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Sustainable urban energy dynamics: Integrating renewable energy and electric vehicles in a European context

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ABSTRACT

The rapid adoption of electric vehicles (EVs) presents significant challenges to urban energy networks due to increased demand and potential overloading risks. Integrating renewable energy sources (RES) offers a sustainable solution, reducing carbon emissions while meeting future energy needs. Using Nottingham, UK, as a representative case within a broader European urban energy context, this study investigates the interactions between EVs, RES, and urban energy systems, focusing on supply–demand dynamics under constrained renewable output conditions. A stochastic modelling approach, guided by the Future Energy Scenarios (FES) developed by the National Energy System Operator (NESO), is employed to analyse EV-RES integration under four distinct scenarios — Consumer Transformation, System Transformation, Leading the Way, and Falling Short — projected for 2035 and 2050.

Key focus areas include balancing energy supply and demand, managing peak loads, and utilising Vehicle-to-Grid (V2G) technology to address grid stability issues. Results demonstrate the heightened challenges of integrating EVs on days with suboptimal renewable energy generation, where energy shortfalls exacerbate system strain. By 2050, low renewable energy generation days aggravate energy shortfalls, emphasising the importance of V2G. In the most constrained scenario, up to 97 % of EVs remain uncharged or partly charged, demonstrating the risk of severe energy deficits. Conversely, in an ambitious renewable energy scenario, significant renewable utilisation is achieved but is accompanied by challenges such as overgeneration and energy management complexities.

1. Introduction

The ongoing transition toward electrified transport and renewable energy generation is reshaping how cities consume, manage, and balance electricity. The rapid growth in global electricity demand, driven by population expansion and technological advancements, emphasises the need for sustainable energy solutions. The International Energy Agency (IEA) [1] reported a resilient global electricity demand, projected to grow by an average of 3.2 % during the years 2024–2025, equivalent to the combined annual consumption of the United Kingdom (UK) and Germany. However, the UK presents a contrasting scenario, with a decline of 3.8 % in 2022 due to high energy prices and record temperatures, despite a 5.3 % increase in electricity generation driven by European interconnectors [2]. These trends also illustrate the growing complexity of energy supply and demand dynamics, particularly in urban systems, which are key components of national and global energy transitions. As major centres of energy consumption and emerging hubs of localised generation, cities are uniquely positioned to address these challenges, balancing local demands with national and global objectives.

As electricity demand rises, integrating sustainable technologies becomes increasingly critical to ensure a reliable and environmentally friendly energy supply. The rapid adoption of EVs and the increasing penetration of renewable energy sources (RESs) are central to this transition. EVs, with their potential to act as mobile energy storage units, and RESs, which provide clean but intermittent energy, are pivotal

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for reducing carbon emissions and driving the evolution towards a sustainable energy future [3,4].

As urban centres adopt EVs and RESs, they face significant challenges in managing the strain on the existing electrical grids [5–7]. Recent UK data shows that the number of EVs reached approximately 1,565,000, including 975,000 battery electric vehicles (BEVs) and 590,000 plug-in hybrid electric vehicles (PHEVs) [8]. Such exponential growth aligns with the National Energy System Operator (NESO), formerly known as National Grid ESO, projection of up to 33 million BEV by 2050 [9], underscores the urgency of developing resilient infrastructure and adopting innovative energy management solutions. As focal points for EV adoption, urban areas can be particularly vulnerable to grid instability due to concentrated demand, which highlights the importance of proactive measures such as smart charging and advanced energy management strategies. These measurements are critical to addressing the challenges strongly highlighted in recent literature and official government reports, which emphasise the urgency of ensuring grid reliability and sustainability as the load continues to increase rapidly [5,6,10].

The transition to more sustainable energy sources in the UK is evident, as 2022 saw low carbon sources, including renewables, contributing a significant 56.2 % of the energy mix. This marked the second occasion where generation from renewable sources (41.5 %) surpassed that from fossil fuels (40.8 %) [2]. RESs, which are critical for decarbonising power grids, are gaining importance despite their integration challenges due to their intermittent nature [11]. These challenges can particularly affect urban energy systems, as overgeneration during periods of low demand can strain grid stability, highlighting the need for flexible solutions. In this context, the increasing adoption of EVs, coupled with their battery storage capabilities, offers a promising avenue to mitigate overgeneration by storing excess renewable energy and facilitating its effective integration into the grid, therefore enhancing the utilisation of renewable energy in the UK [12].

Despite these advancements, integrating RESs and managing the growing EV load pose significant challenges [13,14]. Recent studies have shown that the increase in EVs significantly impacts power grids. For instance, Williams et al. [15] utilised an agent-based model to simulate EV charging behaviour, highlighting the effects of different charging strategies on peak electricity demand. The study revealed that unmanaged charging during peak hours (‘selfish charging’) could increase transformer loading by over 250 %, leading to severe strain on distribution networks and costly infrastructure upgrades. In contrast, delayed charging (‘altruistic charging’) during off-peak hours reduces peak demand by up to 20 %, allowing residential networks to handle higher EV penetration without significant upgrades [15]. Similarly, Stanko et al. [16] demonstrated that low-voltage microgrids suffer from voltage drops, power losses, and excessive transformer loading in scenarios without a charging control mechanism. However, introducing charging control mechanisms, a photovoltaic (PV) power plant, and a battery energy storage system (BESS) mitigated these adverse impacts. Recent research by Apata et al. [17] further emphasise the need for advanced charging infrastructure and energy management systems to integrate EVs into smart cities, highlighting the potential of smart charging algorithms and Vehicle-to-Grid (V2G) capabilities to balance EV energy demand with supply while considering grid constraints and renewable energy integration.

Integrating RES with EVs has emerged as a crucial strategy for enhancing grid stability and reducing greenhouse gas emissions. Recent studies have provided substantial insights into this integration, highlighting challenges and innovative solutions. Ampah et al. [18] explored the role of EVs, power-to-hydrogen, and pumped-hydrogen storage technologies in maximising renewable energy integration. Their findings indicate that these technologies significantly increase renewable energy penetration, lower CO_2 emissions, and reduce total energy costs. Similarly, Dik et al. [19] examined the synergy between EVs, heat pumps (HPs), and RES integration in residential communities. Their research revealed that uncontrolled EV charging could exacerbate grid capacity issues, especially during high-demand periods in colder months. However, smart charging and V2G technologies can alleviate peak loads and improve community grid stability by aligning energy demand with renewable generation. The study also highlights the complementary roles of wind and solar power in enhancing grid reliability, despite the temporal misalignment between solar generation and community demand. Additionally, Liu et al. [20] developed a design and optimisation framework for integrating EVs, rooftop PV systems, and battery storage in net-zero energy buildings. Their findings highlight how vehicle-to-building (V2B) interactions and optimised energy configurations can enhance system flexibility and decarbonisation efforts. Complementing these findings, Jiménez et al. [21] applied a Smart Energy Systems approach, demonstrating that smart charging strategies can improve system flexibility, significantly reduce emissions, and optimise energy costs in high renewable penetration scenarios. Their research emphasises the need for integrated planning to ensure system stability under varying renewable and EV load conditions.

A recent review of research conducted by Barman et al. [6] highlights that relatively few studies have comprehensively explored integrating RES with smart EV charging strategies. They also added that to realise EVs’ full potential as a green transportation solution, integrating smart EV charging with RESs is inevitable. Researchers emphasised a need for cooperation across the generation, transmission, and distribution sectors to improve the potential of EV charging integration [6]. This need becomes even more critical in urban areas, where the complex energy dynamics of highly populated cities—characterised by concentrated energy demand from residential, commercial, and industrial sectors, diverse usage patterns, and higher penetration of EVs—intensify the challenges of integrating RES and smart EV charging. Addressing these challenges requires multi-scale analysis, extending from individual homes to broader city systems, and comprehensive strategies to manage energy transitions effectively. Additionally, another recent study by Turkoglu et al. [22] highlighted that economic and technical challenges still need to be overcome to benefit the potential of V2G technology entirely for grid stability. They also emphasised the necessity for continued research to create more advanced algorithms and protocols to manage V2G systems effectively. Furthermore, recent studies [23–25] emphasise the critical role of advanced EV charging management strategies and Vehicle-to-Everything (V2X) technologies in addressing the integration challenges of RES and improving power grid management. These studies provide a foundation for further research into scalable and effective solutions, particularly in urban energy systems, where these challenges are most pronounced.

2. Research novelty, aims and objectives

Integrating EVs with RESs in urban power grids is gaining momentum in research [19,26–28], but key challenges remain. Urban systems involve high demand density, diverse consumption patterns, and uneven EV uptake—factors often oversimplified in existing studies. Several existing works addresses individual elements (e.g. charging behaviour, grid stability, or renewable variability) in isolation. In addition, deterministic approaches frequently overlook the uncertainty and variability inherent in real-world energy systems.

This study addresses these gaps by employing a holistic stochastic modelling approach that incorporates uncertainty across energy supply and demand, renewable generation variability, and EV charging and discharging behaviours. Utilising UK National Grid ESO’s (now NESO), Future Energy Scenarios (FES), the research evaluates four distinct transition pathways— ‘Consumer Transformation’, ‘System Transformation’, ‘Leading the Way’, and ‘Falling Short’—for 2035 and 2050. These scenarios offer a structured basis for examining the implications of technological, policy, and behavioural shifts on urban energy systems.

The research focuses on a representative UK city to explore the synergistic potential of EVs and RESs integration. It captures realistic urban energy dynamics under low renewable generation conditions by incorporating diverse EV types, real-world charging behaviours, and multiple charger types. Additionally, the study assesses the impact of advanced charging strategies, including V2G technologies, on grid stability, congestion mitigation, and renewable energy utilisation. These findings are intended to inform future urban energy policy and planning by addressing key challenges such as supply–demand imbalances, overgeneration, and network congestion.

While this study focuses on private EVs, which have seen rapid growth and strong policy support in the study region, we acknowledge that a complete picture of sustainable transport must also consider other low-carbon mobility options, such as public electric buses, micro-mobility, and active travel. The chosen focus reflects the availability of detailed operational data for private EVs, as well as the stochastic nature of their energy use, which aligns with the simulation objectives. Nonetheless, the modelling framework is designed to be both modular and adaptable, and can be extended to incorporate additional transport modes in future research, provided that adequate behavioural and energy data are available.

3. Methodology

3.1. Study design and methodological framework

This study's methodology aims to analyse the integration of EVs into urban energy systems, focusing on enhancing renewable energy utilisation and grid stability. Addressing current challenges and exploring future scenarios, it evaluates how EV adoption and charging behaviours influence grid dynamics, renewable integration, and energy balancing under uncertainty.

A systemic approach encompasses energy supply (renewables and conventional), demand sectors (residential, commercial, transportation), the grid, and EV operations. A stochastic modelling framework accounts for uncertainties in renewable generation, energy demand, and EV behaviour, enabling realistic analyses. Including diverse EV and charger types ensures the findings are scalable and relevant to urban contexts.

The framework is grounded in the UK NESO, FES 2023 [9]: 'Consumer Transformation', 'System Transformation', 'Leading the Way', and 'Falling Short'. Simulations for 2035 and 2050 explore grid congestion, renewable overgeneration, and energy balancing challenges under varied energy transition pathways.

The systemic approach of the methodology is shown in Fig. 1, illustrating the interconnections among various energy sources, demand sectors, the electrical grid, and the integration of EVs. This approach combines stochastic modelling, scenario analysis, and real-world data to provide actionable insights into urban energy planning and policy development.

3.1.1. Urban Profile: Nottingham

Nottingham is a key urban centre located in the East Midlands region of England, serving as the principal city within a broader conurbation of approximately 716,800 residents. The city itself had a population of 328,500 as of the 2022 mid-year estimate, with around 70 % of residents of working age [29].

Historically rooted in coal mining and textile production, the Nottinghamshire region has undergone a significant economic transformation. Today, the region's economy is predominantly service based, supported by sectors such as education, health, creative industries, and professional services [30]. Two major universities contribute over 65,000 students to Nottingham's population, fostering an innovation-driven environment. The city's economy generated approximately £11.5 billion in gross value added (GVA) in 2022, representing nearly 15 % of the East Midlands regional output and over 34 % of the GVA within the newly established East Midlands Combined County Authority. This emphasises Nottingham's critical role in shaping regional economic activity and urban sustainability transitions [29].

Nottingham's energy profile reflects its urban character. In 2022, electricity consumption was reported at 1,128.1 GWh [31]. Sector-specific carbon emissions data by Department for Energy Security and Net Zero (DESNZ) and Department for Business Energy & Industrial Strategy (BEIS) [32] highlights transport (422.2 ktCO_2e) and the domestic sector (323.8 ktCO_2e) as the two largest contributors to the city's total emissions of 1,121.9 ktCO_2e. Per capita emissions have decreased significantly—from 7.4 tCO_2e in 2005 to 3.4 tCO_2e in 2022—demonstrating the effectiveness of local decarbonisation efforts. Nevertheless, the city still exhibits relatively high emissions intensity, with 15 ktCO_2e emitted per km^2, underscoring the importance of targeted urban mitigation strategies [32].

Nottingham City Council [33] has committed to becoming the UK's first carbon–neutral city by 2028. This ambitious target is underpinned by extensive sustainability measures, including the deployment of one of the largest electric bus fleets in the UK, a 20-mile electric tram network,

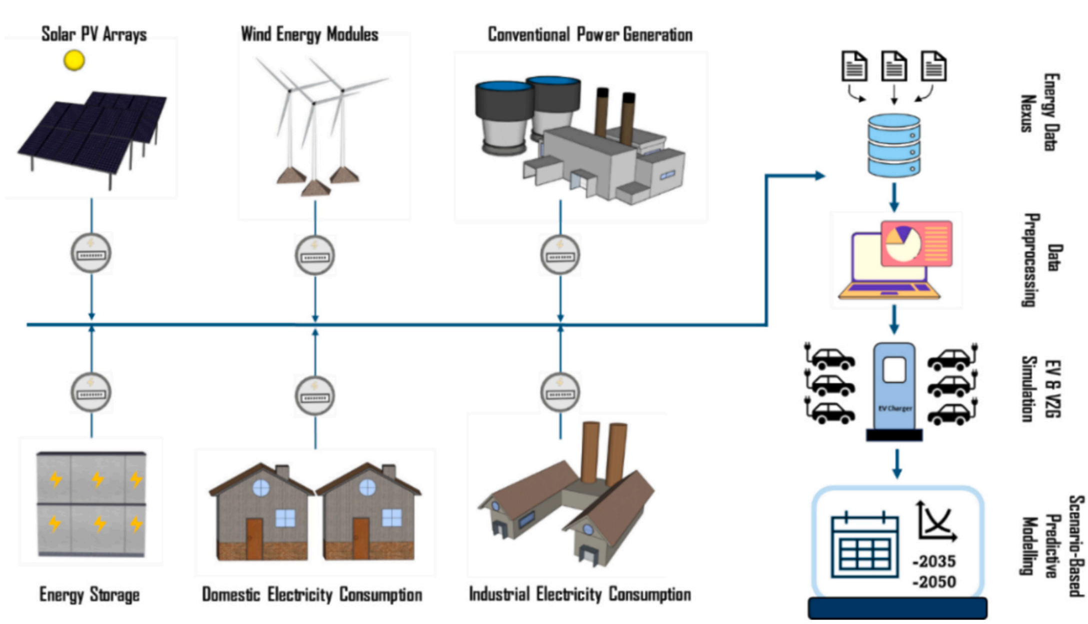

Fig. 1. A systematic overview of the methodological framework with RESs, EVs and grid dynamics.

a workplace parking levy to discourage car use, and a city-wide district heating system supplying over 5,000 homes and businesses [33]. Nottingham City Council [34] also announced that at the end of 2023, over 8,000 homes in Nottingham were equipped with solar PV systems, and more than 400 households had adopted heat pumps. Nearly 48 % of homes now meet an Energy Performance Certificate (EPC) rating of A–C, reflecting improvements in energy efficiency [34].

In the context of this study, Nottingham represents a forward-looking urban environment actively engaged in the transition to low-carbon energy and mobility systems. Its mid-size scale, diverse energy demands, active policy interventions, and growing EV infrastructure make it a strong representative case for examining the challenges and opportunities associated with integrating renewable energy, EVs, and smart grid technologies in European urban settings.

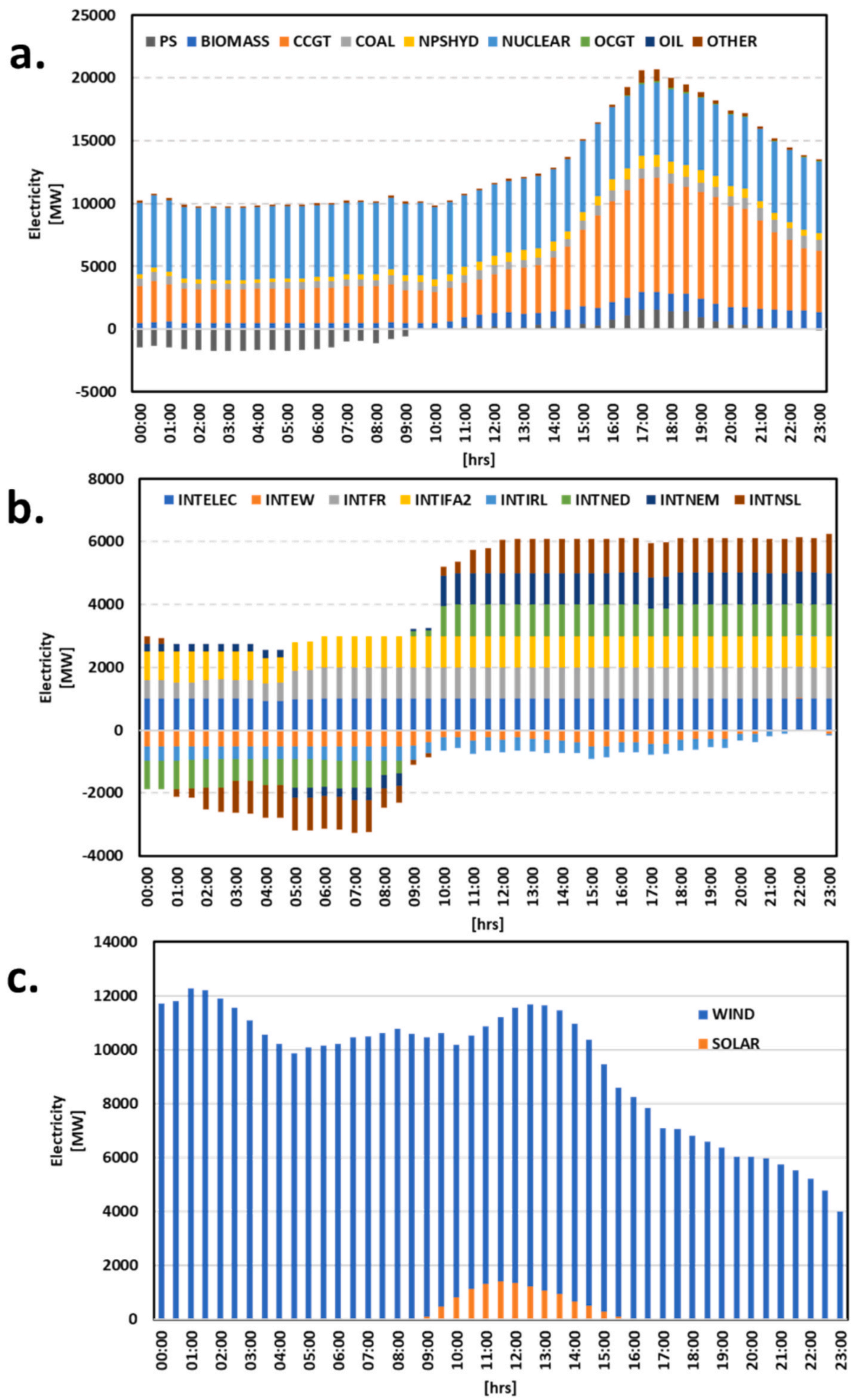

Fig. 2. Hourly electricity profile in GB on January 1st, 2023, a) conventional sources, based on data from Elexon [35], b) interconnections, derived from Elexon [35], c) wind energy from Elexon [35] and solar energy generation from the PV Live service by Sheffield Solar [36].

3.2. Data collection and analytical framework

This study employs a structured and systematic approach to analyse the integration of EVs into urban energy systems, beginning with a detailed assessment of Great Britain's (GB) electricity landscape in 2023. The analysis focuses on the complex interplay of conventional electricity generation, renewable energy integration, and consumption dynamics.

Primary data sources include the Balancing Mechanism Reporting Service (BMRS) managed by Elexon [35], which provides high-resolution, real-time data on generation by fuel type through metering from Balancing Mechanism Units (BMU) connected to the GB transmission network. This dataset offers detailed insights into generation profiles, segmented by energy source, represented as average megawatt (MW) values, forming the foundation for the study's analysis.

A comprehensive data processing pipeline was implemented to ensure the integrity and usability of the dataset. This process involved data cleaning, including the identification and correction of missing, incorrect, or duplicate values, as well as the exclusion of extraneous entries. Normalisation techniques were applied to harmonise data formats, followed by aggregation and transformation to align the dataset with the study's research objectives. These steps enabled the derivation of a robust national energy profile, encompassing generation, consumption, and interconnection flows.

Solar energy data, which is absent from Elexon's real-time monitoring due to its integration into distribution networks, was supplemented using the PV Live service by Sheffield University [36]. This service provides real-time and historical solar generation estimates, updated every 30 min in collaboration with the National Grid. This work uses data licensed under the Creative Commons Attribution 4.0 International License by Sheffield Solar. Wind energy data, however, was directly available from Elexon's dataset [35]. The solar energy estimates were integrated into the Transmission System Demand (TSD) calculation, which traditionally aggregates total generation outputs and imports from interconnection networks to create a comprehensive picture of GB's energy landscape. Adjustments were made to ensure that negative values in the raw dataset—representing electricity exported to pumped storage or other external systems—were set to zero, accurately reflecting the net demand for grid consumption.

Fig. 2 exemplifies the data collected from Elexon [35] and the PV Live service by Sheffield Solar [36], representing an overview of GB's energy flows on January 1, 2023. Fig. 2a shows electricity generation by fuel type, including pumped storage hydropower (PS), biomass, Combined Cycle Gas Turbine (CCGT), Open Cycle Gas Turbine (OCGT), coal, non-pumped hydropower (NPSHYD), nuclear, oil, and other sources, offering a detailed representation of GB's energy mix. Fig. 2b illustrates interconnector electricity flows between GB and neighbouring countries. Fig. 3 complements this by listing the interconnection networks based on the information derived from the DESNZ and BEIS [37]. Meanwhile, Fig. 2c presents hourly wind energy generation from [35] and solar energy production estimates from [36] on the chosen sample day, offering insight into the variability of renewable energy contributions within the national grid.

After establishing a national energy baseline, as outlined in Fig. 4, the study transitions to a localised urban focus by examining Nottingham, UK, as a representative urban energy system. Nottingham is actively shaping the future of sustainable urban development with its bold plan to achieve carbon neutrality by 2028. Its advanced implementations of sustainable technologies and expanding EV infrastructure make it an ideal setting for investigating the integration of EVs and renewable energy [38]. The city's diverse energy consumption profile, encompassing residential, industrial, commercial, and transportation sectors, allows for studying varied consumer interactions within urban energy systems. While Nottingham's energy trends can provide insights into broader national patterns, the analysis acknowledges the unique local characteristics that may influence these findings.

Despite efforts to obtain detailed, hourly energy consumption data specific to Nottingham, such data remained unavailable. As a result, the study adopted a simplified energy profile by proportionally scaling national energy consumption data to the urban level. Using data from the UK's DESNZ [31], Nottingham's annual electricity consumption in 2022 was reported at 1,128.1 GWh, compared to 250,020.7 GWh for GB. From this, a conversion ratio of 0.00451 was derived, enabling the proportional downscaling of national hourly energy patterns to approximate Nottingham's energy use. This approach assumes consistent proportionality across hourly and daily intervals, recognising that actual energy consumption may vary significantly due to seasonal factors, local events, and the specific energy profiles of different sectors.

A similar proportional approach was applied to estimate Nottingham's EV population in 2035 and 2050. National projections for EV uptake under all four FES 2023 scenarios were scaled to the city level

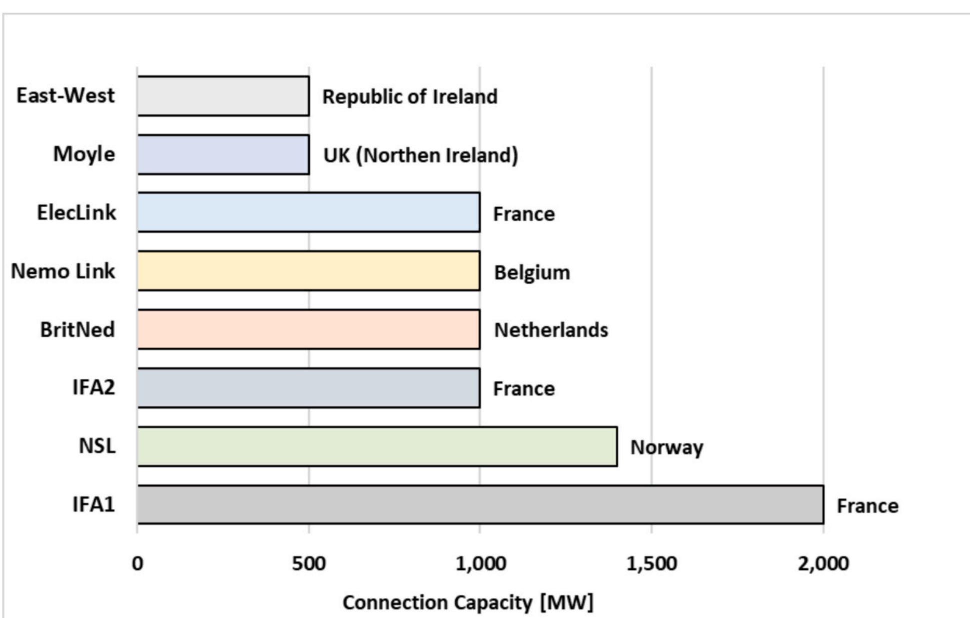

Fig. 3. Interconnection networks and their connection capacities for GB (based on data from DESNZ and BEIS [37]).

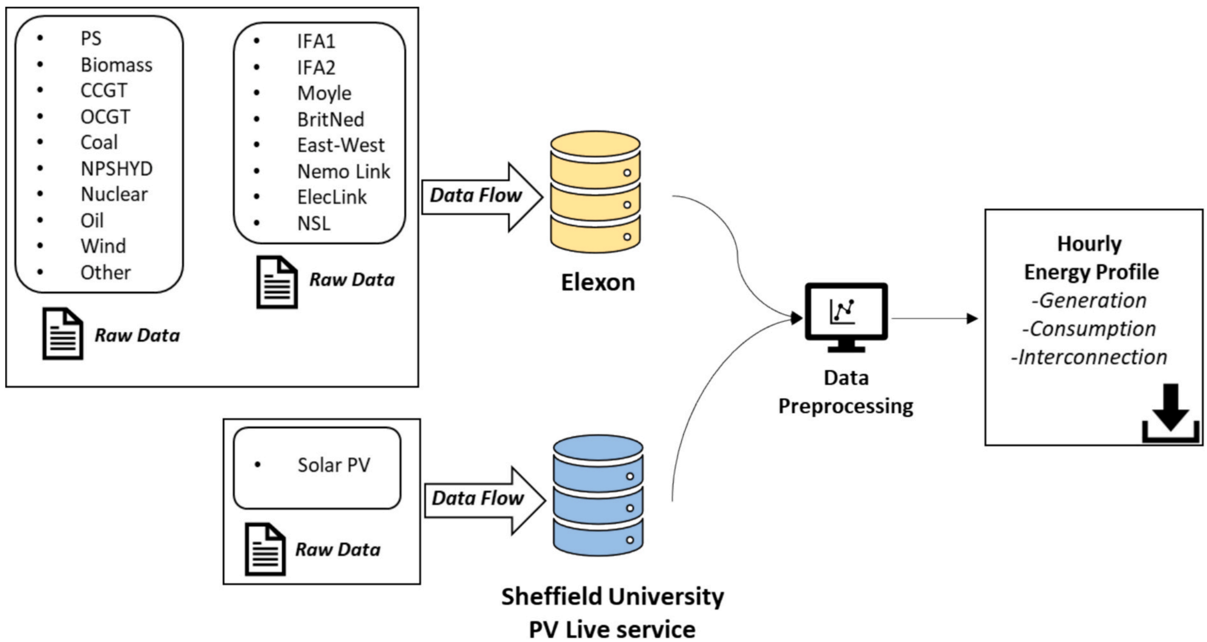

Fig. 4. Data integration flow for hourly energy profile analysis.

using a conversion factor derived from EV registration data published by the Department for Transport (DfT), and the Driver and Vehicle Licencing Agency (DVLA) [39]. As of Q3 2023, Nottingham had 2,183 registered EVs, compared to 1,347,534 across GB, resulting in a scaling factor of approximately 0.00162. These figures were obtained by filtering the DfT and DVLA's vehicle licensing statistics [39] for "Cars" (body type), "Total" fuel type (all electric fuels), and "Total" keepership for both Nottingham and GB in Q3 2023. This ratio was uniformly applied across all scenarios and years to generate consistent, locally adjusted EV projections. While this method assumes a constant share of national EV adoption for Nottingham over time, it maintains methodological consistency with the energy profile conversion and supports coherent scenario comparisons across domains.

It is also important to note that population growth is explicitly embedded in the FES modelling framework. A national population trajectory—sourced from Oxford Economics—is applied uniformly across all scenarios in FES [40,41]. This ensures a consistent demographic baseline for long-term demand modelling. Although population change was not separately modelled for Nottingham in this study, the national-level assumptions incorporated within the FES projections provide a robust and harmonised foundation for proportional urban scaling.

While these scaling methods offer a pragmatic solution in the absence of detailed city-level data, they carry inherent limitations. They do not fully capture the complexity of Nottingham's energy and mobility dynamics, including potential shifts in population share, infrastructure, or behavioural trends over time. As such, the findings presented here should be interpreted as indicative estimates, intended to support comparative scenario analysis rather than precise forecasting of local conditions.

3.3. Scenario analysis and evaluation

The transformation of energy systems towards sustainability is critical for mitigating climate change. This study focuses on the future growth and integration of EVs and RESs, specifically solar PVs and wind energy, due to their pivotal roles in grid dynamics and the UK's sustainable energy targets. While solar and wind energy represent the most widely adopted renewable sources, their inherent variability and intermittency pose significant challenges to grid stability, necessitating advanced energy management strategies to mitigate risks such as overgeneration [5]. Their prominence also aligns with national policies aimed at expanding renewable energy technologies, reflecting their substantial potential for large-scale, sustainable energy production.

This study utilises data from the FES 2023 report [9], developed by the National Grid ESO (now NESO), to analyse projected development in EV adoption, electricity demand, and RES development across GB's evolving energy landscape. The FES [9] employs a scenario-based approach informed by extensive stakeholder engagement and robust data inputs, including technological innovations, policy trajectories, economic factors and consumer behaviours. This ensures the scenarios reflect a broad range of plausible pathways for achieving the UK's net-zero ambitions.

To explore these pathways, the study examines four distinct scenarios presented in the FES [9]: Consumer Transformation, System Transformation, Leading the Way, and Falling Short. Each scenario represents a unique trajectory for adopting EVs, solar PV and wind energy, offering insights into the energy system's performance under varying policy, technological, and behavioural conditions.

The four FES 2023 scenarios used in this study are briefly outlined below:

Consumer Transformation. This scenario proposed meeting the 2050 net zero targets largely through increased consumer and household contributions and impacts. The widespread adoption of EVs by households is anticipated following the 2030 ban on petrol and diesel vehicles and the 2035 ban on PHEVs. Renewable energy, led by offshore wind and solar, will grow substantially, reaching 69 TWh (solar) and 486 TWh (offshore wind) by 2050. Wind, solar, nuclear, and bioenergy with carbon capture and storage (BECCS) collectively deliver 93 % of electricity generation in 2050. Offshore wind capacity is projected to reach 50 GW by 2031, expanding to 116 GW by 2050. [9].

System Transformation. In this scenario, achieving the net zero target by 2050 involves less direct change for consumers, with significant shifts occurring in the power infrastructure. By 2050, in response to bans on petrol and diesel cars in 2032 and PHEVs in 2035, households will transition to EVs. While renewable energy expands in the 2020s, growth in decentralised technologies like solar PV and onshore wind is slower. The offshore wind will reach 50 GW by 2032, supporting rising electrification needs. By 2032, wind, solar, nuclear, and BECCS contribute 92 % of generation output, achieving net-zero emissions for the power sector. [9].

Leading the Way. This scenario reflects the most ambitious pathway, achieving net zero by 2046 through rapid technological advancements and active consumer engagement. The ban on petrol/diesel vehicles will occur in 2030, followed by a PHEV phase-out in 2032. EV adoption is widespread, supported by advanced smart charging infrastructure. The offshore wind will reach the 50 GW target by 2030, with aggressive growth continuing. Solar PV and onshore wind also experience substantial expansion, enabling wind, solar, nuclear, and BECCS to deliver 95 % of electricity generation by 2050. [9].

Falling Short. In this scenario, the net-zero target is missed due to slower decarbonisation progress. The petrol/diesel ban is delayed to 2035, with PHEVs phased out by 2040. While EV adoption increases, public transport and low-carbon alternatives remain underdeveloped. The offshore wind will reach only 31 GW by 2030, with limited growth in solar and onshore wind. By 2050, wind, solar, nuclear, and BECCS contribute 87 % of generation output, but fossil fuels still play a significant role. [9].

To quantify the impacts, the projected outputs of solar and wind energy (offshore and onshore) and the adoption rates of EVs are extracted for two key years: 2035 and 2050. These projections are summarised in Table 1, providing a comparative overview across the four scenarios. This analysis forms the foundation for evaluating the challenges and opportunities of integrating EVs and RESs within urban energy systems under varying transition pathways.

The Consumer Transformation scenario demonstrates an ambitious commitment to renewable energy expansion and EV adoption. By 2050, solar and wind energy outputs are projected to reach 69 TWh and 626 TWh, respectively, while EV adoption grows to 28.2 million.

In comparison, the System Transformation and Leading the Way scenarios exhibit varying strategies and growth trajectories. The System Transformation scenario projects a steady increase in renewable energy, reaching 54 TWh for solar and 564 TWh for wind by 2050, alongside a robust EV penetration of 29.4 million. Meanwhile, the Leading the Way scenario prioritises aggressive renewable growth, particularly in wind energy, targeting 565 TWh by 2050 and achieving an EV count of 27.4 million.

In contrast, the Falling Short scenario highlights the risk of limited policy action and consumer engagement, with the slowest progress among the pathways. Renewable energy output under this scenario remains subdued, reaching 37 TWh for solar and 413 TWh for wind by 2050, while EV adoption climbs more gradually to 33 million, signalling a shortfall in achieving sustainability goals.

The projected growth in electricity demand across appliances, industrial processes, commercial activities, and residential heating is critical for understanding future energy requirements and their potential impacts on GB's electricity grid. To assess this, the FES report [9] was utilised to estimate electricity demand for the target years 2035 and 2050. Fig. 5 illustrates the estimated sectoral electricity demand for these years.

By 2035, demand forecasts show considerable variation across scenarios. The Customer Transformation scenario exhibits the most substantial growth, increasing from approximately 253 TWh in 2022 to around 320 TWh, driven by accelerated electrification and consumer adoption trends. In contrast, the System Transformation scenario shows the most modest increase. By 2050, these trends will be amplified, with the Customer Transformation scenario climbing further to 415 TWh, maintaining its position as the scenario with the highest demand growth, while System Transformation continues to reflect slower progress.

Additionally, while this study evaluates the projected increases in solar PV, wind energy, and electricity demands from appliances, industrial, commercial, and residential heating for the years 2035 and 2050, it assumes that the electricity contribution from other sources and interconnections will remain constant.

The increasing penetration of RESs, which are critical for supporting the growing fleet of EVs, presents both significant opportunities and challenges. As highlighted in the FES report [9], future supply security will be influenced by the variability of renewable sources, particularly solar PV and wind energy, in combination with fluctuating demand patterns. Periods of high renewable supply with low demand, or low renewable supply with high demand underscore the importance of flexibility and advanced grid management strategies to maintain grid stability.

These challenges could be addressed through emerging technologies such as V2G, which utilise the bidirectional charging capabilities of EVs to balance supply and demand [9]. However, this necessitates a detailed analysis to evaluate whether the projected renewable energy generation can adequately meet EV charging demands. Moreover, the role of EVs equipped with V2G capabilities in enhancing grid stability under variable renewable generation conditions must be thoroughly assessed to unlock their full potential.

These scenario narratives provide the foundation for the simulation framework developed in this study. Each scenario's projections—such as EV adoption, RES generation, and electricity demand—are used as key inputs into the stochastic modelling approach. The next section outlines this approach, which quantifies EV-grid interactions and energy system behaviours under each pathway, incorporating both technical and behavioural uncertainties.

Table 1
Projected numbers for EV adoption and solar & wind energy output based on FES 2023 (Derived from the analysis of data provided in NESO, FES 2023 report [9].).

	EV [million]		Solar [TWh]		Wind [TWh]	
	2035	2050	2035	2050	2035	2050
Customer Transformation	26 M	28.2 M	38	69	412 *(315 + 97)*	626 *(486 + 140)*
System Transformation	18 M	29.4 M	34	54	356 *(275 + 81)*	564 *(457 + 107)*
Leading the Way	20.5 M	27.4 M	51	84	465 *(359 + 106)*	565 *(427 + 138)*
Falling Short	11.8 M	33 M	27	37	262 *(180 + 82)*	413 *(323 + 90)*

*In the wind column, the data presented in the format (a + b) represents 'a' as the output of offshore wind and 'b' as the output of onshore wind.

3.4. Scenario-based stochastic modelling of EV-grid interactions

This study develops an advanced stochastic simulation framework to accurately represent energy consumption and production at an urban scale and explore the potential role of EVs in energy balancing through charging and discharging operations. The methodology builds upon the preparatory steps outlined in Section 3.2, including data collection, data analysis and national-to-local energy profile conversation. These steps form the foundation for a probabilistic EV charging and discharging simulation designed to capture realistic usage patterns under projected scenarios for 2035 and 2050. The detailed methodological flow is depicted in Fig. 6, which outlines the probabilistic EV dataset creation, energy profile preparation and modelling process.

To reflect real-world EV usage trends, the simulation focuses exclusively on BEVs for the target years 2035 and 2050. The decision aligns with the FES projections [9], which anticipate a decline in PHEVs due to the phase-out of petrol and diesel vehicles. Consequently, detailed future projections are primarily available for BEVs. Focusing on BEVs ensures the model reflects the anticipated dominance of fully EVs in the UK market.

The simulation incorporates the top 20 BEVs currently prevalent in the UK (Q3 2023), as reported by DfT [42]. For clarity, the top 10 models are listed in Table 2, which is adapted from the DfT [42] and EV-

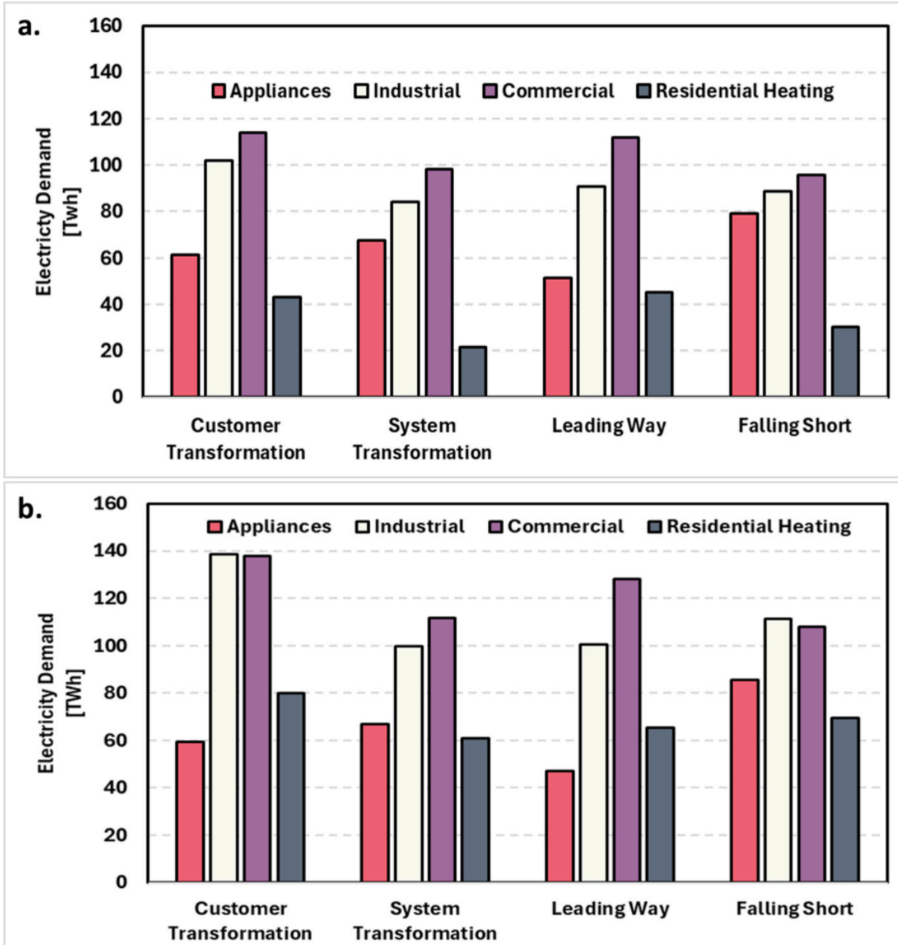

Fig. 5. Projected electricity demand in GB for target years, a. in 2035 and b. in 2050 (Derived from the analysis of data provided in NESO, FES 2023 report [9].).

Database [43]. The analysis progresses by importing EV models, capacities, and usage rates from literature to create a probability distribution for EV selection based on these usage rates, ensuring the model reflects current market trends accurately.

The simulation assigns EV models based on a probability distribution and sets charging locations (Home/Public) based on predefined probabilities to determine the EVs' charging and discharging behaviour at home and public locations. This selection process utilises a probabilistic, randomised approach reflecting the real-world distribution of different EV models based on usage rates. Consequently, each EV is assigned a primary charging location—home or public charging stations—mirroring typical user behaviour with 87 % for home and 13 % for public charging, which includes 'work', 'destination', 'en route' and 'charging station' facilities, as established in [44].

Following the assignment of charging locations, the model categorises charging frequency and patterns for both scenarios, converting these into daily average charging and discharging percentages. This process aids in determining the charging or discharging state of each EV at any given time based on a probability influenced by typical daily usage patterns. Here, the vehicle charging/discharging frequency selection is another randomised process within the model, informed by the DfT survey [45], which explores UK electric vehicle drivers' attitudes, behaviours, and experiences regarding charging habits. A representation of the findings, derived from responses to Question 15 of the DfT survey regarding charging frequency, is illustrated in Fig. 7, which is adapted from the DfT survey [45].

The DfT survey [45] included UK adults from households with continuous access to EVs, totalling 848 respondents. Notably, the distribution within this survey was an overrepresentation of BEV drivers. The predominant car models among respondents were the Nissan Leaf (12 %), Kia Niro (8 %), BMW i3 (8 %), and Tesla Model 3 (8 %), corresponding with the top BEV models in the UK, as outlined in Table 2.

The state of charge (SOC) for each EV is influenced by its charging location and current state (charging or discharging), and in this research, SOC determinations are also performed by utilising findings from the DfT survey [45]. Specifically, Question 18 of the survey inquiries about participants' preferred SOC levels before and after charging operations. This has been instrumental in defining the SOC parameters for the EV dataset developed in this study.

Accordingly, the current research model randomly assigns a SOC of between 20 % and 50 % for EVs set to charge and a SOC of between 60 % and 80 % for those set to discharge. These ranges are based on typical home charging behaviour as identified in the DfT survey [45], where 89 % of respondents usually begin charging when their battery level falls below 50 %, and 84 % charge their vehicles to at least 60 %. The study applies similar logic to public charging operations due to similar data patterns observed for public charging behaviours. Additionally, this study adopts the assumption that vehicles are not charged beyond 80 % and not discharged below 20 % to model a usage trajectory that maximises EV benefits, as detailed in [19].

However, the simulation faces limitations in accounting for EV arrival and departure times, especially within the urban context of this research, which complicates accurate assessments of parking durations at each charging point in the city. Instead, the model focuses on vehicles' potential energy needs based on their full charging and potential supply

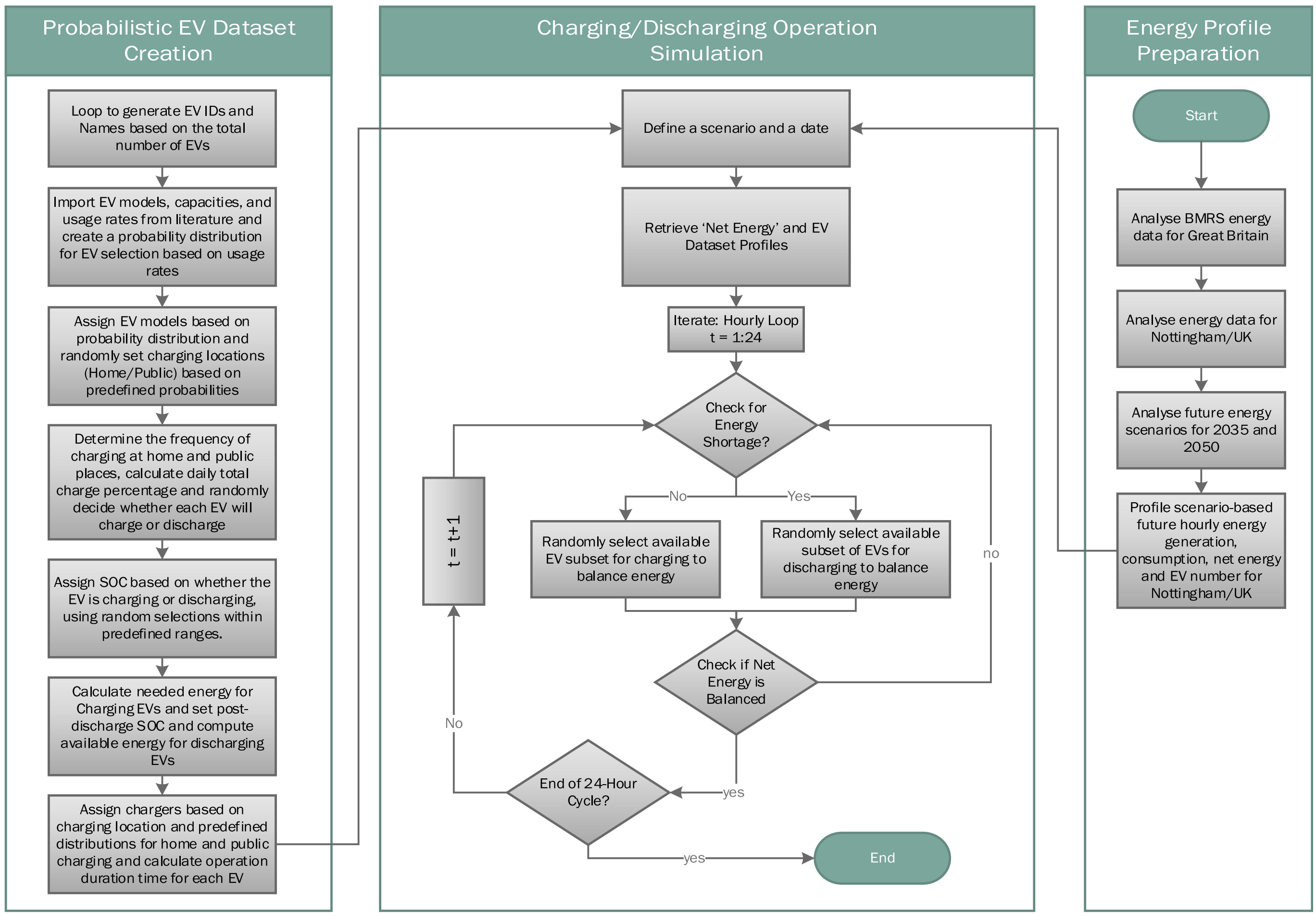

Fig. 6. Flowchart of the model algorithm.

Table 2
Sample of most popular 10 BEVs in the UK.

Popularity Rank	Vehicles	Capacity [kWh]
1	TESLA MODEL 3	60
2	TESLA MODEL Y	60
3	NISSAN LEAF	40
4	KIA NIRO	68
5	VOLKSWAGEN ID3	62
6	RENAULT ZOE	54.7
7	JAGUAR I-PACE	90
8	HYUNDAI KONA	67.5
9	AUDI E-TRON	85
10	MG ZS	51.1

*The order of EV models is based on data from the DfT [42], and battery capacities (kWh) were obtained from the EV-Database [43].

contribution via V2G based on EV owners' targeted post-discharge SOC. The aim is to explore EVs' potential effect on the grid's supporting energy balance. While the EV availability data limitation affects the ability to manage SOC dynamically and instantaneously following the charging and discharging phases, the adopted approach prioritises capturing the most critical aspects of EV-grid interactions.

Consequently, while the simulation assigns a post-discharge SOC within a specified range of 30 % to 60 % to represent the expected SOC after an EV has been utilised for grid services via V2G, it does not incorporate dynamic SOC management for subsequent recharging cycles. Instead, the model adopts a pragmatic approach specifically designed for the available data, focusing on capturing the broader trends and key interactions within urban energy systems. This deliberate simplification enables the analysis to address critical research objectives while remaining aligned with current technological and infrastructural realities.

Further, this study progresses to model the specifications and rates of chargers used in the UK. As of the end of 2023, the number of chargers installed in homes and businesses is estimated to be around 680,000, according to Zap-Map [46], although the precise figure remains unknown. The DfT [47] indicates that these home chargers predominantly feature 3 kW and 7 kW power outputs. Thus, the model assumes home chargers rated at 3 kW and 7 kW, randomly assigning one of these charger types to each EV for charging and discharging sessions based on a 50 % usage rate. Moreover, Zap-Map [46] offers detailed information on the status of public chargers in the UK. Table 3 was specifically developed for the simulation in this paper, informed by Zap-Map statistics [46] for specific data points, with further analysis and assumptions applied to create a comprehensive representation of charger rates and infrastructure share. The column labelled "Infrastructure Share" reflects the percentage of installed public charge points falling into each charger category (e.g., slow, fast, rapid).

The presented values in Table 3 reflect the availability of each charger type—slow, fast, rapid, and ultra-rapid—as a percentage of the total installed chargers. In the simulation used in this study, this distribution is used as a probabilistic input: each EV is randomly assigned to a charger type in proportion to its national availability. This approach reflects the real-world diversity of user charging experiences in urban settings, acknowledging that drivers may charge at home, work, or public locations with varying power levels.

While the current model applies a fixed distribution based on

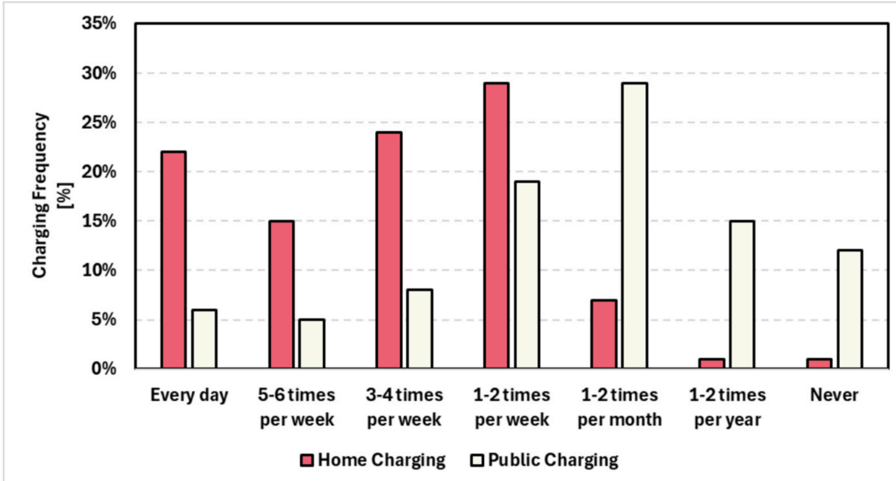

Fig. 7. Charging frequency patterns of EV owners (Data adapted from the DfT survey [45] reflecting responses to Question 15.).

Table 3
Distribution of public EV chargers by power rating and infrastructure share in the UK.

Charger Rate [kW]	Charger Group	Infrastructure Share [%]
3.6	Slow	27
7	Fast – 1	18
11	Fast – 2	18
22	Fast – 3	18
50	Rapid	10
150	Ultra-Rapid	9

*This table incorporates insights from Zap-Map [46], which provided the total number of chargers by type (slow, fast, rapid, and ultra-rapid) as of 2023. Additional assumptions and analyses were applied to determine charger rates and infrastructure shares. The content of this table was independently developed and does not reflect the views or endorsements of Zap-Map or any other entities.

present-day percentages, it is designed to be modular: these proportions can be easily updated to reflect future shifts in infrastructure. This flexibility allows the model to remain relevant as trends evolve.

The DfT [48] reported that Nottingham currently has approximately 300 public charge points, with 87 rated at 50 kW or higher, representing a solid baseline for urban fast charging. The city's public charger density (91.3 devices per 100,000 residents [48]) is also comparable to national urban averages. Across the UK, the public charging network is expanding rapidly, having grown from 28,000 devices in 2021 to over 73,000 by early 2025 [49]. Government initiatives such as the £1.6 billion UK charging investment plan and the £450 million Local EV Infrastructure (LEVI) fund are expected to accelerate deployment further, with a national goal of 300,000 public chargers by 2030 [50].

Although this study does not explicitly model charger availability, spatial distribution, or sufficiency of the infrastructure, it provides a behavioural reflection of real-world infrastructure diversity through charger-type assignment. The energy impact of high-powered charging is embedded in the model via the power levels of each assigned charger, which affect total grid demand over time. Future research could integrate dynamic charger deployment, and geographic placement strategies to more comprehensively model system load and infrastructure efficiency.

The simulation model integrates detailed energy calculations to evaluate EVs' charging and discharging behaviours, computing hourly charging demand and potential discharging supply. These calculations are central to understanding how EVs interact with urban energy systems and are formalised through the following equations.

The energy required for a full charge ($E_{80\%}$), the time required to meet this energy demand ($T_{80\%}$) and the vehicle's hourly charging demand on the grid (E_{load}) are calculated using Eqs. (1), (2), and (3), respectively. Here, $P_{battery}$ denotes the battery's power capacity, $P_{charger}$ represents the charger's power rating, and $\mu_{charger}$ indicates the charger efficiency, set at 90 % in line with [19].

$$E_{80\%,n} = P_{battery,n} \times (0.8 - SoC_n) \tag{1}$$

$$T_{80\%,n} = E_{80\%,n} / \left(P_{charger,n} \times \mu_{charger}\right) \tag{2}$$

$$E_{load,t} = min\left(\left(E_{80\%,n,t}/\mu_{charger}\right), \left(P_{charger,n} \times 1\, hour\right)\right) \tag{3}$$

For EVs participating in V2G services, the energy available for discharging ($E_{\text{available}}$), the time required to supply this energy ($T_{\text{discharge}}$), and the hourly discharging supply (E_{supply}) are similarly computed using Eqs. (4), (5), and (6), respectively. In Eq. (4), SOC_{min} denotes the post-discharge SOC set by EV owners.

$$E_{\text{available},n} = P_{battery,n} \times (SoC_n - SOC_{min}) \tag{4}$$

$$T_{\text{discharge},n} = E_{\text{available},n} / P_{charger,n} \tag{5}$$

$$E_{supply,t} = min\left(\left(E_{\text{available},n,t} \times \mu_{charger}\right), \left(P_{charger,n} \times \mu_{charger} \times 1\, hour\right)\right) \tag{6}$$

The stochastic simulation is designed to explore the operational complexity of daily EV charging and discharging routines under urban conditions. By adjusting key parameters—such as EV population, renewable energy variability, and grid energy status—the model identifies periods of potential imbalance and evaluates the effectiveness of smart charging strategies in mitigating these challenges. The smart charging strategy aligns with UK government targets for grid-friendly charging infrastructure [51], optimising EV energy use during periods of low demand or high renewable availability.

4. Results and discussion

4.1. Overview of the analysis

This section evaluates the integration of EVs and RESs within the urban energy infrastructure under different future energy scenarios, focusing on the years 2035 and 2050. Using a stochastic V2G model, it investigates whether EV charging and discharging can balance energy supply and demand under challenging conditions for renewable energy generation. The analysis also assesses the urban energy system's capacity to meet the demands of an expanding EV fleet while managing the variability of renewable energy sources.

To provide a detailed understanding, the study focuses on March 5, a day marked by suboptimal solar and wind energy generation. This critical day highlights the system's resilience under low renewable energy output, offering valuable insights into grid stability and the role of EVs. By centring the analysis on March 5, the study aims to showcase the challenges and opportunities in balancing supply and demand in urban energy systems under representative but demanding conditions.

The results presented in Table 4 highlight the anticipated EV charging and discharging needs for March 5 under different scenarios for 2035 and 2050. These figures reflect the outcomes of the stochastic V2G modelling framework and illustrate the potential of EVs to support urban energy systems through their dual role as consumers and energy suppliers.

The modelling suggests that on the presented day, discharging-ready EVs consistently outnumber those requiring charging across all scenarios, offering opportunities to stabilise grid fluctuations during periods of low renewable generation. In the Falling Short scenario, the sharp rise in EV numbers from 2035 to 2050 (Tables 1 and 4) underlines the challenges of managing this growth, particularly in the context of limited renewable energy expansion (Table 1). Conversely, the Customer Transformation scenario demonstrates a balanced progression of EV adoption aligned with renewable energy integration. However, the anticipated rise in electricity demand for residential, industrial, and commercial heating by 2050 (Fig. 5) highlights the complexities of managing these interactions. This underscores the necessity of the forthcoming analysis to examine the dynamic interactions among EV penetration, renewable integration, and sectoral energy demands.

4.2. Energy analysis without EV demand

To evaluate the baseline energy system performance, this section examines the energy profiles of the selected day (March 5) in 2035 and 2050 under different scenarios, excluding EV demand. The analysis provides foundational insights into how urban energy systems respond to challenging conditions, such as low solar and wind generation, without any management strategies.

Fig. 8 presents the scenario-based hourly net energy, calculated as the difference between total generation and consumption. Positive net energy values indicate surplus capacity that could accommodate EV charging, while negative values highlight periods requiring strategic interventions to address shortfalls.

In 2035, the Customer Transformation scenario demonstrates a moderate daily net energy surplus of approximately 318 MWh in the selected day. However, evening peaks reveal negative net energy, pointing to potential challenges even before accounting for EV demand. By 2050, these challenges will be significantly magnified, shifting to a daily net energy deficit of −102 MWh and up to 17 h of sustained shortfalls. This reflects a mismatch between the projected 50 % increase in renewable capacity and the approximately 30 % rise in demand from residential, industrial, and commercial sectors, especially for heating. The grid's ability to adapt to these dynamics will require substantial upgrades and advanced management strategies.

The System Transformation scenario offers a contrasting narrative, with consistently higher net energy values. In 2035, a significant daily surplus of 792 MWh suggests ample capacity to meet existing demand, negating the immediate need for discharging operations. However, by 2050, the surplus will diminish to 639 MWh, with occasional deficits during evening peaks, emphasising the growing importance of V2G capabilities and other adaptive strategies as the decade progresses.

The ambitious renewable integration in the Leading the Way scenario eliminates net energy deficits in 2035, achieving a robust daily surplus of 846 MWh on the selected day. By 2050, however, evening peaks introduce brief periods of negative net energy, with the daily surplus reducing to 738 MWh. This scenario emphasises the need for strategic planning and investment in grid management solutions to fully harness the benefits of high renewable penetration while addressing emerging challenges like overgeneration and renewable curtailment.

Conversely, the Falling Short scenario exhibits the most significant vulnerabilities. With limited renewable energy growth (as noted in Table 1) and the highest EV penetration, this scenario sees a decline from a minimal surplus of 159 MWh in 2035 to a severe deficit of −386 MWh by 2050. Extended periods of negative net energy throughout the day highlight the pressing need for advanced energy infrastructure and innovative demand-side management to mitigate risks.

Across all scenarios, a clear trend emerges: the energy network is anticipated to face substantial challenges in balancing renewable energy supply with rising demand. By 2050, prolonged periods of energy deficits during low-generation conditions underscore the urgent need for improved grid resilience and adaptability. Conversely, scenarios with high renewable integration reveal significant energy surpluses, highlighting the inherent variability of renewable energy sources. These findings underscore the critical importance of integrating energy storage solutions, smart grid technologies, and advanced energy management strategies to ensure system reliability and flexibility. The following sections will examine how EV charging and discharging operations can effectively address these surpluses and deficits, contributing to grid stability and sustainability.

4.3. Impact of EV charging and discharging on energy profiles

This section examines how EV charging and discharging operations influence net energy profiles, highlighting scenario-specific dynamics in 2035 and 2050. Through probabilistic simulations, the results assess the feasibility of integrating EVs into urban energy networks under varying renewable energy penetration and demand growth scenarios.

4.3.1. Simulation of EV operations and System interactions

Table 5 provides a representative snapshot of EV-grid interactions, illustrating the simulation framework employed in this paper. The table captures the stochastic variability in EV operations, including SOC levels, charger power outputs, post-discharge SOC, and the duration of charging or discharging events. By simulating various EV types and configurations, the model highlights the complex, dynamic demands EVs place on urban energy systems.

The inclusion of randomised simulations ensures the model captures real-world variability in charging behaviours and infrastructure interactions. For instance, high-battery-capacity EVs may often be paired with lower-capacity chargers—or vice versa—resulting in prolonged charging sessions or underutilised infrastructure. Such scenarios, typically overlooked in deterministic approaches, underscore the importance of probabilistic models in representing the inherent complexity and randomness of EV-grid interactions.

4.3.2. Scenario-based energy balances and grid implications: 2035

The integration of EV operations reshapes energy dynamics, introducing unique challenges and opportunities in each scenario. Fig. 9 illustrates the dynamic interaction between energy supply, EV demand, and grid balance on the selected day across different scenarios. The analysis reveals the temporal distribution of net energy surpluses and

Table 4
Projected EV charging or discharging needs on the selected day under different scenarios.

Scenarios	2035		2050	
	Charging	Discharging	Charging	Discharging
Customer Transformation	20,174	21,947	21,864	23,821
System Transformation	13,853	15,308	22,910	24,719
Leading the Way	16,005	17,206	21,163	23,226
Falling Short	9,152	9,964	25,505	27,956

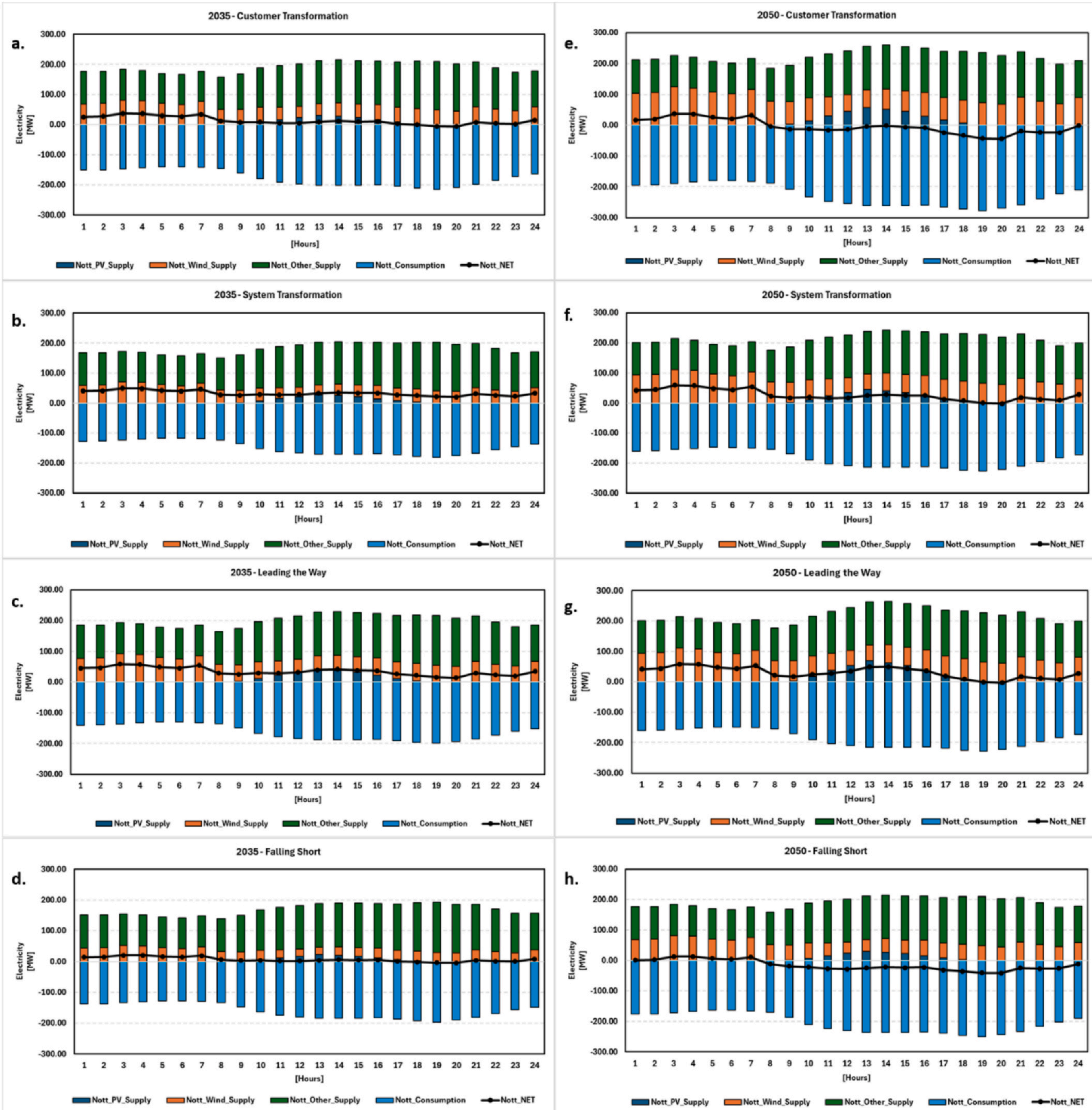

Fig. 8. Hourly net energy profiles for the selected day under different scenarios in 2035 and 2050: a-d) 2035 (Customer Transformation, System Transformation, Leading the Way, Falling Short), e-h) 2050 (Customer Transformation, System Transformation, Leading the Way, Falling Short).

deficits, as well as the extent of EV connections for charging and discharging. These insights form the basis for evaluating the energy system's capacity to accommodate EV operations under varying conditions. Building on these observations, Table 6 presents a consolidated summary of key indicators—such as net energy surplus/deficit, EV charging performance, and residual storage capacity—for each scenario in 2035 and 2050, supporting comparative evaluation.

Customer Transformation: This scenario achieves a net energy balance post-EV operation, efficiently utilising nighttime surpluses to meet some charging demands. Up to 8,000 EVs connect for charging at 6 am, utilising the available surplus energy. However, 52 % of EVs remain uncharged, requiring an additional 289.57 MWh of energy to fully meet their needs. After necessary discharging operations to support grid balance, 291.85 MWh of residual energy remains within vehicles, representing untapped potential that could be redirected to address the uncharged EVs. Discharging operations are minimal, occurring over three hours and involving a limited number of EVs, with up to 1,557 connections at 7 pm supplying the required power. By prioritising vehicles with unmet charging needs and employing smart charging scheduling, this residual energy could bridge the energy gap, optimising resource utilisation and improving the system's overall efficiency.

System Transformation: This scenario demonstrates a robust energy surplus post-EV operation, with + 363.85 MWh remaining after meeting all demands. Nighttime surpluses efficiently supply the

Table 5
Sample selection of EVs undergoing charging and discharging operations on the selected day under the Customer Transformation scenario.

EV ID	Type	Location	Charge/ Discharge	SOC [%]	Charger [kW]	Post-Discharge SOC [%]	Operation Duration [Hour]
'EV432'	'TESLA MODEL Y'	Public	C	25	3.6	0	10.19
'EV486'	'VOLKSWAGEN ID4'	Home	D	73	7	55	2.11
'EV530'	'RENAULT ZOE'	Home	C	33	3	0	9.52
'EV679'	'MG 4'	Home	C	25	7	0	4.45
'EV14'	'NISSAN LEAF'	Public	C	50	7	0	1.90
'EV13'	'VAUXHALL CORSA'	Home	D	68	3	34	5.67
'EV27'	'HYUNDAI KONA'	Home	C	48	3	0	8.12
'EV183'	'JAGUAR I-PACE'	Public	D	79	11	32	3.85
'EV258'	'MERCEDES EQC CLASS'	Public	C	39	22	0	1.76

*In the table, 'C' indicates that the car is set for charging, while 'D' indicates that the car is set for discharging.

majority of EV charging needs until morning, effectively utilising the available capacity to balance the grid. By the end of the day, only 25 EVs (0.2 % of the total) remain partially charged, requiring just 0.05 MWh of additional energy to fully charge—a negligible amount compared to the surplus. While discharging is not required to balance the grid on the selected day, a significant portion of the surplus energy remains underutilised due to the limited number of connected EVs in the later hours and the scenario's high-RES capacity, even under challenging conditions. This surplus highlights opportunities to enhance resource allocation and efficiency through strategies such as energy storage or improved demand management.

Leading the Way: Like the System Transformation scenario, this scenario demonstrates a robust energy surplus post-EV operation, with + 352.95 MWh remaining after meeting all demands. Nighttime surpluses effectively support EV charging, with up to 11,844 EVs connecting per hour during peak wind energy generation. By the end of the day, only 29 EVs (0.2 %) remain partially charged, requiring just 0.14 MWh of additional energy. Its enhanced capacity for EV connections sets Leading the Way apart, reflecting its ambitious renewable energy integration strategy. This underscores the potential of high-RES systems to support widespread electrification. As with System Transformation, surplus energy remains underutilised during later hours, highlighting the need for energy storage solutions, demand response, and dynamic charging schedules to optimise resource use and strengthen the system's adaptability for future growth.

Falling Short: This scenario presents significant challenges for the energy system, with the lowest EV connection numbers among the scenarios. Early morning surpluses support up to 4,000 EV connections during high supply times, but connection counts drop sharply post-dawn. Supply falls short of demand by evening (5–7 pm), necessitating discharging operations to maintain grid stability. By the end of the day, 46 % of EVs (4,199 units) remain partially charged or uncharged, requiring an additional 112.48 MWh of energy to fully meet their needs. Despite this shortfall, a residual surplus of 128.59 MWh is available, exceeding the energy needed for uncharged EVs. This indicates a potential underutilisation of the available energy, which could be addressed with optimised and scheduled EV smart charging strategies.

4.3.3. Scenario-based energy balances and grid implications: 2050

In 2050, the energy profiles highlight increased challenges for the system, reflecting higher energy demands despite expanded renewable energy capacity. Fig. 10 illustrates the dynamic interactions between net energy, EV demand and supply, and the number of connected EVs for charging and discharging under each scenario. Additionally, the key metrics for energy balance and EV charging status across the scenarios for 2050 are summarised in Table 6, as previously detailed for 2035 scenarios.

Customer Transformation: This scenario faces growing difficulties, with 18,313 EVs left partially charged—up from 10,431 in 2035—requiring an additional 483.39 MWh of energy. Nighttime surpluses allow up to 7,279 EVs to charge during peak net energy periods. However, the residual energy surplus of 38.74 MWh is insufficient to meet the rising demand. Discharging is vital, with up to 11,618 EVs per hour contributing to grid balance during peak evening hours. While EVs can maintain the grid balance, the unmet charging demand underscores the need for improved scheduling and integration strategies.

System Transformation: With a reduced surplus of + 8.31 MWh compared to 2035, this scenario reflects a more balanced yet strained system. Only 3,908 EVs (17 % of the total) remain partially charged, requiring 71.83 MWh to meet their needs. Discharging operations are minimal, with 308 EVs supporting grid balance at 7 pm. The 340.23 MWh of dischargeable residual energy stored in EVs underscores the potential for enhanced resource utilisation through energy storage and smart EV charging strategies. While the system effectively manages existing loads, the growing pressure from increased demand signals a need for optimisation.

Leading the Way: This scenario maintains a strong surplus of + 101.04 MWh, demonstrating its robust renewable integration capacity. At the end of the day, 1,150 EVs (5 % of the total) remain partially charged, requiring only 9.36 MWh. Discharging operations are limited, with up to 660 EVs supporting the grid during minor deficits. A residual surplus of 317.61 MWh underscores the need for strategies to handle overgeneration and optimise resource allocation. Despite its strengths, the scenario reveals inefficiencies in fully utilising available resources.

Falling Short: This scenario presents the most severe challenges, with a net energy deficit of −60.17 MWh and 24,714 EVs (97 % of the total) left uncharged or partly charged, requiring an additional 730.05 MWh. Discharging is heavily relied upon, with nearly all available EVs connected, yet the grid still struggles to meet demands. Despite a residual energy surplus of 6.65 MWh during limited periods, the system's inability to support EV integration highlights the need for substantial infrastructure upgrades and innovative demand management.

Table 6 presents a consolidated summary of the key energy and charging indicators for each scenario across both time horizons, supporting the comparative discussion that follows.

4.3.4. Comparative analysis across scenarios

A cross-scenario evaluation for 2035 and 2050 reveals distinct energy network stability and EV integration trajectories. In 2035, the System Transformation and Leading the Way scenarios demonstrate robust energy surpluses, effectively meeting and exceeding EV charging demands without requiring discharging. However, this surplus raises concerns about overgeneration and underutilised renewable energy capacity, suggesting a need for improved storage and demand-response strategies.

Conversely, the Customer Transformation and Falling Short scenarios face notable challenges. Nearly half of the EV fleet remains uncharged or partly charged, highlighting current infrastructure limitations and the pressing need for smart grid management. Despite having residual energy available within EVs, these scenarios underscore the importance of prioritising vehicles with unmet needs and enhancing charging efficiency through smart charging scheduling.

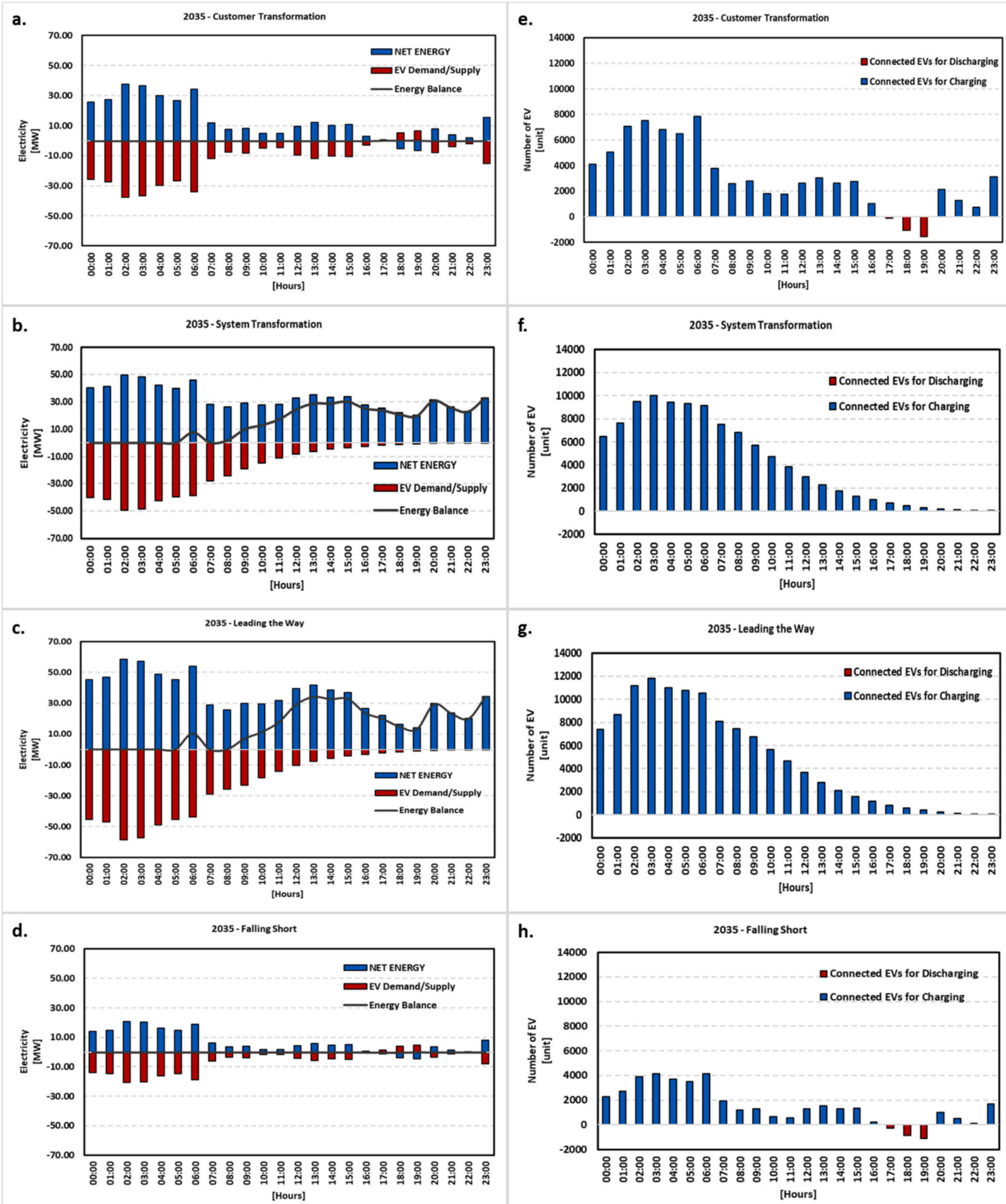

Fig. 9. Energy and EV connection profiles for the selected day in 2035: Panels (a-d) comparative analysis of net energy, EV demand/supply, and energy balance across scenarios; Panels (e-h) the temporal distribution of EVs connections for charging and discharging operations.

Table 6
Energy balance and EV charging status across scenarios on the selected day in 2035 and 2050.

	CT 35	CT 50	ST 35	ST 50	LW 35	LW 50	FS 35	FS 50
Net energy surplus/deficit post-EV operations [MWh]	0	0	+363.85	+8.31	+352.95	+101.04	0	−60.17
Total EVs pending charge or incomplete charging [Unit]	10,431	18,313	25	3,908	29	1,150	4,199	24,714
Percentage of EV pending or incomplete charging [%]	52	84	0.2	17	0.2	5	46	97
Required energy for charging pending EVs [MWh]	289.57	483.39	0.05	71.83	0.14	9.36	112.48	730.05
Residual energy available for discharging [MWh]	291.85	38.74	213	340.23	237.31	317.61	128.59	6.65

*In the table, 'CT', 'ST', 'LW', and 'FS' indicate the Customer Transformation, System Transformation, Leading the Way, and Falling Short scenarios, respectively. Furthermore, '35′ refers to 2035, and '50′ refers to 2050. For instance, 'CT 35′ specifies the Customer Transformation Scenario 2035.

By 2050, increased energy demand will strain all scenarios, and the importance of V2G capabilities becomes increasingly vital. While System Transformation and Leading the Way still manage to maintain surpluses, inefficiencies in charging operations lead to increased uncharged or partly charged EVs compared to 2035. In contrast, Customer Transformation and Falling Short face pronounced deficits, reflecting a critical reliance on V2G operations and significant infrastructure upgrades.

These findings emphasise the necessity of strategic planning, including dynamic energy management, smart EV charging scheduling, demand response mechanisms, and storage solutions, to ensure resilient and efficient energy systems capable of supporting future EV penetration.

4.4. Renewable energy integration with electric vehicles

This section explores how integrating EV charging operations with RESs supports sustainability goals in 2035 and 2050. By examining scenario-specific dynamics, the analysis highlights the potential of EVs to absorb excess renewable generation, particularly on days of suboptimal renewable output.

Fig. 11 provides the hourly profiles for wind and solar PV energy generation, compared with the energy absorbed through EV charging operations across scenarios on a representative day of low renewable output.

In the Customer Transformation scenario, nighttime charging, aligned with robust wind generation from midnight to 6 am, facilitates the integration of 330.8 MWh of RES through EV charging in 2035. By 2050, however, increased energy demand and reduced net energy during the day limit solar PV's contribution, and lower absorbed RES to 189.5 MWh. This decline highlights the growing challenge of aligning renewable energy output with EV charging needs as demand scales.

The Falling Short scenario follows a similar pattern but reflects reduced integration potential due to limited surplus energy availability. In 2035, only 169.4 MWh of RES is utilised for charging, with solar contributing a modest 30 MWh. By 2050, despite the scenario's high EV penetration, energy shortages restrict integration to a mere 52.2 MWh, highlighting systemic inefficiencies.

Conversely, the Leading the Way and System Transformation scenarios exhibit the highest levels of RES absorption. In 2035, nighttime surpluses and robust wind generation enable the integration of 493.1 MWh and 428.4 MWh of RES, respectively. By 2050, expanded renewable capacity and distributed charging patterns further enhance RES utilisation, with the Leading the Way scenario achieving 641.9 MWh and System Transformation 633 MWh of integrated renewable energy.

It is important to note that this analysis focuses solely on RES absorption through EV charging, excluding the potential contribution of discharging due to uncertainties in the energy mix during prior charging events. EVs could theoretically achieve full charging capacity on days with higher-than-average renewable generation, further boosting RES utilisation.

These results underscore the pivotal role of EVs in facilitating renewable integration. Strategies such as dynamic smart charging—synchronising charging schedules with peak renewable generation—and energy storage solutions are critical to maximising RES absorption and improving overall grid efficiency. As EV adoption scales, these approaches will be essential to utilising the full potential of renewable energy sources in urban energy systems.

4.5. Extending the framework to other sustainable transport modes

Although this study focuses on private EVs, the stochastic simulation framework is modular and can be extended to other forms of sustainable urban transport. Electric public buses, shared EV fleets, and delivery vans—particularly those using depot-based charging—represent important future extensions. These systems, for example urban bus services [52], typically follow scheduled and predictable patterns, differing from the more stochastic private EV behaviour explored in this study.

However, the availability of high-resolution operational and charging data remains a key barrier to integration. Public electric transport data (e.g., for buses or trams) is often not publicly available in the same detail as private EVs. In contrast, the projections used in this study—drawn from the FES 2023 scenarios [9]—already incorporate assumptions about broader urban travel shifts, including modal shifts toward public transport and shared autonomous mobility services, particularly under the Leading the Way and the Consumer Transformation scenarios [41].

Future research could combine electrified public transit systems, shared mobility platforms, and pedestrian-focused transport policies into the framework to evaluate more comprehensive climate adaptation strategies. Expanding the simulation model in this direction would improve its applicability to a broader range of urban planning and sustainability contexts, particularly in cities where car ownership is less dominant or underdeveloped.

4.6. Transferability of the framework to developing urban areas

Although developed urban centres provided the reference context for this study, the underlying modelling framework is designed to be modular and may be adapted to a range of city types, including those in developing regions. With appropriate input data—such as EV adoption rates, charging behaviours, car usage profiles, grid characteristics, and energy generation profiles—the methodology could support scenario-based planning in diverse infrastructure and policy settings.

Applying this framework in lower-income or developing cities presents several challenges. In many such regions, open-access datasets are scarce or non-existent [53,54], especially concerning charging infrastructure, EV penetration, and hourly energy flow. Vehicle ownership patterns may differ substantially, with greater reliance on informal or shared transport modes. Additionally, consumer charging behaviour may be less predictable due to fewer home chargers and highly constrained public networks.

Another critical factor in many developing urban areas is the frequency of grid-outage periods, which can significantly affect energy accessibility and system resilience [55]. The method used in this study—capable of identifying periods of grid overloading or overgeneration—could serve as a useful early-stage diagnostic tool in such

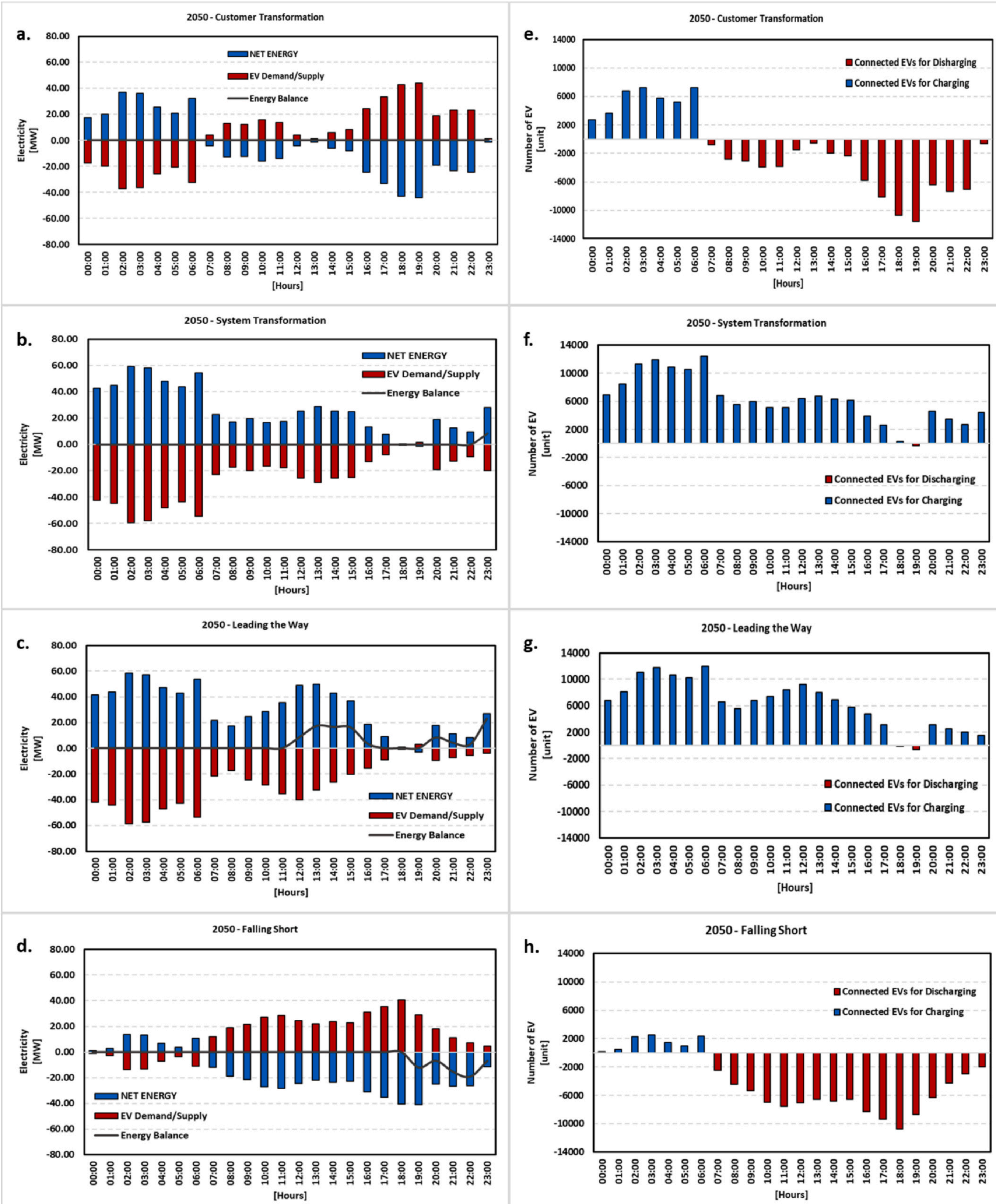

Fig. 10. Energy and EV connection profiles for the selected day in 2050: Panels (a-d) comparative analysis of net energy, EV demand/supply, and energy balance across scenarios; Panels (e-h) the temporal distribution of EVs connections for charging and discharging operations.

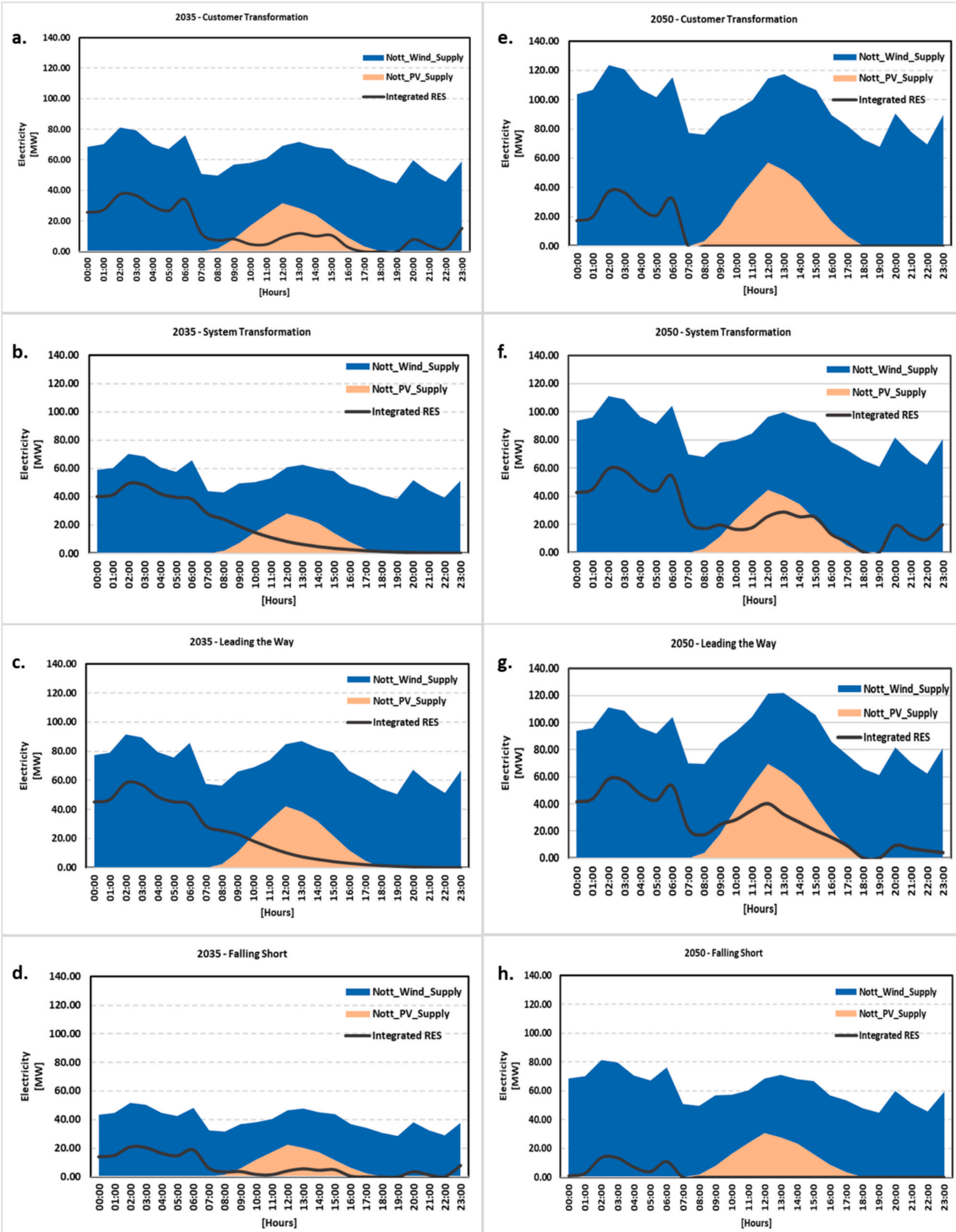

Fig. 11. Hourly profiles of wind and PV energy vs integrated RESs through EV charging operations on a representative day: Panels (a-d) for 2035; Panels (e-h) for 2050.

contexts. By highlighting vulnerable hours within a day or across seasons, the framework can support assessments of load flexibility, supply–demand mismatches, and stress points in urban energy systems where interruptions are more likely.

Despite these challenges, there is growing potential for adaptation. Several emerging economies have demonstrated accelerating investment in electric mobility [56] and renewable energy integration [57] alongside efforts to build national data repositories [58]. As energy and transport systems mature and where appropriate data become available, the framework presented in this paper could offer value to planners and researchers working in diverse urban contexts. To fully realise this potential, future research should focus on adapting the framework to context-specific conditions—accounting for local parameters, service performance, and travel behaviour patterns.

5. Conclusions and future works

Based on the findings of this study, key insights into the integration of EVs and RESs within an urban energy framework have been identified. These conclusions reflect energy patterns on days with suboptimal renewable generation and highlight challenges and opportunities.

- In 2035, System Transformation and Leading the Way exhibit robust energy surpluses; however, overgeneration challenges begin to emerge. In contrast, Consumer Transformation and Falling Short show signs of system strain, with a portion of the EV fleet left partially or completely uncharged due to energy limitations.
- By 2050, all scenarios predict net energy deficits during days with poor solar and wind availability, with extended periods of energy shortfall testing the system's resilience. These issues become particularly pronounced in Falling Short, which shows a critical 97 % uncharged EV rate and severe energy deficits, emphasising the urgent need for grid reinforcement and more responsive energy strategies.
- Across all scenarios, V2G becomes increasingly vital by 2050, helping to reduce energy gaps, particularly in the most constrained scenarios. Nevertheless, even with V2G, low renewable output days may still present risks, reinforcing the need for greater grid flexibility and multi-layered management approaches.
- RES integration through EV charging varies significantly by scenario and year. In 2050, Leading the Way and System Transformation achieve high-RES absorption levels of up to 641.9 MWh/day and 633 MWh/day, respectively. In contrast, Falling Short struggles to integrate renewables, managing just 52.2 MWh/day.
- To address both overgeneration and energy shortfalls, urban energy systems will require expanded storage, smart charging schedules, and strengthened infrastructure. These elements are essential to ensure reliability, sustainability, and flexibility in future urban power systems.

This study offers valuable insights into EV-RES integration within a European urban context but acknowledges certain limitations. The use of generalised energy profiles, due to the lack of detailed hourly consumption data, limits the precision of the analysis. Similarly, the scaling of national EV projections to the urban level assumes a fixed proportional relationship over time, which may not reflect future demographic or policy-driven changes in EV uptake at the city scale. Dynamic, spatially adaptive modelling frameworks could offer more accurate insights in future work. Incorporating high-resolution datasets in future research could better capture real-world energy dynamics. The model also assumes static non-renewable energy contributions, excluding potential changes in energy imports or supply diversification. Future studies could explore dynamic supply scenarios to provide a more comprehensive understanding of evolving energy systems. Likewise, the current model applies a static distribution of public charger types and does not account for charger deployment dynamics or spatial accessibility. Future research could incorporate dynamic charger installation rates, utilisation patterns, and geographic optimisation to more accurately represent infrastructure efficiency and its impact on grid demand. A macro-level approach to EV temporal dynamics also constrains the assessment of parking durations and, dynamic and instantaneous SOC management. Integrating behavioural data and real-world EV usage patterns could enhance predictive accuracy and operational strategies. Additionally, this analysis focuses primarily on renewable energy absorption through EV charging, with limited consideration of discharging contributions. Future work should include a holistic view of V2G operations to evaluate their full impact on urban energy stability. Moreover, while this study focuses on private EVs, future extensions could incorporate electrified public transport, shared mobility services, or micro-mobility systems to better reflect the full landscape of sustainable urban mobility and its interactions with energy infrastructure. By addressing these limitations and exploring advancements in EV, RES, and grid technologies, future research can strengthen strategies for sustainable and resilient urban energy networks. Furthermore, adapting this framework to developing urban contexts, where data scarcity, infrastructure variability, and grid reliability issues present distinct challenges, represents a valuable avenue for future research. Designing the model to account for these local constraints could broaden its applicability and support more inclusive global energy planning.

CRediT authorship contribution statement

Abdullah Dik: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hao Sun:** Visualization, Resources, Methodology, Investigation, Software. **John Kaiser Calautit:** Writing – review & editing, Supervision, Resources, Conceptualization. **Cagri Kutlu:** Writing – review & editing, Visualization, Investigation. **Rabah Boukhanouf:** Writing – review & editing, Supervision. **Siddig Omer:** Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data used in this study is licensed by respective entities, and the authors do not have permission to share it. All data sources and links are fully referenced within the manuscript.

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