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Sector coupling: accelerating renewable energy integration in transport with electric vehicles

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Abstract

Energy and transport have long operated in 'silos', creating inefficiencies and conflicting goals. Breaking these silos through sector coupling links electricity and transport, aligning policies and actions to decarbonise mobility while boosting renewable energy use. By substituting fossil fuels with renewable electricity across transport and other end uses, sector coupling strengthens sustainability and accelerates climate goals. Building on prior research on electric vehicles and renewable energy, this paper examines the challenges and opportunities of sector coupling between energy and transport to maximise renewable integration in EVs, advancing a more sustainable and decarbonised transport system. Through a systematic literature review and interviews with relevant stakeholders, it examines various use cases in urban and rural settings, including strategies for controlled charging, bidirectional interactions between vehicles and the power grid, and off-grid solutions. The findings highlight a range of technical, regulatory, and economic challenges but also indicate promising pathways for collaboration among policymakers, industry, and civil society. Ultimately, by bridging the gap between energy and transport, this paper underscores how cross-sectoral approaches can help achieve a more sustainable and low-carbon mobility system

Keywords Sector coupling, Cross-sectoral collaboration, Transport, Energy, Electric vehicle

Introduction

Electrifying road transport plays a vital role in decarbonising the transport sector, alongside model shifts and spatial planning strategies. With the increasing electrification of the global vehicles fleet, the integration of transport and electricity sectors becomes much more critical than it used to be in a fossil fuel-based system. Enhancing the energy efficiency of the transport sector can help limit the overall demand for electricity, but ensuring a stable supply of renewable energy to power electric vehicles for passenger and freight transport remains a major planning and investment challenge [1]. While sales in Electric Vehicles (EV) grew substantially in recent years, the share of renewable energy sources (RES) remains relatively low in key markets such as China and the United States, where renewables account for approximately 31 and 21% of total electricity generation, respectively [2].

Utilising RES, particularly solar and wind comes with several challenges. Flexibility and reliability, particularly intermittency, are major constraints for renewables [3–6]. Integrating these variable RES into existing energy systems, particularly those that rely on inflexible coal or nuclear power that cannot be rapidly ramped up or down to respond to fluctuations in renewable energy feed-ins, is more challenging than integrating other renewables such as hydropower [7]. This necessitates further

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development in renewable energy management including energy storage systems, load shifting, and smart integration with new demand sectors such as heat pumps and EVs [7].

Despite the recently growing uptake of EV registrations, the transport sector still relies significantly on fossil fuels. The International Energy Agency has reported that in 2022, 91% of global energy consumption in the transport sector was fuelled by oil products [8]. Meanwhile, a surge in EV adoption, if not carefully managed, risks overwhelming the electricity grids due to rising energy demand [6, 9–13].

Energy and transport sectors have traditionally and institutionally been addressed as separated "silos" by decision makers [14–16], with different regulatory frameworks, objectives, and implicit assumptions. In particular, the disconnect between the transport and energy sectors can lead to inefficiencies, misaligned trajectories and contradicting policies, investments and incentives [16]. For example, the delayed roll-out of smart charging infrastructure in several European countries[1] limits EV owners' ability to benefit from lower electricity prices during off-peak periods and reduces opportunities to align transport demand with electricity system flexibility. Breaking these silos can lead to a significantly more efficient use of resources, which requires a more concerted approach across energy and transport sectors and related actors to align policy, research, and implementation [16].

This paper aims to identify the opportunities and challenges of increasing renewable energy integration in EVs, contributing to a more sustainable and decarbonised transport system. Several studies have explored the integration of EVs and renewable energy sources. This article builds on and expands on the literature on the integration between renewable energy sources and EVs [17], explore microgrids [18] and possibility of vehicle-to-grid (V2G) [19] to enhance overall efficiency. Specifically, it identifies research gaps and complements the existing body of literature with stakeholder interviews representing underrepresented areas and solutions.

This paper explores how integration strategies between the energy and transport sectors can mutually foster renewable energy uptake, promote EVs, and improve the efficiency of the transition in both sectors. The analysis focuses on use cases in urban and rural contexts and addresses the following research questions:

1. How can coupling the transport and energy sectors through EVs support greater integration of variable RES?
2. How do urban and rural use cases differ, and what unique opportunities emerge?

Scope and limitations

The paper focuses on the integration of electricity-based energy and road transport, particularly the use of renewable sources such as solar and wind. The scope is limited to battery electric vehicles, excluding hydrogen-powered and fuel-cell vehicles.

Conceptual framework

Sector coupling

The definition of sector coupling varies between different literature sources but can be described as a combination of two main components: (1) the systematic electrification of different energy-using sectors, including transport, heating and cooling, and industry, and (2) the integration of these sectors with electricity production and infrastructure into a unified energy system, including flexible technologies (e.g. storage, smart charging) to balance supply and demand across sectors. Ramsebner et al. [15] concentrate on the transition from fossil fuels to renewable energy sources across all end-consumption sectors, while Fridgen et al. [3] place emphasis on the purposeful integration of the electricity production sector and energy-consuming sectors. In line with the findings of Straub et al. [20], this study emphasises the integration of RES in EVs and electricity grid.

Conventionally, energy-using sectors have operated separately on different carriers, but the importance of joint and integrated consideration is growing. [14, 16]. Sector coupling, which involves integrating energy across sectors, can contribute to reducing emissions and increasing the flexibility, energy efficiency and use of renewable energy of the power system [9, 14, 15, 21–23]. One of the key examples is integrating parked EV batteries into the electricity grid, enabling bidirectional charging and temporary electricity storage [9, 24, 25]. This system maximizes electricity usage during periods of surplus renewable energy supply, minimizes consumption during times of low renewable energy generation, and supplies stored energy from EV batteries during electricity shortages [9].

Breaking the silos

The breaking the silos approach applied in this paper, addresses systemic disconnects between sectors [16], particularly energy and transport sectors. The concept of the silo represents a fundamental organising principle in the structure of social institutions, including government departments [26]. Albeit necessary to simplify decision-making processes and organisational structures [26, 27], silo-thinking has been criticised for its inability to resolve complex, crosscutting, and comprehensive

[1] The EU's Alternative Fuels Infrastructure Regulation will only require all new chargers to support smart communication from 2027, meaning many current installations lack advanced flexibility features.

Table 1 List of literature related to use-cases in energy and transport integration

No	Authors	Year	Unidirect-ional Charging		Bidirectional Charging			Off-Grid Solutions		Other uses	Geographic Context	Location Context		RES		
			Uncontrolled Charging	Controlled Charging	V2G	V2B	S2G	Standalone Microgrids	VIPV			Urban	Rural	Solar	Wind	Other RES
1.	Barman et al. [33]	2023		•												•
2.	Bogdanov and Breyer [9]	2024	•	•	•											•
3.	Borge-Diez et al. [34]	2021				•					Spain	•				•
4.	Corsetti et al. [35]	2024		•							Germany	•		•		•
5.	Dan and Zhou [36]	2024				•								•	•	
6.	Dik et al. [37]	2024	•		•					Heating (building)	UK	•		•	•	
7.	Dixon et al. [38]	2023					•				Lao PDR					•
8.	Gschwendtner and Krauss [24]	2022			•						Germany, Switzerland					•
9.	Gschwendtner et al. [6]	2021			•											•
10.	Gschwendtner et al. [39]	2023	•	•	•						Germany	•	•	•		
11.	Guéret et al. [10]	2024			•									•	•	
12.	Guo et al. [40]	2021			•					Hybrid Microgrids				•	•	
13.	Hasan et al. [41]	2023			•			•	•		Bangladesh					
14.	Heinisch et al. [21]	2021		•							Sweden	•		•		
15.	Horak et al. [42]	2024					•							•		
16.	Irfan et al. [43]	2024			•			•			Australia		•	•	•	
17.	Jing and Zhao [44]	2024				•								•		
18.	Kern and Kigle [45]	2022			•						Europe			•	•	
19.	Khardenavis et al. [46]	2021			•						Canada	•		•	•	
20.	Lehtola et al. [47]	2025		•												•
21.	Lerbinger et al. [48]	2024	•	•		•					Switzerland	•				•
22.	Mangipinto et al. [49]	2022	•	•							Europe					•
23.	Meha et al. [50]	2024			•					Heat pumps	Kosovo					•
24.	Misconel et al. [51]	2024			•						Germany			•	•	
25.	Nadimuthu et al. [52]	2024			•			•	•	Hybrid Microgrids	India		•	•		
26.	Oladigbolu et al. [13]	2024			•											•
27.	Ortega-Cabezas et al. [53]	2021				•					Spain	•				•
28.	Pastore [54]	2023		•						Heat pumps	Italy	•		•		
29.	Pochont and Sekhar Y [55]	2023							•					•		
30.	Raveendran et al. [56]	2020	•		•						Spain		•	•		
31.	Ravi and Aziz [57]	2022	•	•	•	•										•
32.	Revankar and Kalkhambkar [58]	2021	•				•									•
33.	Salehpour and Hossain [59]	2024			•											•
34.	Sethuraman and Rudhramoorthy [60]	2024			•											•
35.	Sevdari et al. [5]	2023		•												•

Table 1 (continued)

No	Authors	Year	Unidirect-ional Charging		Bidirectional Charging			Off-Grid Solutions		Other uses	Geographic Context	Location Context		RES		
			Uncontrolled Charging	Controlled Charging	V2G	V2B	S2G	Standalone Microgrids	VIPV			Urban	Rural	Solar	Wind	Other RES
36.	Sharifi et al. [61]	2020			.											.
37.	Siregar and Möller [23]	2023	.	.						District cooling	Indonesia					.
38.	Straub et al. [20]	2023			.						Germany	.		.		
39.	Strobel et al. [62]	2022	.	.							Germany					.
40.	Topel and Grundius [12]	2020		.							Sweden	.				.
41.	Yang et al. [63]	2024			.						China	.				.
42.	Zhang et al. [64]	2024					.				China	.				.
43.	Zhou et al. [65]	2019				.										.
44.	Zou et al. [66]	2024			.											.

issues [26–28]. The sectoral disconnect, such as in mobility, energy, and urban development, is characterised by isolated planning processes and time plans, fragmented policies and goals, and a tendency to overlook cross-sectoral co-benefits [16].

Breaking the Silos calls for cross-sectoral integration, where representatives of different sectors and groups of actors collaborate to maximize their collective impact. Climate change, as one of the pressing cross-sectoral issues, requires policy integration between silos to achieve the expected progress [26, 29, 30]. This paper focuses on breaking sectoral silos, particularly between the energy and transport sectors, with a specific emphasis on integrating electric vehicles and renewable energy.

Methodology

This paper employs a systematic literature review to explore use cases of EVs and RES integration within the energy mix, as well as to analyse research trends on this topic. The results of the literature review will then be analysed to identify the opportunities and challenges associated with each use case and literature gaps. The systematic literature review focuses on sector coupling use cases through the energy and transport sectors, with electricity as the main energy vectors, that are published between 2019 and 2025. This scoping review employs a search of the Directory of Open Access Journals [31] and Science Direct [32] database using the following Boolean strings to identify relevant journal articles:

("Sector coupling" OR "energy integration") AND ((transport AND electricity) OR electric vehicle)

A total of 188 articles were identified that matched the specified keywords, with the exclusion of any duplicates. 44 articles are identified to be relevant to the topics and touch upon RES integration.

To enrich the study, semi-structured interviews were conducted for use cases that are under-represented in the literature. As shown in the next section, the systematic literature review highlights that off-grid solutions are under-represented, with research also indicating a lack of representation from the Global South and emerging economies. To address this gap, five interviews were carried out in 2025 with key players in microgrids and vehicle-integrated PV, who have operated use cases across diverse regions, including South Africa, Bangladesh, Kenya, Sweden, India, and Italy. Detailed background of the interviewee is provided in the appendix.

Systematic literature review

Articles that are reviewed in this paper based on the previously mentioned method are summarised in Table 1. As seen in Fig. 1, this paper categorised the energy and transport use cases as follows:

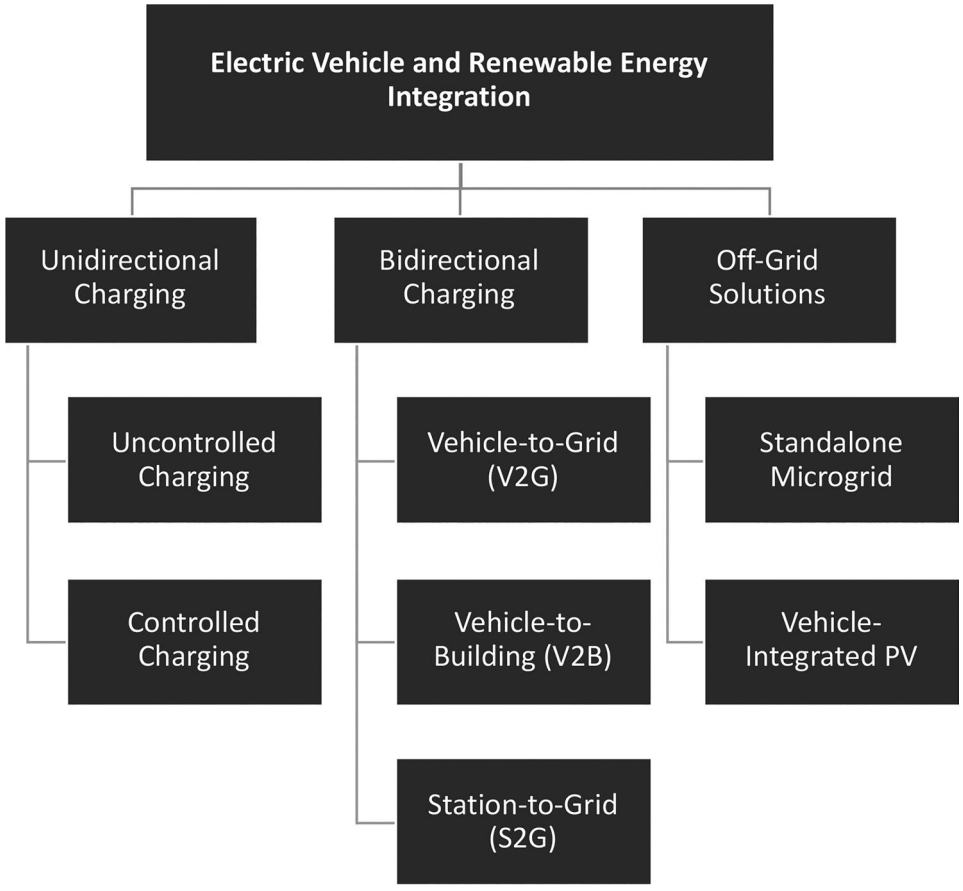

Fig. 1 Use-case categorisation

(1) Unidirectional charging: uncontrolled charging and controlled charging;
(2) Bidirectional charging: V2G, vehicle-to-building, and station-to-grid; and
(3) Off-grid solutions: standalone microgrid and vehicle-integrated photovoltaics (VIPV)

Based on the reviewed literature, Figure 2 shows that V2G (under bidirectional charging) and controlled charging (under unidirectional charging) have attracted more research attention in the context of transport and energy integration, while off-grid solutions such as standalone microgrids and VIPV are less frequently represented. When considering geographic context, 68% of the identified literature focuses on Europe. Additionally, use cases in urban settings are more prevalent than those in rural contexts, as illustrated in Fig. 3. Several studies also explore the coupling of other sectors, particularly heating and cooling.

As mentioned in the previous section, based on these results, interviews were conducted to explore less represented use cases of off-grid solutions, with a particular focus on countries outside of Europe.

Use cases related to energy and transport integration

Unidirectional charging

Uncontrolled charging

Uncontrolled charging of EVs is the most conventional approach in charging the vehicles. Vehicles draw electricity from the grid without scheduling and flexibility, and without considering electricity generation imbalances or market price signals [9, 56]. While it requires least infrastructure, uncontrolled charging may place significant strain on electricity grids due to load demand [5, 6, 9–13, 42]. In addition, uncontrolled EV charging exacerbates the challenges of integrating EVs and renewable electricity into the grid due to limited capability of uncontrolled charging in increasing RES' flexibility [39].

Dik et al. analyse the impact of uncontrolled EV charging in a renewable energy-integrated community network, noting its potential to cause grid capacity issues at high EV penetration, especially in colder months [37].

Controlled charging

Controlled charging, also called smart charging, enables control of the EVs charging power, in response to the current electricity supply and cost [9]. Controlled charging

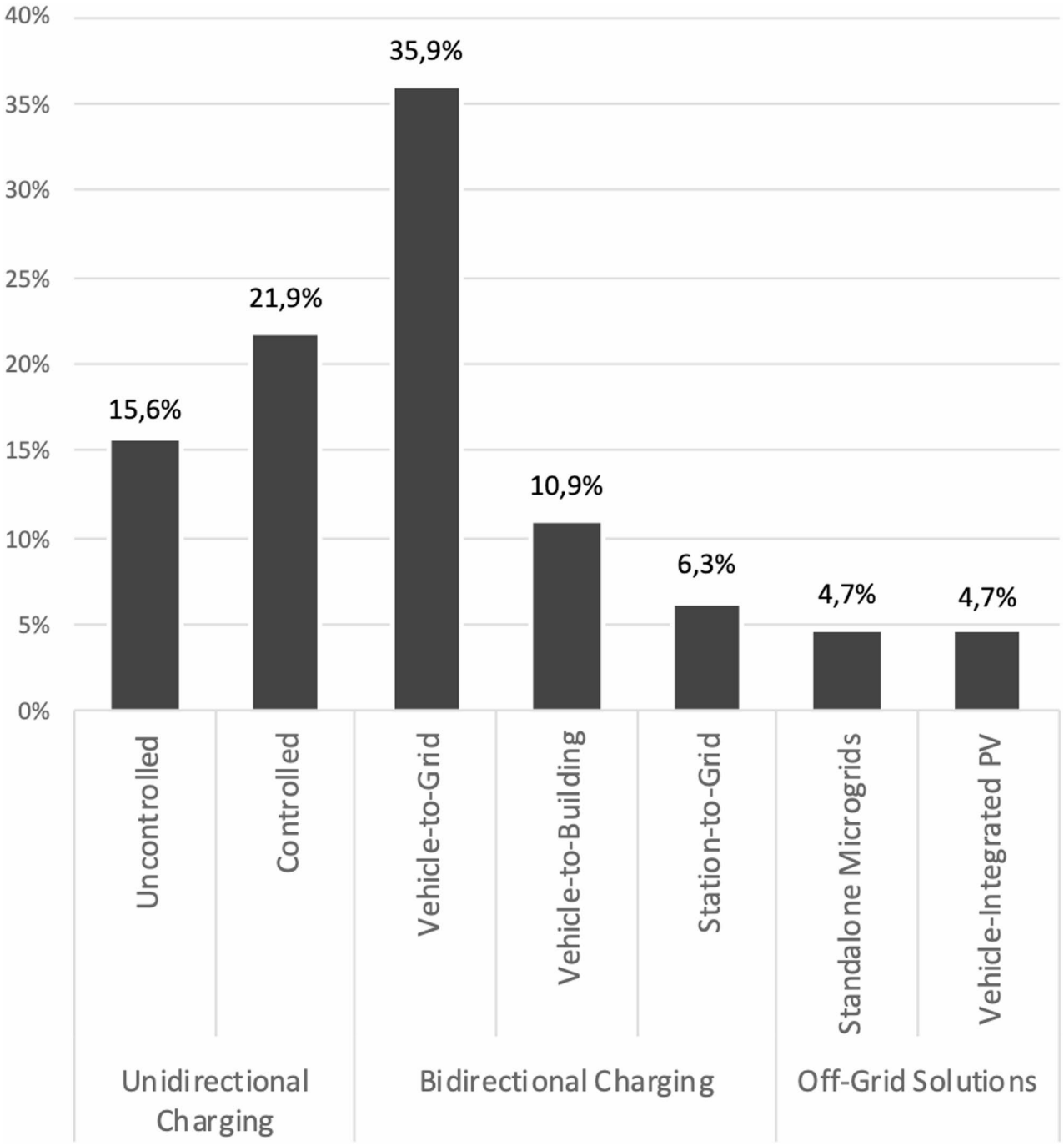

Fig. 2 Overview of use-case distribution

facilitates communication between EVs and charging devices through a network, enabling remote management, monitoring, and optimised energy distribution [33].

Compared to uncontrolled charging, controlled charging offers various advantages. Controlled charging can help to flatten demand peaks, reduce the cost of charging, increase safety, assess vehicle energy consumption, and ease charging location identification [33]. Controlled charging also allows a higher accommodation of intermittent renewable energy by providing flexible load [5, 9, 21, 62]. A study by Strobel et al. shows that controlled charging optimisation at a national level can potentially integrate a significant amount of renewables into the national grid [62]. Another study by Heinisch [21] shows that controlled charging can facilitate a significant share of solar PV in the charging electricity mix, compared to uncontrolled charging. Compared to V2G, other advantages

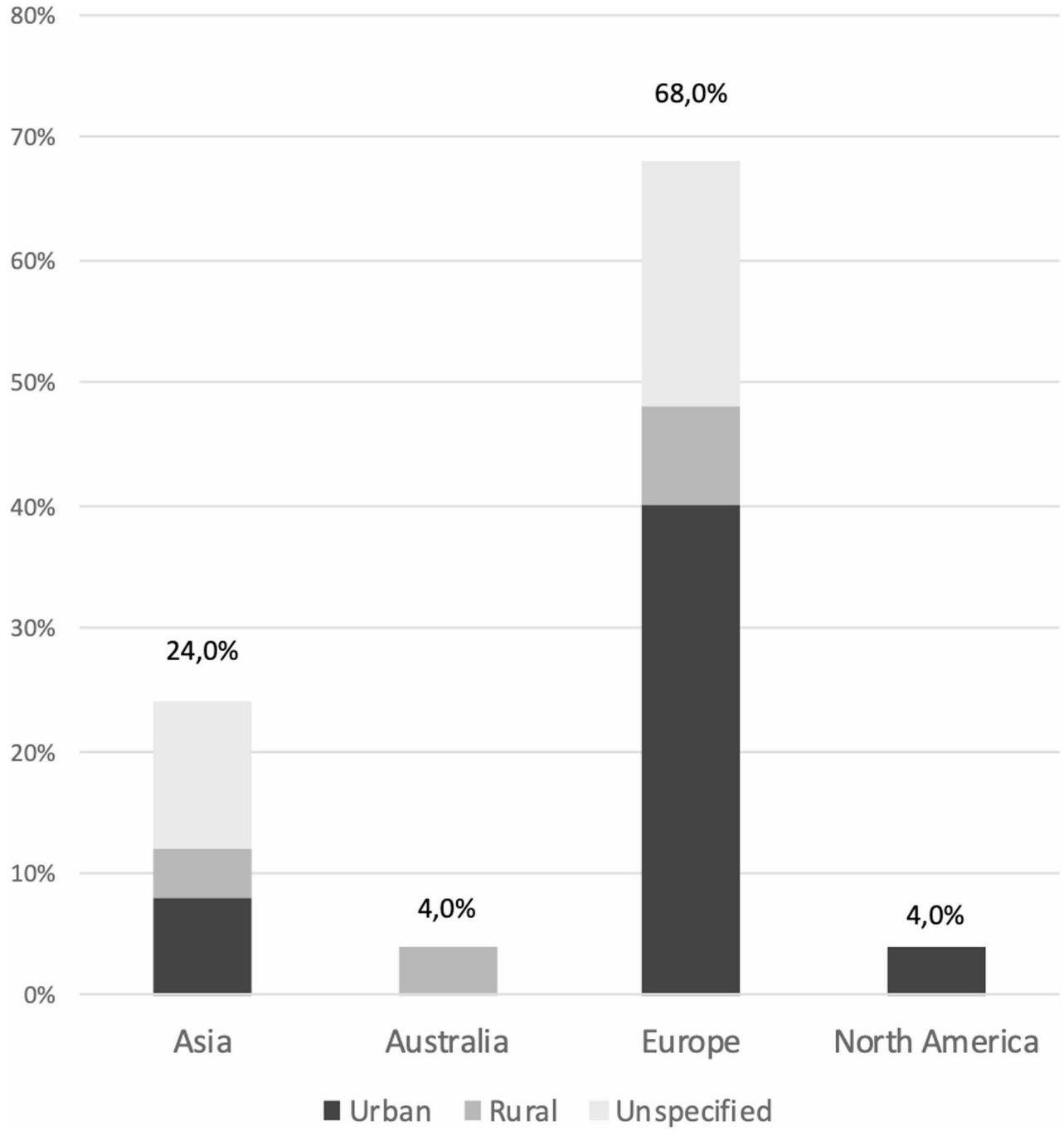

Fig. 3 Overview of geographic and location context

of controlled charging include lower costs and initial investment, and minimal social barriers [57]. Corsetti et al. also noted the opportunity for operational cost reduction through the implementation of controlled charging for commercial EVs in urban areas, and further cost reduction through the integration of solar PV in the system [35]. In addition, a study by Gschwendtner et al. [39] shows that controlled charging in urban areas with high EV and charging station diffusion show higher impact on flexibility (e.g., load shift, daily peak reduction).

Sevdari et al. [5] identify technical (e.g., grid observability, battery degradation), market (e.g., interoperability, privacy), and investment-cost barriers to controlled charging. Implementing it also requires the roll out of smart meters and the availability of flexible tariffs reflecting daily electricity price variations. Yet, Lerbringer et al. [48] and Corsetti et al. [48] note that cost savings remain

limited due to current tariff designs and the high capital cost of solar PV and batteries.

Bidirectional charging

Vehicle-to-grid (V2G)

Effective integration of renewable energy into the energy system necessitates storage capacity to buffer electricity during periods of excess production and low demand and to discharge it during periods of low production and/or peak demand. V2G technology enables EVs to not only draw power from the grid but also to contribute to it by discharging power back into the grid during periods of electricity supply deficits, reducing strain on the electricity grids [9, 13, 66].

V2G technology enhances the integration of renewable energy by leveraging existing EV batteries, reducing the need for costly dedicated storage infrastructure [9, 13, 24, 45]. Commercial urban EV fleets, operating on predictable schedules and centralized parking locations, are well-positioned as early adopters of V2G technology, as they can leverage shared infrastructure to reduce costs [24]. Studies have explored the potential of V2G in the context of shared EVs, particularly the potential for additional revenue and better renewable energy integration [10, 24, 63]. Furthermore, Straub et al. [20] highlighted the link between spatial distribution and V2G potential in European cities, noting that outer-city districts have greater capacity to meet RES demand through V2G because of their higher motorisation rates. In the rural context, Raveendran [56] pointed out the potential of V2G implementation in tourist islands, highlighting biodiversity protection and ecotourism potential.

Concerns about V2G-induced battery degradation is one of the main barriers that is discussed in the literature [5, 13, 24, 34, 53, 59, 65], however, the opinions are mixed. Gschwendtner et al. pointed out that this is more of a social rather than technical issue, emphasising on user's perception and worries that V2G can impact their battery health [6]. Other studies argue that optimised V2G strategies can even potentially increase the lifetime of EV batteries [9, 59, 61], particularly by regulating storage temperature and state of charging [47].

As most EV manufacturers do not enable V2G technology yet, modification and adaptation in charging infrastructure and EV design might be required [9]. V2G deployment is limited by legal and regulatory barriers, including unclear grid connection rules, particularly in electricity taxation [6], a lack of standard and enforcement [6, 33]. ownership and liability issues, privacy and cybersecurity concerns [57, 59], and insufficient remuneration structures for grid services [13]. Licensing, permitting, and the lack of harmonized technical standards further complicate adoption. Whilst certain countries, including the US, UK and Australia, have initiated measures to encourage the adoption of V2G, the absence of adequate incentives continues to represent a significant challenge in the majority of regions [6, 13].

Vehicle-to-building (V2B)

The integration of vehicle-to-building (V2B), in some cases, vehicle-to-home, facilitates the interconnection of the energy, transportation, and building sectors. Unlike V2G, which mainly distributes the surplus energy back to the grid, V2B allow EV owners to supply their home/building with energy stored in EV batteries and reduce their reliance on the electric grid [9, 53, 65].

One of the key advantages of V2B is the ability to increase the reliability of renewable energy sources by enabling the possibility to draw and transfer energy from/to buildings and homes [21, 34, 36]. A study by Jing and Zao [44] shows that integrating solar energy with V2B increases the system's efficiency and reduces daily electricity expenses. V2B also contribute to achieving net-zero energy buildings, not only by increasing renewable energy integration but also by managing the building's power consumption [34, 53, 65]. In addition, V2B can also be used locally, providing home energy storage and serving as emergency backup power [57].

The main challenges for V2B range from user behaviour, and technical challenges, to costs. EV charging schedules often mismatch the availability of on-site renewable generation, resulting in ineffective V2B interaction [65]. Users may also experience range anxiety when discharging EV batteries for building usage [65]. Moreover, the diverse range of available EV models complicates compatibility with building energy systems [1]. In addition, without any incentives and supportive policies, investors and users will likely be less motivated to install renewable energy and integrate V2B in their buildings [36, 65].

Station-to-grid (S2G)

Battery swapping allows EV users, notably for smaller vehicles, to remove the depleted batteries from their vehicles and swap them with recharged ones. Battery swapping stations allow decoupling of vehicle use and battery charging time, increasing further flexibility of small EVs [38, 42]. Battery swapping also significantly consumes less time and can potentially reduce the purchase cost of EVs, by enabling a battery rental system [58, 64].

Battery swapping stations and grid integration can significantly enhance renewable energy integration, stabilise load fluctuation, and further reduce carbon emissions [64]. This integration, called station-to-grid (S2G) or battery-to-grid, utilises the battery swapping stations' stored batteries for backup power during outages [58]. A study conducted by Zhang et al. [64] shows that integration between battery swapping stations and V2G for

different EV fleets (e.g., private cars, taxis, buses) in an urban context significantly increases renewable energy penetration, reduce load fluctuation, and further reducing annual CO2 emission.

The main challenges to battery swapping station and grid integration include high investment cost, lack of standard harmonisation and battery interoperability, regulation for battery swapping station planning and operation, as well as safety issues related to thermal, mechanical, and electrical abuse [58, 64].

Off-grid solutions

Standalone microgrids

A microgrid, or also called mini grids, is a small-scale, low-voltage electrical system consisting of distributed energy resources and interconnected loads that function as a coordinated and controllable unit within defined electrical boundaries and typically integrate renewable energy sources [41, 43]. Microgrids can be connected to the main distribution grid, as seen in [40, 52, 67], or disconnected from the main grid, also known as islanded or standalone microgrids [41, 43].

One of the key advantages of standalone microgrids is their capacity for self-sufficiency and reduced reliance on the main utility grid [41, 43, 52]. This renders them a reliable energy source for rural areas, particularly in areas with less dependable power systems [41, 52]. In countries with consistent rolling blackouts or areas not yet connected to the national electricity grid, microgrids help reduce reliance on the unreliable national grid and can accelerate efforts to increase energy access for communities [Int 1, Int 2]. Additionally, it allows to maximise of renewable energy integration, focusing on locally available renewable energy such as solar and wind [52]. Pilot activities in South Africa and Kenya tested out solar-powered microgrids, feeding RES to Light Electric Vehicles (LEVs) and battery-swapping systems and further decarbonising the energy and transportations sector [Int 1, Int 2]. While these solutions successfully increased clean energy access for the community, they also faced several challenges, such as interoperability of components, availability of land, lack of technical skills, as well as high equipment and R&D costs [Int 1, Int 2, Int 3].

Some microgrids can also be connected to the national grid, enhancing the grid reliability and flexibility [43, 52]. In Bangladesh, this solution is solidified by the net metering policy, which encourage users to integrate solar to the national grid by feeding the excess electricity to the grids, enabling users to get discount on electricity bills as the incentive [Int 3]. A V2G and microgrids pilot project in Bangladesh demonstrates the potential of feeding electricity from vehicles back to the national grid, with most vehicles returning to garages during the evening peak load, where an estimated over 30,000 charging garages across the country could collectively help shave peak demand [Int 3]. However, in countries without a clear mechanism supporting policies for feeding back electricity to the grid, such as South Africa, feeding excess energy from the microgrids to the grid is challenging [Int 1].

Vehicle-integrated photovoltaics

Vehicle-integrated PV (VIPV) presents a promising opportunity to enhance the share of off-grid renewable energy sources in EVs by mounting solar PV directly onto the vehicle [41, 55]. This approach enables onboard energy generation, reducing dependence on the main electricity grid and supporting a more sustainable and self-sufficient mobility system [52, 55].

PV integration extends vehicle's driving range by supplementing battery power with solar energy, reducing charging needs, costs, and emissions [55]. In addition, integrating VIPV with V2G can be an effective way of utilising excess energy [Int 4]. However, due to the limited energy generated by solar panels and the associated high costs, this approach may be insufficient and expensive [Int 5]. Another opportunity is to use this excess energy for smaller electricity generation, such as kiosk or coffee wagon, particularly in areas with limited electricity [Int 5]. Additionally, PV allows the vehicle to maintain its battery charge by providing supplementary energy when needed, thereby preserving battery health and ultimately extending battery lifespan [Int 4].

Despite its benefits, the implementation of vehicle-integrated PV also comes with challenges. While being especially beneficial in regions with consistent solar radiation, maximising energy yield and EV efficiency [55], users in regions with less solar intensity, such as Nordic countries, might find difficulties to solely rely on the sun [Int 5]. The advanced technology also leads to higher vehicle and development costs [55]. Reducing costs is a key factor in ensuring vehicle market acceptance; however, the panels and maintenance expenses of VIPV remain significant challenges [Int 4, Int 5]. Another challenge is regarding vehicle design and aesthetic concerns [55], particularly on the roof design due to the thin and fragile nature of the panels [Int 4]. Lastly, VIPV developers emphasise the challenges of obtaining permits, meeting standards, and complying with regulations for passenger VIPV [Int 4, Int 5].

Discussions

Key opportunities in urban contexts

Controlled charging and V2G implementation for commercial ev fleets

The implementation of controlled charging and V2G technology for commercial urban EV fleets can significantly support RES integration and to some extent,

enhance grid stability. As mentioned in the previous section, well-managed charging schemes for high-mileage fleets, supported by incentives, can potentially reduce operational costs while optimising renewable energy consumption. Fleets with manageable schedules and centralised parking, such as taxis, car-sharing services, and buses, can effectively connect to renewable sources during off-hours, facilitating energy exchange during surplus and deficit periods. The SOLUTIONSplus project, for example, has demonstrated that smart charging in electric bus depots in Madrid, Spain that has the potential to significantly cut demand peaks, reduce electricity costs, reduce the amount of required infrastructure, and accommodate more renewable energy consumption [68].

Battery-as-a-service businesses

The battery-as-a-service (BaaS) model for small EVs holds strong potential in urban areas, where EV adoption is highest due to greater population density. This growing market highlights opportunities at the intersection of mobility and energy, particularly through subscription-based battery-swapping services. BaaS has been implemented by major e-motorcycle taxi providers in major cities in East Africa, offering benefits such as quick battery swaps and improved reliability for drivers with lack of stable home electricity access [69]. For EV users, the key benefits of this service include the reduction of downtime and charging time for EVs, making it particularly convenient for urban fleets with intense use. Baas, when equipped with V2G technology and integrated with renewable energy, allows operators to centralise batteries and increase renewable energy reliability by enabling energy exchange between swapping stations and the grid.

Grid-integrated mobility hub

A Grid-Integrated Mobility Hub can combine RES, EVs and the core principles of transit-oriented development. It focuses on high-density, mixed-use urban areas that are built around public transport hubs. The hub operates as a central microgrid powered by solar energy and supports e-bus fleets, shared EV parking and advanced V2G integration. This model demonstrates sector coupling between energy, transport and land use, transforming transit infrastructure into a multifunctional system that optimises land efficiency, decarbonises mobility and strengthens energy resilience. This approach aligns with Net Zero Corridor concept, integrating distributed renewable energy, electrified transit, and corridor-based land use regeneration [70].

VIPV for last-mile passenger and freight

VIPV for last-mile passenger and freight transport offers a sustainable urban mobility solution by extending the mileage of LEVs through on-board solar power. VIPV-enabled vehicles can meet the last-mile transport needs of both passengers and goods, reducing the need for conventional delivery vans and private cars. Seamlessly connecting passengers to the public transit network while facilitating goods delivery at a neighbourhood scale, this approach supports compact, low-carbon urban design. GIANTS project, for example, is currently developing LEVs integrated with PV elements for passenger and cargo, improving affordability, efficiency, and technological maturity of the solution [71, 72].

Key opportunities in rural contexts

Microgrids in areas with limited electricity grids

In rural areas with limited access to centralised grids, standalone and hybrid microgrids provide clean energy from locally-available RES such as solar, wind, and micro-hydropower energy, to homes and businesses. Microgrids can provide self-sufficient and reliable power, especially in areas with unreliable or no access to the national grid. Microgrids are a key emerging business model because they can operate independently or with the grid, integrate with virtual power plants, reduce network costs, and enable flexible energy services and revenue streams [73]. In Nepal, for instance, hydropower microgrids are common in rural areas, supported by the net metering policy which allows them to sell the excess energy to household or energy authority [74]. In SESA projects, these solar-powered microgrids also powered EVs in rural areas, further reducing local emissions [75]. Additionally, swarm grids - a specific type of microgrid that enables electricity sharing between households solar home systems and is primarily implemented in the countries of the Global South countries, such as Bangladesh - can enable productive uses of electricity [76], such as LEVs [77]. Furthermore, integrating EVs into the microgrid via V2G technology can improve the reliability and resilience of these systems. In rural areas with unreliable main electricity grids, standalone microgrids can significantly increase access to energy, enabling the productive other uses of energy, such as water pumps and clean stoves.

V2B integration for houses

In areas with low population density and prevalent single-family housing, V2B integration can boost renewable energy flexibility and enable energy exchange between EVs and homes when vehicles are idle. This implementation can also be coupled with heating and cooling systems to enhance energy efficiency and improve energy management. This setup offers a reliable solution for optimising energy use, increasing energy security in less grid-reliable areas especially in regions with limited or decentralised energy infrastructure. Lastly, V2B facilitates decentralised renewable energy usage, supporting self-sufficient rural homes and buildings, energy

reliability, and actively supporting the achievement of net-zero energy buildings.

Key challenges in EV and Renewable energy sources integration

Technical challenges

Integrating EVs and renewable energy into the electricity mix presents major technical challenges, including uncontrolled charging that risks overloading the grid, reduces power quality, and limits renewable integration. Cybersecurity vulnerabilities in V2G systems, safety risks from battery handling, and compatibility issues between diverse EV models, batteries, and building systems complicate deployment, while a lack of standardisation and interoperability exacerbates these issues. While an ISO standard on V2G is emerging (EN ISO 15118), and the EU mandated that all new chargers must comply with the standard under the Alternative Fuels Infrastructure Regulation (AFIR), its broad uptake still requires adaptation of software and vehicles. Significant infrastructure upgrades, limited technical expertise, and land constraints for renewable installations further hinder progress, underscoring the need for coordinated solutions to enable a secure and efficient transition.

Regulatory challenges

Regulatory challenges stem from the weak enforcement of essential interoperability standards, coupled with insufficient incentives, such as subsidies and tax credits, to encourage the adoption of EVs and the integration of renewable energy. Social barriers, including transparency and privacy concerns, as well as insufficient regulation and planning for battery swapping stations, also hinder progress. The absence of policies that enable microgrid operators to feed excess electricity into national grids creates uncertainty, while supportive measures such as net metering, which has been shown to be effective in countries such as Bangladesh, remain underutilised.

Economic challenges

Economic challenges include high upfront investment costs for EVs, batteries, PV panels, and renewable energy installations, with additional expenses from integrating controlled charging, V2G, V2B systems and advanced technologies that increase maintenance needs. Existing tariff structures often fail to support these use cases, making operations less financially viable and discouraging adoption. High equipment and R&D costs limit scalability, while opportunity costs and limited revenue from V2G services further deter investment, leading to user reluctance without strong financial incentives.

Conclusions and policy recommendations

The strategic integration of EVs into energy infrastructure has a transformative capacity. It facilitates the accommodation of intermittent renewable energy sources within electrical grids, in parallel with mitigating transport-related emissions of GHG, air pollutants, and noise. The systematic literature review identifies different degrees of integration, from uncontrolled unidirectional charging up to smart bidirectional charging. It also revealed that off-grid solutions, particularly microgrids and VIPVs, are underexplored, indicating further research necessity. The vast majority of studies have been conducted in industrialised countries, resulting in a lack of case representation from emerging and developing countries. Exploring adequate and context-specific electrification pathways, however, is particularly needed in highly dynamic regions with strong population growth, continued urbanisation, and growing motorisation rates, which will contribute an ever-growing share of transport related emissions in the future.

Urban and rural contexts present distinct opportunities shaped by population density, spatial availability, and infrastructure readiness. Urban areas offer prospects in V2G and controlled charging for commercial fleets, battery-as-a-service business model, grid-integrated mobility hub, and utilisation of VIPV for last-mile passenger and freight services. Rural areas, meanwhile, hold the potential to integrate EVs with decentralised renewable systems through microgrids and V2B integration for housing. In addition, rural areas in countries that do not have universal energy access yet can also benefit from enhanced access to energy, minimising the dependency on, in some cases, unreliable main electricity grid.

Despite contextual differences, both face similar technical, regulatory, and economic challenges, requiring targeted policy recommendations for effective EV and renewable energy integration. In tackling this issue, this paper presents the following policy recommendations:

Research and implementation

Effective EV and renewable energy integration requires a strong focus on research and implementation. Pre-feasibility studies and pilot projects, such as the electrification of public bus depots and administrative fleets, can provide valuable insights into practical use cases and inform decisions on scale-up potential. Demonstration projects should actively involve fleet operators, including public transport providers, logistics companies and shared vehicle services, while drawing on academic expertise for rigorous evaluation. More broadly, national EV and grid integration roadmaps must be developed in line with renewable energy targets and coordinated across transport, energy and land use planning departments to prevent fragmented strategies. Equally important is building

human capital, with targeted vocational programmes helping to close the expertise gap in EV and renewable energy integration.

Standardisation

Effective standardisation is essential to unlocking the full potential of EV integration and sector coupling. Forming a multi-stakeholder group comprising grid operators, utilities, manufacturers, suppliers and developers can accelerate the adoption of industry standards, reduce reliance on proprietary solutions, support regional integration and create economies of scale that encourage wider deployment. Digital and cybersecurity standards for smart and bidirectional charging must be developed and enforced to protect data and ensure system resilience against cyberattacks. Once future-proof standards are established, building codes should be updated to require bidirectional charging and V2B readiness in new developments, thereby reinforcing infrastructure compatibility across sectors. Incentivising early adoption of standards can accelerate interoperability, enabling EVs to function as transport solutions and active components in a flexible, integrated energy system.

Infrastructure

The rollout of smart, bidirectional charging infrastructure, covering both company-owned and private installations, should be promoted through targeted financial incentives from national and local governments. Emerging standards such as ISO 15118–20 for V2G communication should be incorporated into product regulations, funding programmes and public tenders, ensuring seamless interaction between vehicles, chargers and the grid. Smart, two-way metering should be mandated for all new grid connections while conventional meters are gradually phased out to support more flexible energy flows. Investments in new infrastructure should prioritise renewable-powered charging systems to reduce dependence on fossil-intensive grids. Additionally, streamlining the permitting process for co-located renewable projects can optimise land use, mitigate availability constraints and enhance synergies between transport and energy systems, thereby realising the full benefits of sector coupling.

Economic

Smart, real-time electricity tariffs can create stronger incentives for bidirectional charging. Reducing legal and administrative barriers for end users feeding power back into the grid, through simplified processes or exemptions, encourages participation. Linking existing support programmes for charging infrastructure to V2G/V2B readiness ensures that economic support, such as subsidies, promotes technologies that strengthen grid flexibility. Integrating feed-in options with charging card payment functions and encouraging usage-based or state-of-health warranty schemes for vehicle batteries can address concerns about battery degradation and build consumer trust. In addition, expanding net metering schemes for small-scale PV and EV owners alongside tariff reforms that reward off-peak charging and V2G services makes active participation financially attractive. Finally, targeted incentives for R&D and local manufacturing, in the form of grants or tax credits, will support innovation and the development of the domestic industry.

Supplementary information

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Supplementary Material 1

Author contributions

The authors participated in the drafting, revision and approval of the manuscript.

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Data availability

All data generated or analysed during this study are included in this published article.

Declarations

Ethics approval and consent to participate

This research project did not require ethics approval and consent to participate as it did not involve human subjects or sensitive data.

Consent for publication

This research project did not contain any individual person's data in any form.

Competing interests

The authors declare no competing interests.

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