	Vehicle mass[kg]	40000
	Wheel radius [mm]	500
	Frontal area [m^2]	7.2

	Air resistance coefficient	0.75
	Rolling resistance coefficient	0.007
Battery	Energy [kWh]	930
PV	Total Peak Power [kW]	3.9
	Efficiency [%]	16.4
TRU	Refrigeration Capacity [kW]	8
	Cargo Air Volume [m³]	40

3 Priority-Driven Energy Management System

The primary objective is to develop a real-time energy management strategy for PV-integrated electric refrigerator trucks that optimally allocates available power among the propulsion system, refrigeration unit, and auxiliary systems. At each time step, the total available power (see equation 3) is distributed by evaluating subsystem demands in order of descending priority. Subsystems with higher priority receive their full demand until available power is exhausted. Lower-priority systems are served only if surplus power remains and are further limited or disabled in ECO and EMG modes to conserve energy and extend range. Refrigeration always receives the highest priority to preserve cold chain integrity.

$$P_{drive}(t) + P_{refr}(t) + P_{aux}(t) \leq P_{avail}(t) \tag{3}$$

$$P_{refr}(t) = \min(P_{refr,dem}(t), P_{avail}(t)) \tag{4}$$

$$P_{avail}^{(1)}(t) = P_{avail}(t) - P_{refr}(t) \tag{5}$$

$$P_{drive}(t) = \min(P_{drive,dem}(t), P_{avail}^{(1)}(t)) \tag{6}$$

$$P_{avail}^{(2)}(t) = P_{avail}^{(1)}(t) - P_{drive}(t) \tag{7}$$

$$P_{aux}(t) = \min(P_{aux,dem}^{mode}(t), P_{avail}^{(2)}(t)) \tag{8}$$

$$P_{avail}(t) = P_{batt}(t) + P_{PV}(t) + P_{reg}(t) \tag{9}$$

where $P_{drive}, P_{ref}, P_{aux}$ are the power allocations for the drive system, refrigeration system, and auxiliary systems, respectively. P_{PV} is the power generated by the PV panels, P_{batt} is the power available from the battery and P_{reg} is the regeneration power recovered through regenerative braking during deceleration. $P_{aux,dem}^{mode}(t)$ is mode-specific caps in ECO or EMG mode.

In brief, the proposed PDEMS utilizes a priority-driven sequential power allocation mechanism that resembles a greedy algorithm in structure based on predefined subsystem priorities. At each control instance, the total available power P_{avail}, which includes contributions from photovoltaic generation the battery and regeneration, is distributed among the vehicle's subsystems according to their priority levels.

The allocation rule for each subsystem i at time t is defined as follows: If the available power is greater than or equal to the requested power $P_{req,i}(t)$, the subsystem is provided with its full requested power (see equation 10). If the available power is less than the requested power, the subsystem is allocated the remaining available power (see equation 11). After each allocation, the available power is updated by subtracting the allocated power.

$$if\ P_{avail}(t) \geq P_{req,i}\ then\ P_{alloc,i}(t) = P_{req,i}(t) \tag{10}$$

$$otherwise\ P_{alloc,i} = P_{avail}(t) \tag{11}$$

The remaining available power is then updated as shown in equation 12:

$$P_{avail}(t) \leftarrow P_{avail}(t) - P_{alloc,i}(t) \tag{12}$$

This process is repeated sequentially across all subsystems, starting from the highest-priority subsystem and proceeding in descending order of priority. Once the available power is fully allocated, no further subsystems are served during that control interval. This deterministic allocation strategy ensures that the most critical systems, such as propulsion and refrigeration, are prioritized during periods of energy scarcity, while lower-priority auxiliary systems are curtailed as necessary to maintain vehicle operability and cargo integrity.

As shown in Figure 2, the proposed energy management strategy defines three primary operating modes-Normal (NML), Economy (ECO), and Emergency (EMG)-each corresponding to a distinct power prioritization policy based on the system's energy status and battery SOC.

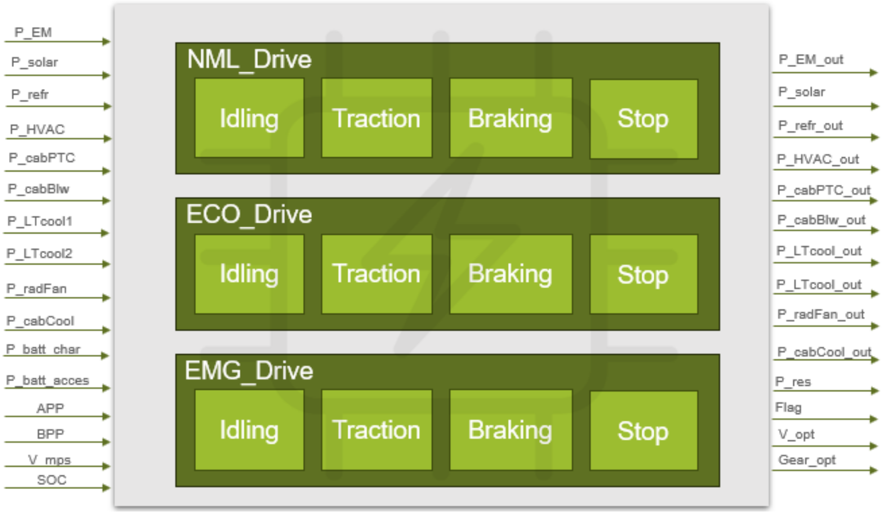

Figure 2: Driving modes

In NML mode, the system ensures efficient operation by supplying energy to all major subsystems, including propulsion, refrigeration, and auxiliary loads, thereby maintaining normal performance without power limitations. ECO mode activates when the battery drops below a mid-range SOC threshold ($20\% < SOC < 50\%$) and is designed to extend the driving range by limiting power to non-essential subsystems. In this mode, critical functions such as propulsion and refrigeration remain active, while lower-priority auxiliary components are selectively curtailed to preserve energy. EMG mode is triggered under low SOC conditions ($SOC < 20\%$) and restricts power allocation to only essential components-primarily the refrigeration system and minimal propulsion support-ensuring thermal integrity of the cargo and basic vehicle operability during critical energy shortfalls.

Complementing these driving modes, the system implements four dynamic sub-states; idling, traction, braking, and stop; that refine energy distribution based on the vehicle's operational state. During the idling state, which occurs when the vehicle is stationary, power is primarily directed to the refrigeration unit to sustain required thermal conditions, while propulsion and auxiliary systems are deactivated or minimized to conserve energy. In the traction state, the system prioritizes energy delivery to the electric motor to meet acceleration demands, with continuous operation of the refrigeration unit to maintain cargo stability. The braking state is engaged during deceleration events and activates regenerative braking to capture kinetic energy, which is subsequently routed to recharge the battery. Finally, the stop state corresponds to mandatory rest periods, such as those imposed by regulations requiring breaks after 4.5 hours of continuous driving [10]. In this condition, the system deactivates all non-essential components, maintaining only the refrigeration function to preserve cargo quality while maximizing energy conservation. Together, these adaptive modes and sub-states enable real-time power distribution, aligning energy use with both dynamic driving conditions and regulatory compliance to improve overall system efficiency and reliability.

The proposed power allocation strategy operates under a hierarchical structure where priority levels (1–4) are assigned within each operational driving mode and substate. These priorities govern the real-time distribution of available power among the vehicle's subsystems based on their criticality to safety, performance, and cold chain preservation. In each driving mode and substate, the priority level "1" is assigned to mission-critical systems, such as the refrigeration unit, to ensure uninterrupted temperature regulation, while Priority "2" is typically assigned to propulsion components required for maintaining mobility. These two tiers are guaranteed power allocation unless the total available energy is insufficient. Priority levels "3" and "4" are allocated to auxiliary and comfort-related systems, which are activated only when surplus power is available. Priority "3" components (e.g., radiator fan, coolant pumps) serve thermal management but are non-essential for immediate vehicle function, while Priority "4" systems (e.g., cabin blower, PTC heater) are purely comfort-oriented and receive energy only in favorable conditions.

4 Results and Discussion

To evaluate the effectiveness of the proposed PDEMS, simulations were conducted under three strategy using the Dundee–Southampton drive cycle, which offers a representative combination of urban, suburban, and highway driving patterns (see Figure 3).

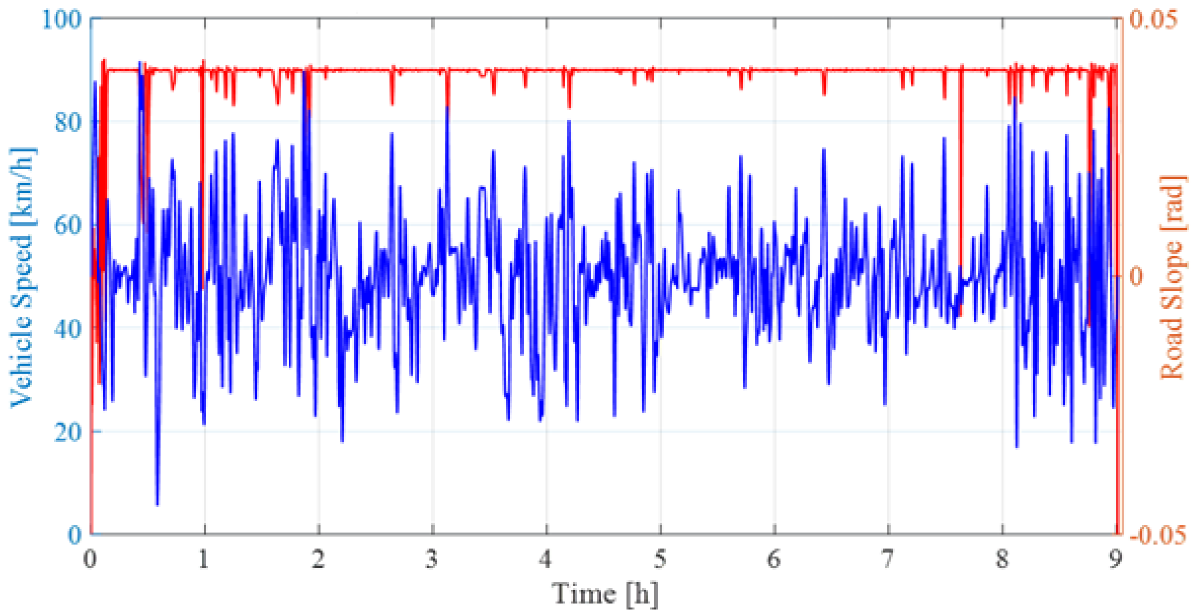

Figure 3: Speed and road slope profile of the Dundee–Southampton drive cycle

Three scenarios ruled by three strategies are simulated in MATLAB to assess key performance metrics, including driving range, specific energy consumption, and percentage range improvement, as summarized in Table 2. The baseline strategy 1 utilizes NML mode only over the whole cycle. It achieves a driving range of 451.9 km. Strategy 2 starts with NML and switching to ECO after SOC drops below %50. Strategy 2 continues with ECO mode to the end of the cycle. This strategy extends the range to 476.5 km. EMG mode is further included within strategy 3. This strategy starts with NML, switching to ECO mode after SOC drops below %50, and again switching to EMG when dropping below %20 SOC. Strategy 3 yields a slight additional increase to 476.78 km. Specific energy consumption remains relatively stable across all modes, recorded at 179.24 $kWh/100\ km$ for strategy 1, 170.08 $kWh/100\ km$ for strategy 2 and 169.97 $kWh/100\ km$ for strategy 3. Notably, the strategy 2 configuration achieves the most significant range improvement, enhancing driving range by 5.44% relative to baseline, while the strategy 3 provides a slightly higher range increase of 5.51%.

Table 2: Impact of Driving Modes on Vehicle Range and Energy Consumption

Strategy	Modes Involved (Base on SOC)			Range (km)	Specific Energy Consumption (kWh/100km)	Increase in Range (%)
	100%-50%	50%-20%	20%-0%			
1	NML			451.9	179.24	0 (Baseline)
2	NML	ECO		476.5	170.08	+ 5.44

3	NML	ECO	EMG	476.8	169.97	+ 5.51

Figure 4 illustrates the evolution of the battery SOC over time for each strategy. The horizontal axis represents the simulation time in hours, while the vertical axis indicates the battery SOC in percentage. The plot is divided into three regions corresponding to operational modes employed for each strategy. Strategy 1 (Baseline) follows a constant priority setting and does not adjust subsystem power allocations based on SOC. Strategy 2 introduces ECO mode when the SOC drops below 50% which limits non-essential power consumption. Strategy 3 incorporates full PDEMS functionality with transitions across all three modes, including aggressive energy conservation below 20% SOC in EMG mode. It can be observed that SOC depletes more gradually under ECO and EMG modes compared to NML, confirming that auxiliary power reductions in these modes effectively extend the vehicle's operational time. Adding EMG mode shows the slowest SOC decline, prioritizing refrigeration while minimizing auxiliary and propulsion energy use.

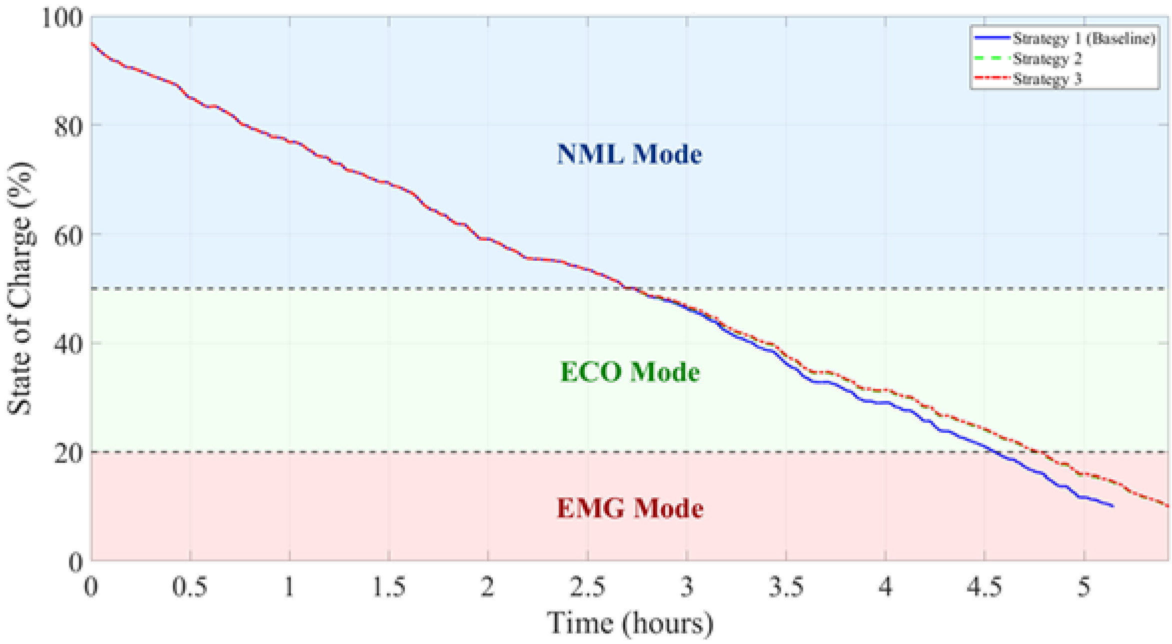

Figure 4: Battery SOC over time (for all modes).

5 Conclusion and Future Work

A Priority-Driven Energy Management System (PDEMS) for athe PV-integrated electric refrigerator ELECTRA's truck of ESCALATE project is designed in this paper. PDEMS manages power sources (battery, PV and regeneration) in real-time based on demand and battery status, prioritizing essential components and enhancing energy efficiency, safety, and scalability for diverse EV applications. This study demonstrates that dynamic prioritization significantly enhances vehicle range, with NML+ECO mode maximizing range efficiently.

Future work will integrate AI techniques to enable predictive power allocation. Additionally, real-world testing will be conducted under a variety of driving and weather conditions to validate the system's performance. The scope will also be expanded to include other types of PV-integrated electric vehicles.

Acknowledgments

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Presenter Biography

Mehmet Zahid Erkesim holds an MSc in Autonomous Vehicle Dynamics and Control from Cranfield University and is currently a Research Engineer at the University of Surrey, developing Energy Management algorithms for the ESCALATE project (Grant No: 101096598).