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Electric vehicle hosting capacity analysis: Challenges and solutions

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ABSTRACT

The significant rise of electric vehicles (EVs) and distributed energy resources (DERs) poses critical challenges to the distribution systems for maintaining statutory limits of technical and operating constraints. This review investigates the challenges and explores innovative solutions for EV hosting capacity analysis in the distribution network based on existing literature and industry reports published in recent years (2014–2023). The study emphasizes the significance of multiple performance constraints, scenarios, availability of data, and methods in hosting capacity analysis. In addition, it provides insights into the technical aspects, performance, and practicability issues of open-source and commercial tools for assessing hosting capacity. The study also highlights industrial hosting capacity projects in international and Australian contexts, showcasing the importance of region-specific integration capacity analysis due to diverse EV profiles, charging facilities, and network topologies. Based on the existing research and industry reports, active network management, flexible operating limits, demand response, optimal placement methods, and network reconfiguration are identified as promising solutions for hosting capacity enhancement. The review concludes by discussing future research scopes, considering accuracy, computational time, and data requirements for EV hosting capacity analysis to guide the researchers and the distribution grid planners.

1. Introduction

The power systems sector is currently experiencing a significant paradigm shift, focusing extensively on strategic planning and adept management to address emerging challenges brought about by the proliferation of electric vehicles (EVs). This shift is propelled by the compelling amalgamation of techno-economic advantages and environmental sustainability associated with EVs, signaling a marked movement towards transport electrification. Recent statistics indicate that global EV sales, encompassing battery and plugin hybrid EVs (BEVs and PHEVs), surged to 10.52 million by the end of 2022, a 55% increase compared to the previous year [1]. This substantial upswing in EV production and sales firmly establishes China as the dominant player in transport electrification, accounting for approximately 60% of global sales in 2022, followed by European countries and the United States [2]. Fig. 1(a) illustrates the global EV sales statistics from 2013 to 2022, while Fig. 1(b) provides insights into the growth of EV sales across various regions as of the end of 2022 [1,2] (see Tables 1–13).

While EV integration into distribution grids via residential and workplace charging stations offers numerous benefits, it has also brought about adverse impacts, as evidenced by several studies [22,25,90,91]. These impacts encompass a range of issues, such as voltage violations, thermal overloading, voltage unbalance, load variations, and short-circuit current within the protection system. In addition to the EV surge into distribution networks, residential solar photovoltaic (PV) systems are increasing swiftly. For instance, Australia is a global leader in installing more than 3.4 million solar home systems, showcasing substantial energy-transferring capacity to the grid [92]. Therefore, it is essential to determine the impacts of EV integration in a solar PV-connected grid. A study [7] emphasized the necessity of using voltage-controlling schemes and network protection devices for combined PV-EV distribution networks. Although EV deployment is in the early stages, the capability of accommodating EVs in conventional and renewable-rich networks and their necessary upgradation for coping with large penetration are required in the grid planning and

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Abbreviations

AI	Artificial intelligence
AMI	Advanced metering infrastructure
ARENA	Australian Renewable Energy Agency
BEV	Battery electric vehicle
BESS	Battery energy storage system
C4NET	Center for New Energy Technologies
DL	Deep learning
DER	Distributed energy resources
DNSP	Distribution network service provider
EV	Electric vehicle
EVCS	Electric vehicle charging station
HC	Hosting capacity
LV	Low voltage
MV	Medium voltage
MCS	Monte Carlo Simulation
OPF	Optimal power flow
OLTC	On-load tap changer
THD	Total harmonic distortion
PV	Solar Photovoltaic
QSTS	Quasi-static time-series simulation
PHEV	Plugin hybrid electric vehicle
SCADA	Supervisory control and data acquisition
SOC	State of Charge
V2G	Vehicle-to-grid
DRIVE	Distribution resource integration and value estimation

policymaking process [7,93]. For this reason, evaluating the maximum EV integration capability in the distribution networks by maintaining the technical and operational constraints is crucial, often referred to as EV hosting capacity (HC) [3].

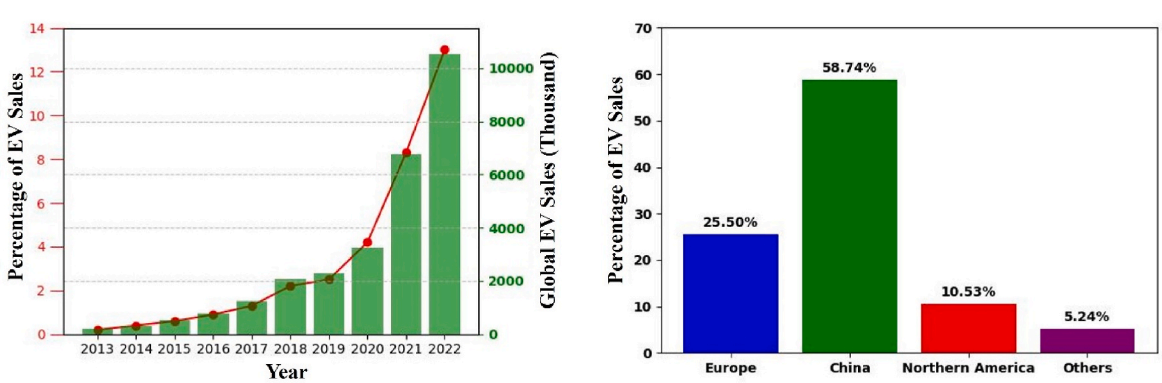
In recent research and industry reports, simulation-based and optimization-based methods have been introduced for assessing hosting capabilities in distribution networks. These methods are further categorized into deterministic, probabilistic, and streamlined approaches based on the scenarios and uncertainty considerations. Diverse EV specifications and plugin uncertainties in the charging process [94] necessitate stochastic solutions, requiring numerous scenarios and significant computational time [90,95]. Additionally, the deterministic approach only studies the worst-case scenario in HC estimation with a small computational burden [49]. The streamlined process takes a small number of cases, although it gives approximate results for the assumed constraints [8]. All these methods have merits and demerits, including accuracy, computational time, and data requirements. Besides, the performance of the HC estimation tool varies based on the selected constraints, cases, objectives, execution time, and data availability. Commercial tools typically use only a deterministic approach, time-series analysis, and a streamlined approach for HC calculation, as discussed in Ref. [5]. Conversely, several simulation-based and optimization-based HC studies leverage open-source software with customizable options, offering a more versatile approach [95,81]. Therefore, it is necessary to review commercial and open-source tools concerning their performance and applicability in EV HC studies.

One of the primary challenges in HC studies revolves around data requirements, specifically on the EV load profile, network topology, loads, and PV ratings [96]. The use of advanced metering infrastructure (AMI) and supervisory control and data acquisition (SCADA) in the distribution network improves network visibility and data quality in HC analysis [16]. In Ref. [10], research has been carried out to mix conventional methods for finding the most approximate results with a short computational time. Artificial intelligence (AI) techniques, including machine learning (ML) and deep learning (DL), have been utilized in HC calculations for distribution grids. These AI techniques demonstrate promise in seamlessly integrating EVs and renewables into smart grids, warranting further in-depth exploration [55].

To align with EV integration, distribution network service providers (DNSPs) are bolstering HC by employing several technical solutions considering technology readiness, investment cost, and regulatory compliances [97,98]. A study [3] underscores the significance of stakeholder-centric solutions for improving HC with increasing customer acceptance of cleaner technologies. In recent studies, PV HC enhancement has been a focal point, guiding DNSP-centric solutions, such as controlling active/reactive power, harmonics mitigation, on-load tap changer (OLTC), and network reconfiguration [3,6]. Only a few studies [81,99] conducted DNSP-oriented EV HC enhancement in test networks, often overlooking prosumer capabilities.

HC assessment and improvement projects have been undertaken worldwide in recent years, primarily focusing on solar PV integration. Moreover, diverse EV models, network settings, and charging facilities in different regions lead to region-specific EV HC analysis. The international and Australian industrial HC projects are discussed in this study to showcase the importance of region-specific EV HC analysis considering renewable-rich distribution networks. Additionally, it emphasizes the need for initiatives in EV HC estimation, especially in Australian industry projects that predominantly revolve around charging station installations.

Considering the emerging growth in transport electrification, this



(a) (b)

Fig. 1. Statistics on global EV sales. a) growth in EV sales and b) growth in different regions.

Table (1)
Comparison of this study with other reviews on hosting capacity in the distribution grid.

Features	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	Current
Hosting capacity assessment	DG	PV	DER	DER	PV	PV	PV	PV	EV
Impacts of EV charging	×	×	×	×	×	×	×	×	✓
Identifying performance constraints	✓	✓	✓	×	✓	✓	✓	✓	✓
HC assessment methods	✓	✓	✓	×	✓	✓	✓	✓	✓
HC evaluation tools	×	×	✓	×	×	×	×	×	✓
Review of EV HC determination	×	×	×	×	Δ	×	×	×	✓
AI for HC calculation	×	×	×	×	×	×	×	×	✓
Summarizing international HC industry projects	×	×	×	×	✓	×	×	×	✓
Australian projects on DERs and EV integration	×	×	×	×	Δ	×	×	×	✓
EV HC enhancement technologies	Δ	Δ	×	Δ	Δ	Δ	×	×	✓
Discussion on accuracy and computational time	Δ	Δ	×	×	×	✓	✓	✓	✓

√ = Yes× = No Δ = Partly.

Table (2)
Review the positive impacts of EVs in the utility grid.

Ref.	Features	Methods	Outcomes
[11]	**Energy-transferring technology**	Review the benefits and challenges of vehicle-to-grid (V2G) technology in the distribution network.	V2G benefits include EV owner profits, smoothing load curves, and adding power to the utility grid during peak hours.
[12]		Discusses the impact of V2G technologies on the grid	V2G provides better ancillary services, voltage regulation, peak shaving, spinning reserve, and reduction of renewable intermittence.
[13]		Fuzzy logic-based charging cost optimization	It demonstrates an innovative pricing scheme to sell excess electricity at a higher tariff during peak hours.
[14]	**Controlling renewable intermittence**	Renewable-based EV charging station (EVCS)	It depicts EVs connected with a renewable-based distribution grid that handles the intermittent properties.
[15]		EV charging through renewable resources	It shows that the energy cost is considerably reduced for EV charging with control of renewable intermittence.
[16]		EV interaction with smart-grid	It depicts that the V2G deployment can control voltage fluctuations and intermittent renewables.
[17]	**Environmental Impacts**	Design of complete renewable-powered EVCS	The proposed EVCS emits around an average of 2018.49 kg CO_2 equivalent yearly, including well-to-wheel emissions.
[18]		Solar-biogas based EVCS	It reduces 34.68% of CO_2 emissions compared to utility-based EVCS.
[19]		Solar -wind-based EVCS	The proposed method offers a 50% reduction in CO_2 compared to the grid-based EVCS.
[15]	**Economic Impacts**	Hybrid solar-wind-fuel cell- battery storage-based system	Research in Qatar shows that the Levelized cost of electricity varies from $0.285 to $0.329 per kWh.
[20]		Economic and environmental benefits of 10 kW PV-based EVCS	It shows that PV-based charging costs are lower than grid-based charging with less emission.
[18]		Hybrid PV-biogas-based EVCS	It reveals that the EV charging tariff is around $0.1302 per kWh, with a monthly savings of $ 17.75.

Table (3)
Outline of the negative impacts of EVs and DERs on the distribution network.

Ref.	Test Network	Performance Indicators	Method	HC
[21]	PV-based Swedish LV distribution grid	Under voltage	Stochastic Monte Carlo Simulation (MCS)	PV and EV
[22]	LV Australian distribution grid	Under voltage index and power delivery index	OpenDSS simulation	EV
[23]	LV/MV distribution grid of Terni, Italy	Voltage violations and line congestion	Iterative approach	EV
[24]	Residential MV/LV network	Voltage and current limits, harmonics	Mixed deterministic and probabilistic method	EV
[25]	Spot Network with PV and three feeders	Reverse-power flow, short-circuit current	Positive sequence current-based method	PV
[26]	IEEE-33 Test distribution	Voltage violations	Stochastic MCS	EV
[27]	Non-synthetic LV grid	Voltage unbalance	Load flow analysis using NEPLAN	EV and PV
[28]	MV distribution grid in Skopje, Macedonia	Overloading limit and power loss	MCS with control strategies	EV
[29]	LV grid San Savarino Marche, Italy,	Voltage and thermal limits, grid efficiency	MCS-based analysis	EV
[30]	Standard 17 bus LV network and real Budapest city network	Voltage limits, overloading, and harmonics	Stochastic simulation	EV
[31]	IEEE-33 bus system	Voltage stability index, reliability, and power loss	Genetic algorithm	EV
[32]	Real- Australian distribution network	Voltage unbalance	Heuristic genetic algorithm	EV
[33]	LV network	Power loss and harmonics	Fast-Fourier Transform	EV

research aims to review challenges and innovative solutions for EV HC estimation and enhancement by examining research studies and industry reports published in recent years (2014–2023). Table (1) depicts a relative comparison with the contemporary literature on HC studies, which differentiated the current work from previous studies.

In summary, the key contributions of this research are as follows-

- Identification of key performance constraints for EV HC calculation by studying the positive and negative impacts of EV charging in the distribution grid.
- Proposed innovative HC assessment methods, including AI techniques, reviewing accuracy, computational complexities, and data requirements by the traditional methods.

Table (4)
Comparison between simulation and optimization-based methods in HC analysis.

Features	Simulation-based Methods	Optimization-based Methods
Focus	Emphasizes dynamic HC analysis using network behavior	Concentrates on finding maximum HC for assumed constraints
Methods [34]	Load-flow simulation based on system modelling	Optimal power flow for defined objective functions and constraints
Data Requirements	Requires extensive data for accurate modelling [24]	Relies on input data for optimization with relatively less data-intensive [35]
Complexity [5]	Often involves detailed system modelling and can be computationally intensive	Streamlined and efficient, suitable for large-scale networks
Performance [8]	Depending on the network topology and uncertainty modelling	Depending on the visibility of network state estimation through smart devices, AMI and SCADA
Application [7,3]	Useful for real-time simulation for HC analysis under various scenarios	Ideal for decision support, planning, sensitivity analysis, and quick HC assessments

Table (5)
Comparison of different HC analysis methods.

Methods	Complexity	Data Needs	Scenarios	Accuracy	Computational time	Ref.
Deterministic	Simple	A few	Worst	Approximate	Small	[36,37]
Stochastic	Complex	Large	Many	Depends on uncertainties	Large	[10,38]
Streamlined	Complex	Moderate	Several	Depends on the scenario chosen	Relatively small	[39,40]

Table (6)
Review of EV HC studies considering methods, networks, constraints, and future scopes.

Ref.	Methods and Networks	EV Parameters	Performance Indexes	Research Outcomes	Future Works
[41]	▪ Linear programming and MCS ▪ Modified IEEE-33 Bus	Type and energy demand, SOC, parking duration, plug-in periods	Voltage violations	The daily expected maximum HC of the PV-Diesel microgrid system changes between 20 and 41 EVs for selected nodes.	▪ The intermittent of PV systems and more performance constraints might be considered
[42]	▪ MATLAB Simulation ▪ IEEE-33 bus system	Initial SOC, charging levels	Voltage deviation and power loss	It shows that fast charging causes voltage degradation and increases EV penetration more steadily than slow charging.	▪ Period/duration of charging and coordinated charging scheme may be explored.
[43]	▪ Experimental investigation using a voltage quality meter, ▪ Real MV/LV network in Italy	Two scenarios- short-term term- 150 EVs, and long-time- 2590 EVs	Total harmonic distortion (THD)	In the short-term scenario, THD stays below 2.6% of the Italian standard but increases to 3.9% when other feeders are disconnected.	▪ The intermittent PV systems and more performance constraints can be considered in the MV/LV grid.
[44]	▪ Mixed Integer linear programming, ▪ IEEE-123 system	Network capacity, driving range, investment cost	Line loss, phase unbalance	It presents an optimal solution for EV HC in planning the distribution system considering best- and worst-case scenarios.	▪ EVCS allocation, EV uncertainties, and system upgradation might be future research points.
[45]	▪ Stochastic MCS technique ▪ Practical LV residential data	Active power consumption, charging power, penetration rate	Voltage limits	It shows that EV penetration rate in the network can allow up to 45%, and it will be around zero for more than 50%.	▪ More uncertainties may be used, i. e., arrival and departure time, time of use, and DER integration.
[46]	▪ OpenDSS ▪ Different feeders	X/R ratio with a different EV penetration level	Voltage violations	The X/R ratio explicitly extrapolates the feeder's capacity, preventing voltage violations while EV charging.	▪ DER penetration and other constraints, i.e., line loss and harmonic generation, can be explored.
[47]	▪ Time-series analysis ▪ PV-EV-based grid	EV and PV penetration	Voltage and thermal limits	EV charging causes 90% thermal violations during peak hours without PV integration.	▪ Harmonic disturbances and other feeder analyses are required.
[48]	▪ Interval and Affine arithmetic method ▪ Seoul National University Microgrid	Arrival and departure time, SOC, and choice of charging levels	Voltage Violation Index (VVI)	It reveals that the maximum HC limit rises with increasing VVI, which specifies network flexibility.	▪ This method does not consider multiple constraints, charging control, and V2G.
[49]	▪ Taylor series expansion and a quadratic approximation ▪ Orion's LV grid	New Zealand-centric EV penetration inputs	Voltage limits and overloading limits	It shows that most sub-network voltages are expected to fall below 0.94 p. u. during peak hours.	▪ Data quality and renewable integration may be considered.
[50]	▪ Probabilistic approach ▪ Four LV grids	Different EV penetration	Overloading limits, voltage deviation	It shows that the EV load profile is a dominating factor for HC measurement.	▪ Renewable integration and harmonic generation require consideration.
[51]	▪ Stochastic Time-series analysis ▪ Swedish LV distribution grid	Stochastic load, PV generation, and EV demand	Voltage violations and power losses	The result shows a slight positive correlation between PV curtailment and smart EV charging for HC enhancement.	▪ PV-wind-heat pump-battery storage with EV integration can be deployed.
[8]	▪ MCS, QSTS, and parallel computing ▪ IEEE-123 bus system	EV load, charger type	Voltage violations and harmonics	Considering power quality impacts, this method reduces the computational time for HC calculation.	▪ EV load profiles and DER penetration need to be included.

Table (7)
Review of Artificial Intelligence for EVs and DERs integration.

Ref.	Methods and Network	Objectives	Findings	Future scopes
[52]	- AI techniques - LV network	Harmonic study of DER-based system	It reviews harmonic source categorization, source location, harmonic data clustering, and DER HC estimation.	- Hybrid AI techniques can apply more robustness and adaptability in DER performance estimation. -Privacy and legal issues may be considered.
[53]	- AI-based hybrid optimization	Minimizing power losses	It shows hybrid AI approaches are suitable for improving network performance.	- The incorporation of EVs and renewables can be explored.
[54]	- ML and DL	Investigate charging behavior	It explains EV charging behavior using AI approaches.	- The impacts of weather, traffic, and more events may include.
[55]	- Support Vector Machine	Finding LV grid HC	It uses the ML approach for grid clusters for network reinforcement.	- More experts' opinions might enhance grid modeling, planning, and HC estimation accuracy.
[56]	- Reinforcement learning - IEEE-33 bus	Resolve overvoltage problem	This method considers storage capacity, bus voltages, and line losses maintained within limits.	- Effect of thermal overloading in unbalanced power systems can be explored.
[57]	- Long-short-term-memory method	EV load forecasting	It demonstrates better load forecasting accuracy than conventional AI methods.	- HC forecasting may perform for finding better accuracy than conventional methods.
[58]	- DL	EV load forecasting	It uses four DL methods to predict the short-term EV demand.	- Managing data proliferation, requires innovative models to enhance speed and accuracy.

Table (8)
Lists of available tools acting as the load-flow engine in HC analysis.

Type of Software	Software	Method	Considered Parameters	Features
Commercial	PSS SINCAL [59]	Iterative time-series	Voltage and overloading limits, harmonic limits, reverse power flow, and protection limits	• HC can be calculated at independent nodes considering several performance indexes and uses a deterministic approach. • It performs unbalanced dynamic simulation.
	Dig silent Power factory [60]	Stochastic binomial search	Voltage and thermal overloading limits, power quality, and fault protection	• It can select strong nodes for worst and average cases during HC calculation. • It performs quasi–dynamic simulation, balanced and unbalanced power-flow analysis, state estimation, and short-circuit calculation with EMT simulation.
	NEPLAN [61]	Stochastic MCS	Voltage and thermal limits	• It visualizes violated nodes after load-flow simulation, performs dynamic simulation, and pre-filtered worst-case scenarios to lower the computational burden in HC calculation.
	SYNERGI ELECTRIC [62]	Stochastic and iterative time-series	Overvoltage, thermal overloading limits, and reverse power flow	• This tool offers a collection of power distribution planning tools for HC and reliability analysis customized options with COM solver and Python scripting.
	CYME [63]	Iterative and streamlined method	Voltage and thermal limits, reverse power flow, protection, and reliability	• The CYME Integration Capacity Analysis module computes the maximum HC at all nodes of the distribution networks using the iterative time-series method.
	ETAP [64]	Time-series analysis	Voltage and thermal limits	• It performs time-series unbalanced power flow using real-time operational data and models unbalanced load.
	WINDMILL MILLSOFT [65]	Real-time load-flow analysis	Voltage limits	• It runs individual or multiple outage scenarios sequentially and visualizes the grid network with actual data.
	PSCAD [66]	Time-domain analysis	Voltage limits, active and reactive power, phase angle	• It is famous for dynamic EMT simulation in power systems. • It uses steady-state equations for modeling electrical circuits and solves differential equations using machine dynamics.
Open-Source	OPENDSS [67, 68]	Quasi-static time-series analysis	Voltage limit, voltage unbalance, transformer overloading, harmonics, and power loss	• OpenDSS performs balanced and unbalanced power flow, fault, harmonic, and short-circuit calculations with electro-mechanical transient analysis. • It has a graphical user interface, 'OpenDSS-G', and a customized option to integrate with Python, MATLAB, C++, JAVA, and VBA.
	PANDA POWER [69]	Time-series analysis	Voltage and overloading limits, power loss	• It executes unbalanced load-flow analysis, OPF, and state estimation based on the data analysis tools 'pandas' and power system analysis tool 'pypower.' • It performs load-flow calculations using element modeling by the Newton-Raphson algorithm.

- Comprehensive review and evaluation of both commercial and open-source tools concerning technical features, performance, and applicability in EV HC analysis.
- Presentation of the findings from international and Australian projects, showcasing the importance of EV HC analysis in renewable-rich distribution networks.
- Thorough review of HC enhancement technologies in contemporary literature and suggestion of stakeholder-centric solutions.

The rest part of this study is segmented as follows. Section 2 describes the overview, methodological steps, and use cases in EV HC analysis. Section 3 covers HC assessment methods, including AI, focusing on EV deployment and highlights industry projects on HC analysis. It discusses key performance constraints and software tool selection factors in HC studies. In Section 4, HC enhancement strategies in distribution networks are presented with innovative solutions, highlighting EV integration. Section 5 discusses challenges and research directions in EV HC estimation and augmentation process with practical implications of this study. In conclusion, Section 6 summarizes the findings with future research scopes.

Table (9)
Lists of international HC projects on DERs and EVs.

Project Title	Methods, organization	Project Aims	Project Results
HAWAIIAN PROJECTS on HC [70]	• QSTS simulations with four inverters • NREL, USA	• This project addresses the following: a) specify the inverter function for voltage regulation, b) impacts of customer exports, and c) determine the priority for power exports.	• Voltage increases throughout the feeder by employing smart inverters, and the reactive power increases for high PV penetration.
Pacific Gas and Electric Company Studies [71]	• Laboratory test of the two PG & E feeders, USA	• Assess the performance of smart PV-inverter in terms of reliability under various grid conditions and determine PV curtailments.	• Exhibits the functionality of smart inverters may lower the voltage and minimum PV curtailment.
HC Map XCEL Energy [72]	• Minnesota Public Utilities Commission, USA	• It aims to identify DER integration with visualization.	• This report assesses DER's capacity to adopt without breaching constraints on the HC map.
InterFlex Increasing of renewables HC in the Czech Republic [73]	• Five European Union member countries	• This project focuses on increasing renewable HC in the LV network using smart inverters, smart EV charging, and a BESS.	• This project established HC enhancement using renewables by controlling reactive power and smart EV charging.
Carpathian Modernized Energy Network project [74]	• Hungary and Romania	• This project improves the efficiency and quality of network operations powered by renewables.	Ongoing
Gabreta project [75]	• Czech Republic and Germany	• It enhances system optimization by swapping real-time information, improving flexibility and renewable HC.	Ongoing
Green Switch project [76]	• Austria, Croatia, Slovenia	• It optimizes infrastructure utilization and integrates the latest technologies to enhance HC, maintaining power quality.	Ongoing

Table (10)
ARENA-funded projects on DER and EV integration in Australian perspectives [77].

Project Title	Project description	Period
EleXsys DER HC Demonstration	• The project will determine the capability of the eleXsys technology to be a cost-effective choice for enhancing HC in the LV network.	October 2021 - onwards
ACT DER Demonstration Pilot – Project Converge	• This project will demonstrate dynamic operating envelopes to integrate ancillary services and manage DER congestion with regulatory changes.	August 2021 - onwards
Western Australia DER Orchestration Pilot	• It directs the composition of customer-owned DER and essential appliances to participate in a future energy market.	July 2021 - onwards
Project SHIELD	• It plans to develop software combining data from various sources to manage DERs in LV networks.	December 2020- onwards
Advanced Planning of PV-Rich Distribution Networks	• It developed methods for evaluating the residential PV HC in the distribution grid using network and customer data.	January 2019–August 2021
Decentralized Energy Exchange (deX) Program	• This project targets expanding DERs in the network with better coordination and control.	March 2019–December 2021
evolve DER Project	• It intends to enhance HC by exploiting DER participation in energy markets and ancillary services, securing technical limits.	February 2019- onwards
Demonstration of Three dynamic Grid-Side technologies	• It improves the HC of two sites within Victoria's Jemena and AusNet Services' LV network.	January 2019–2021
DER Hosting Capacity Study	• The project determines Australian distribution networks' issues preserving energy security and power quality with increased DERs.	December 2018–December 2020
Dynamic Limits DER Feasibility Study	• This study explored employing dynamic export limits using voltage and thermal constraints in the distribution system.	December 2018–August 2021
NOJA Power Intelligent Switchgear	• This project developed intelligent switchgear to decrease the difficulty and cost of DER integration and thereby enhance HC.	July 2017–2020
Monash University and Climate Works Low Carbon Study	• This project focuses on EVs to decarbonize Australia's economy and shrink the intermittent properties of renewables.	November 2016–July 2018
Future Fuels	• This project establishes 400 public EVCSs throughout Australia.	July 2021- onwards
Realizing Electric V2G Services	• The project presents Australia's economic and grid benefits of V2G services.	June 2020- onwards
SA Strategic Regional EV Adoption Program	• It aims to speed up EV adoption and foster renewable-based charging penetration by determining barriers and solutions in South Australia.	January 2018–October 2018

Table (11)
List of C4NET projects on DERs and EVs integration from Australian perspectives.

Project	Project Description	Present Status
Assessing the EV impacts on the urban and rural grid in Australia	• This project assesses the EV impacts on urban and rural grids, considering voltage limits and asset utilization.	2021-ongoing
Electrification of Victoria's Future Fleet	• It will analyze EV technologies' techno-economic and socio-environmental impacts and suggest future policies in Victoria, Australia.	2021-ongoing
Model Free Operating Envelopes at NMI Level	• It provides a scalable approach to assess individual customers' power export/import limits without engaging the electrical circuit model employing a neural network and historical AMI data.	2022-ongoing
EVs: An Exploration of Adoption and Impacts	• The project demonstrates management techniques' influences and role, including future directions for EV adoption.	2022 - ongoing
LV network visibility and optimizing DER HC	• It enables visualization to observe DER penetration and shows a 2% increase in HC, providing a $50 M/annum consumer benefit.	Completed
EV & the Grid	• This project presents the benefits and costs of DER integration and identifies and addresses the barriers to EV adoption.	Completed

Table (12)
HC enhancement technologies in existing studies.

Ref.	Network	Considered parameters	Technologies used	HC Enhancement
[78]	IEEE-24 bus and Egyptian extra-high voltage network	Load shedding, short-circuit current and investment cost	The network planning system, ANFIS-supported load forecasting, and hybrid INFO-SCA algorithms	Renewables
[51]	IEEE European LV grid	Voltage profile and system losses	Combination of PV curbing and EV smart charging	Both PV and EV
[79]	4-bus LV distribution network	Voltage violations and current limits	SPEC as Dynamic Voltage Conditioner	Entire LV grid
[80]	Residential LV grid	Bus voltage and overloading limits	Smart-EV charging techniques with net-metering technology	Both PV and EV
[81]	IEEE-13 node feeder	Voltage profile	Optimal power flow	EV penetration
[82]	33-bus and a real 56-bus network	Voltage and current limits, substation capacity limit	Risk-constrained tri-level model for grid-scale storage system	Renewables
[83]	Typical distribution network data from Thailand	Line capacity and overvoltage issues	Coordination of smart PV inverter control with OLTC technologies	PV
[84]	IEEE 69-bus distribution system	PV size, tap position, voltage limits, and reactive power	Double-layer metaheuristic optimizer based on the grey-wolf optimization approach	PV, EV
[85]	LV network integrated with PV	Voltage constraints and transformer loading	MILP optimization approach consisting of smart-grid technologies, i.e., reactive power control, OLTC, and BESS	PV-rich grid
[86]	LV grid serving 170,000 households in Switzerland	Voltage violations and line overloading	GIS-based approach	PV, Heat Pump, and EV
[87]	Rural 59-bus distribution network in China	Thermal and voltage constraints	Stochastic PV HC assessment for geographically dispersed PVs	PV
[88]	IEEE-69 MV grid	Voltage constraints and transformer overloading	Stochastic and deterministic approach	DERs
[89]	A rural distribution grid in South Australia	Reliability, power quality, and electricity tariff	Community-based BESS	PV

2. Methods

EV hosting capacity analysis involves considering multiple scenarios and uncertainties related to existing loads, EV load profiles, and residential PVs present in the network, as shown in Fig. 2.

There are four basic steps in the HC analysis method: i) creating scenarios DER deployment, ii) running an algorithm for observing feeder responses, iii) checking violation to identify hosting capacities, iv) applying HC enhancement techniques [100]. This research explores challenges and innovative solutions in estimating and enhancing EV HC within distribution networks. The study used recent literature and industry reports relevant to the hosting capability studies while selecting resources. The methodological steps in Fig. 3 indicate different phases in analyzing EV hosting capacity.

2.1. Deciding on the use case

The required level of accuracy for HC analysis depends on specific use cases and intended applications. Defining use cases is the first step affecting the choice of method and tools for EV HC analysis. Only the technical challenges and solutions are discussed in this study excluding economic and environmental factors of EV hosting capabilities. The use cases are as follows-

- Purpose of EV HC analysis: The primary objectives of conducting EV HC analysis are to optimize EV integration and enhance the

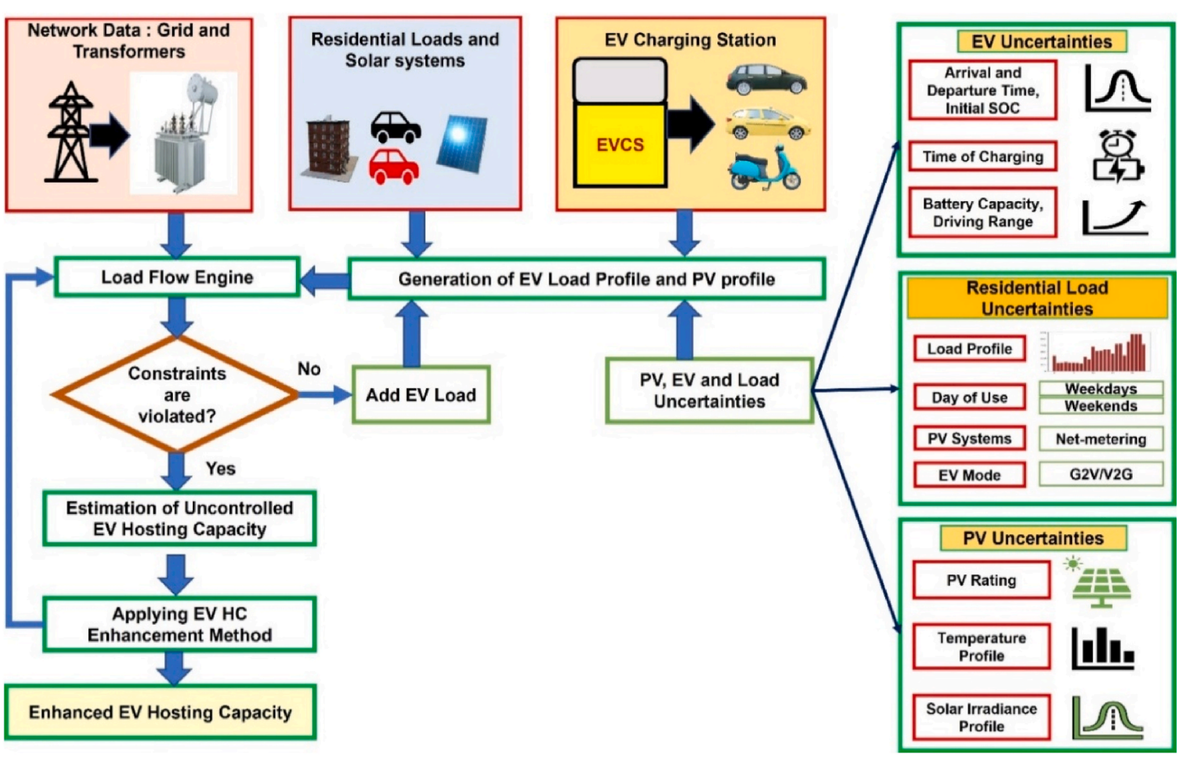


Fig. 2. Overview of EV hosting capacity assessment and enhancement.

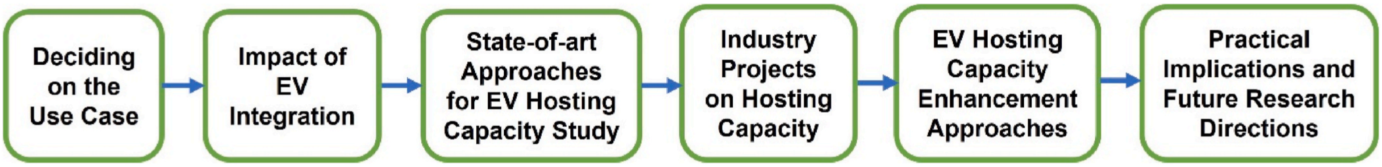


Fig. 3. Methodological steps for reviewing EV HC assessment and enhancement.

robustness of network augmentation planning. The HC estimation methods will be explained in Section 3.0, depending on scenarios, data needs, availability of tools, accuracy, and computational burden. The EV HC enhancement techniques must have techno-economic viability for accommodating higher EVs in the distribution networks, especially focusing on stakeholder-focused adaptive solutions, as described in Section 4.0.

- Scalability and practicality: Underscores the importance of conducting EV HC studies on real distribution networks, focusing on the granularity of specific feeders and addressing various uncertainties.

3. EV hosting capacity assessment

This section comprises a discussion of the impacts of EV charging, existing HC assessment methods, a review of EV HC studies, and industrial projects.

3.1. Impacts of EV charging

The impact of EV charging with different charging levels, such as Level-1, Level-2, and DC fast Level-3 charging in the distribution grid, is classified into positive and negative [101]. Table (2) depicts the positive techno-economic and environmental impacts of EV integration in the distribution grids, as evidenced by the existing studies.

The positive impacts of EVs include improving grid stability, managing renewable intermittence, reducing emissions, and saving transportation costs. Indeed, the grid HC can be significantly enhanced by adopting energy-transferring technologies, particularly in peak hours [11]. In contrast, negative impacts breach performance constraints can decrease the grid HC [96]. Table (3) reviews the detrimental effects of EVs and DERs in the distribution grid, indicating key performance indicators.

Most studies focused on voltage fluctuations, and a few concluded thermal overloading, harmonics, power loss, voltage unbalance, and reverse power flow were performance indicators. Careful selection of constraints is essential for a comprehensive overview of network HC, as claimed in studies [8,5]. A sensitivity analysis is necessary during EV HC estimation to identify the most influential performance indicators.

3.2. EV hosting capacity assessment methods

HC assessment employs two main approaches: simulation-based and optimization-based. The selection of a particular method depends on study objectives, scalability, granularity, availability of data, and tools. Table (4) compares simulation and optimization-based approaches in HC analysis.

Existing studies categorize simulation and optimization-based methods into deterministic, stochastic, and streamlined approaches based on their chosen uncertainties and scenarios [7]. Each HC assessment method has merits and demerits, as presented in Table (5).

- Deterministic Approaches: This method emphasizes worst-case scenarios with predefined data, potentially overlooking dynamic DER behavior. Quasi-static-time-series (QSTS) analysis, a deterministic process, solves steady-state power flow problems suitable for small datasets and becomes computationally intensive in larger systems, capturing dynamic behavior. However, it predominantly addresses aleatory uncertainties while disregarding epistemic uncertainties in HC studies [96].
- Stochastic approaches: This approach accounts for intermittent generation and varied load profiles across multiple scenarios [10]. Stochastic HC methods such as Monte Carlo Simulation (MCS) reflect real-world conditions but may not yield optimal results. The stochastic HC method often assumes similar DER profiles and locations, resulting in inaccurate outcomes and increased computational time [21,102].
- Streamlined approaches: This method considers a few scenarios and prioritizes uncertainties to get the approximate HC with a relatively short computational time [39,103]. In this method, the load-flow analysis is done to find the initial network conditions, and then the constraint violation is checked for a specific period [40]. Initially, the streamlined approach was suggested by PG & E for distribution network planning to identify the HC values.

3.2.1. Simulation-based approaches

Simulation-based strategies involved load-flow analyses to evaluate voltage profiles, line and transformer loading, power loss, and voltage unbalance factors in different scenarios. This method offers flexibility and granularity by providing dynamic hosting capabilities [95]. However, these methods rely on significant computational time and extensive data, including network topology and load profiles, which can be challenging to collect.

Deterministic load-flow analysis is common in HC formulation for small-scale systems. For large-scale systems, accuracy and computational complexities arise due to the network topology [104]. In a practical distribution grid, a deterministic method is used for assessing EV HC, considering voltage limits, transformer overloading, and thermal limits [49]. Although it offers short computational time, HC, by skipping uncertainties, might be inaccurate for planning [37,104]. Besides, probabilistic simulation methods integrate multiple DER uncertainties to enhance accuracy and incorporate realistic scenarios with a significant computation burden [95,21,105]. In Ref. [103], a streamlined approach is used to predict hosting capabilities in distribution networks to reduce computational complexities. While streamlined HC evaluation studies offer rapid estimations, the choice of scenarios can impact the accuracy of the results, as claimed in Ref. [40].

3.2.2. Optimization-based approaches

Optimization-based methods aim to find the maximum HC through optimal power flow (OPF) while maintaining grid constraints [106]. These methods offer scalability and computational efficiency relative to simulation-based approaches, simplifying uncertainty models [107]. An OPF-based deterministic approach in PV HC analysis for worst-case scenarios with load changes as grid constraints showed faster computational times than simulation-based methods [107]. However, stochastic simulation-based optimization approaches have improved accuracy by incorporating uncertainties and many scenarios, as shown in Refs. [108,109]. In Ref. [108], net-load volatilities and uncertainties in renewables are considered when designing a multi-timescale stochastic optimization formulated, considering voltage, thermal, and load variation limits as performance indexes. Another study focused on stochastic optimization through a single objective function using voltage sensitivity analysis for PV HC assessment [109]. In Ref. [99], a multi-objective framework for optimizing EV HC through a demand response program is proposed, considering voltage and thermal limits in a microgrid. In most cases, voltage imbalance and fault current protection limits are absent in optimization-based HC studies.

HC analysis through OPF methods discussed OLTC [110], active power curtailment [51], reactive power compensation [111], power factor control [83], controlled EV charging [110], adding soft open points [112], and network reconfiguration [113] as control parameters. In a multi-objective optimization for HC formulation, the impacts of voltage regulators, battery energy storage systems (BESS), and static var compensators are identified for several scenarios to minimize energy losses [114]. Besides technical constraints, economic constraints must be included in HC analysis [111]. In Ref. [115], an OPF-based dynamic export limits for prosumers in distribution networks. However, all these scenarios deal with PV systems, while V2G effects need investigation.

3.2.3. Other approaches

In traditional HC studies, a lack of spatial and temporal uncertainties leads to inappropriate estimation [116]. To improve this, researchers have integrated spatial-temporal uncertainties into deep-learning models for online HC estimation [117]. In Ref. [118], using second-order conder programming to consider spatial-temporal uncertainties, a case study in a rural distribution network is carried out to enhance PV HC for only voltage violations. In HC analysis, two uncertainties must be managed-possibilistic and probabilistic. To manage uncertainties, fuzzy-MCS methods have been used in a few studies [119, 120], providing faster computation, higher accuracy, and superior uncertainty modeling. A study used fuzzy-MCS for risk analysis and resource planning [119], including probability distributions for aleatory and epistemic uncertainties [121]. Another research on freight transport forecasting in Slovenia found that the fuzzy-MCS approach provided the best-fit model for actual data [120].

Fig. 4 shows the proposed hybrid fuzzy-MCS technique for EVHC analysis. The probability density functions of random variables X1 and X2 from continuous monitoring of data and fuzzy variables *Z1*, *Z2*, and *Z3* are extracts from previous experience and historical data. In EV HC analysis, driving distance, battery capacity, charging period, and levels may be used as fuzzy variables. In contrast, plug-in and out time, initial state of charge (SOC), solar irradiation, and temperature profile can be considered random variables.

3.3. Review of EV HC assessment studies

In Table (6), EV HC studies are summarized in terms of methods and network, considered EV parameters, research outcomes, and future research directions. Actual grid data, residential and commercial appliance data, and data regarding renewable resources integration and EV loading characteristics are required to assess HC accurately.

HC calculation for accommodating DERs into the distribution grid is performed in many research using different approaches such as deterministic (iterative and time-series approach) [49,23,36,104,51,47, 122–124], probabilistic MCS approach [90,95,10,100,26,29,30,102,40, 38,41,44,45,125–131], QSTS approach [8,96,46,132], streamlined approach [39,103,106], optimization approach [31,35,107,133–135], and few other approaches [55,24,32,33,136–141]. Fig. 5 presents a statistical summary of HC assessment methods, indicating that the probabilistic MCS approach is the most prevalent, followed by the deterministic approach.

Other approaches included in this study are mixed integer linear programming, interval and affine arithmetic method, heuristic approach, the hybrid of the conventional techniques, Fast-Fourier transform-based approach, ML, and DL approaches.

3.4. Artificial intelligence in EV HC assessment

Researchers and industries are looking for innovative AI-based HC analysis approaches with the rapid expansion of DER and EV penetration. Table (7) summarizes the AI technologies for DER integration in the distribution grid, indicating methods, networks, objectives, and findings.

3.5. Available tools for HC analysis

The choice of tool depends upon the objectives, data requirements, technical and operational constraints, methodology, and computational time. Most commercial software can perform balanced and unbalanced load-flow analysis, state estimation, and dynamic simulation (Electromagnetic transient -EMT, and RMS- Root Mean Square or Phasor). In contrast, open-source software has a co-simulation platform for customizing the simulation environment for more accessible analysis in distribution system planning. HC calculation typically uses distribution planning tools such as CYME, Synergi, or Windmill. These tools enable

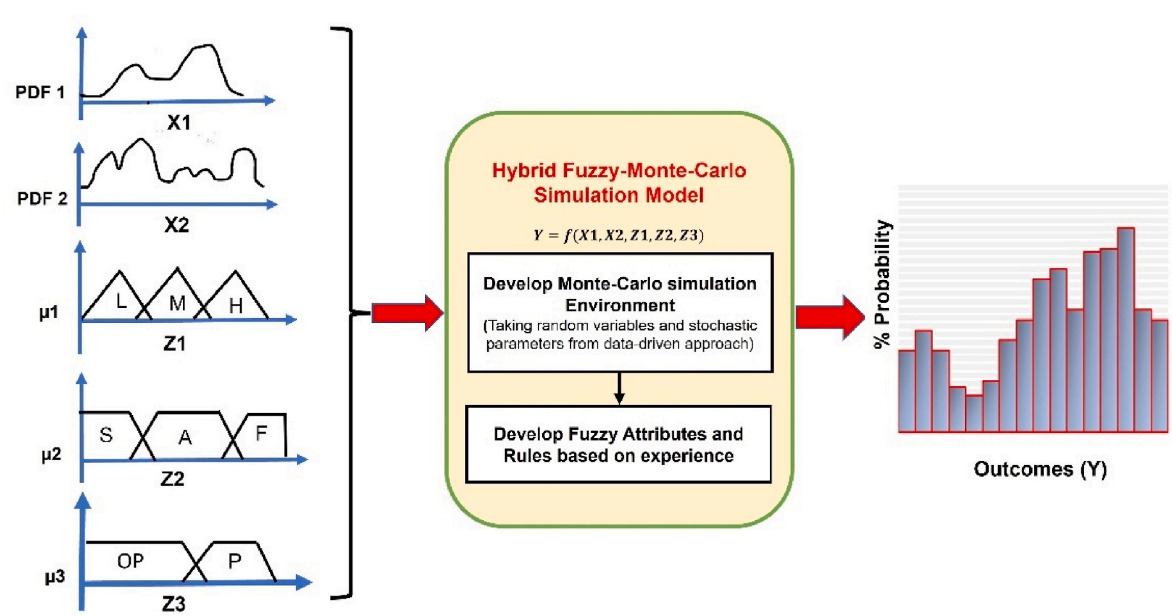


Fig. 4. Hybrid Fuzzy-MCS Simulation technique.

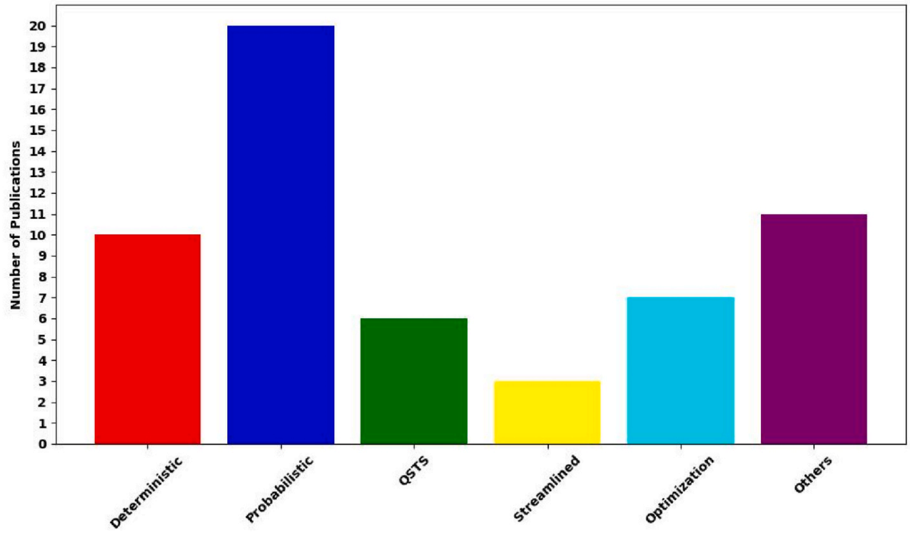


Fig. 5. Statistics of publications regarding HC assessment methods.

the simulation of each circuit node using an iterative approach and look for desecrations during each reiteration of the simulation. Electric Power Research Institute (EPRI) has also industrialized software named "Distribution Resource Integration and Value Estimation (DRIVE)" to calculate HC, enabling grid and load data from SCADA and AMI.

PSS Sincal uses an iterative time-series method, considering a few scenarios requiring significant computational time. Besides, a Dig SILENT Power factory is appropriate for planning for defining long-term load and generation profiles. Another tool, CYME, uses an iterative and streamlined approach for HC analysis. While load-flow engines, i.e., Dig Silent and OpenDSS, do not inherently manage optimization tasks, customizing options with MATLAB and Python provide flexibility to incorporate optimization routines. This integration enables users to leverage simulation tools and conduct advanced optimization tasks within a unified framework, facilitating industry-standard solutions. Table (8) displays commercial and open-source tools used for load-flow analysis in the HC estimation, sourced from providers' websites.

3.6. Industrial hosting capacity projects

Research and industrial projects run worldwide for EV HC estimation and improvement using advanced technologies. As of April 2021, 70 subnational and city governments of the world declared 100% zero-emission vehicle targets by 2050 [142]. Also, more than ten of the world's largest equipment manufacturers announced a huge investment in the EV sectors by 2030 and beyond. The Interstate Renewable Energy Council (IREC), USA, has actively engaged in network HC visibility projects showing a snapshot of the network HC throughout different cities, including California, Colorado, Massachusetts, New York, Nevada, and Minnesota [97]. Many utility companies in North America have already established HC analysis methods and regularly published the results in heat maps or tabular format for usual operation. Most projects assess PV HC, although only a few are engaged in EV HC assessment. Table (9) summarizes the international HC projects, describing methods, objectives, and results.

3.7. Australian hosting capacity projects

Globally, Australia is leading in deploying solar home systems, with nearly 3.4 million installations [7]. Meanwhile, EV sales are increasing nationwide due to government incentives and priorities. Therefore, distribution system planners are looking for scalable methods for HC estimation and amendment in renewable-rich distribution networks [7]. Different Australian states set individual targets of attaining net-zero emissions in the transport sector by 2050. Besides, one of the largest coal-fired energy companies has already applied to close its operation in 2025 and developed a plan to install a 700 MW battery storage system powered by renewables [143]. Fig. 6 shows public EVCS with fast charging (≥50 kW) and regular charging (<50 kW) in different states of Australia [144]. There are 356 fast/ultra-fast and 1791 regular public EVCS available in Australia. EV HC assessment is essential for the renewable-rich distribution grids as the number of charging stations increases.

Australian industries and universities have conducted trials to comprehend the effects of DERs on the grid. Government incentives encourage EV adoption and household DER connection, aligning with a net-zero emissions goal. Hence, the various projects are looking for solutions to the problems leveraging due to the DERs integration.

Fig. 7 shows the fund estimated for EV projects in Australia supported by the Australian Renewable Energy Agency (ARENA). Fourteen of the ARENA-funded projects until 2022 are for establishing charging infrastructures in Australia, where less importance has been given to EV HC assessment and enhancement. Also, diversity in EV models, charging facilities, and network settings in Australia and other countries facilitates the need for region-specific HC analysis. Table (10) demonstrates the impact of industrial projects on EVs and DERs, HC enhancement technologies based in Australia, funded by ARENA.

Most Australian HC projects performed a deterministic approach, whereas a project led by the University of Melbourne uses hybrid methods [145,146]. The report describes the PV HC estimation of a distribution grid based on historical data. Also, this report focuses on using a smart-meter-driven approach along with both traditional methods (network reconfiguration) and non-traditional methods (PV inverter controlling, use of voltage regulators, and BESS) for HC enhancement [147]. A DER hosting capability project improves network visibility, mapping, and reliability in grid planning by addressing network constraints [148]. In another project, to increase HC, phase shifting and power compensation devices have been installed on the Jemena and AusNet Services networks [149]. The Australian Energy Market Operator (AEMO) proposes increasing LV network visibility and understanding standards to increase DER penetration [150]. Table (11) reveals the industry projects headed by the Center for New Energy Technologies (C4NET), Australia [151].

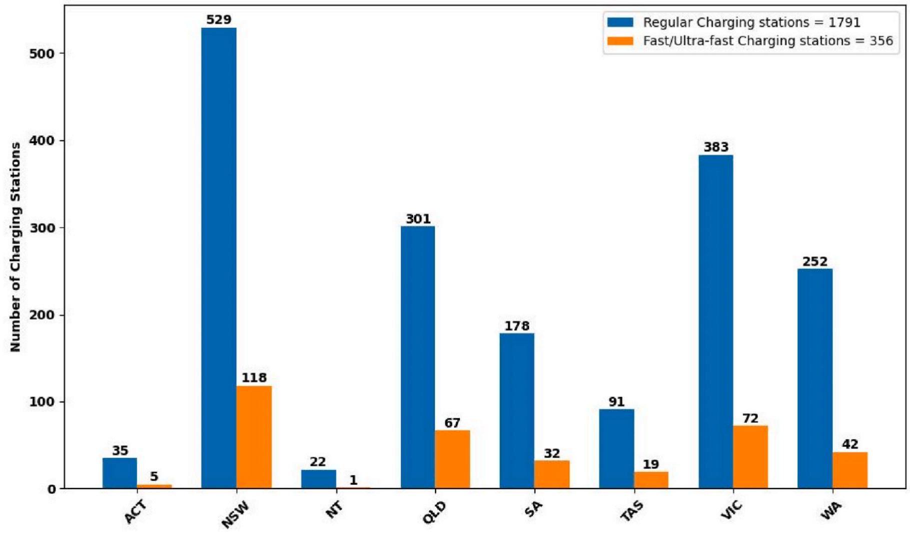


Fig. 6. EVCS (regular and fast/ultra-fast charging) in Australia.

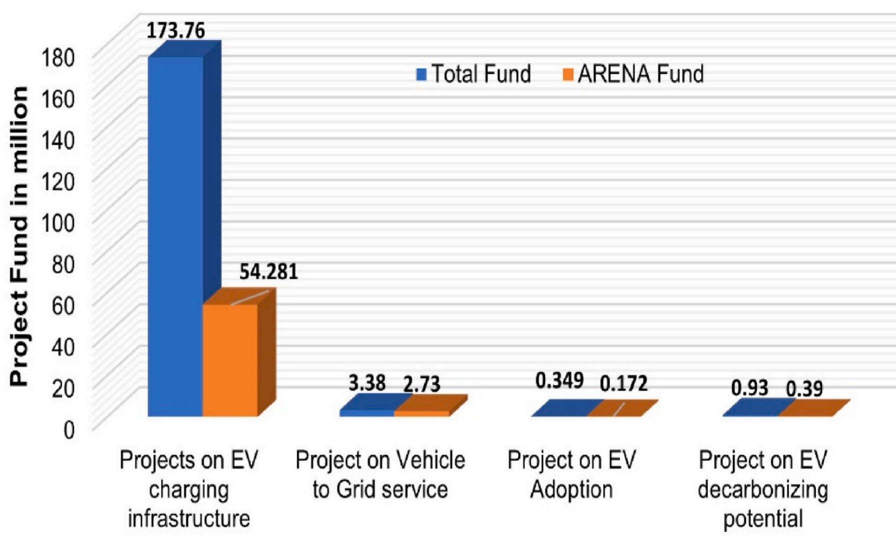


Fig. 7. EV projects in Australia funded by ARENA from 2017 to August 2022.

4. EV HC enhancement techniques

The areas identified for improvement to maximize HC are controlling active/reactive power, harmonics mitigation, use of OLTC transformers, battery storage technologies, and network reinforcement [3,6]. Fig. 8 shows existing techniques grouped for EV HC enhancement. In Ref. [152], stakeholder-centric solutions are proposed where the effectiveness of these solutions varies with technology readiness, investment costs, and stakeholder acceptance. Table (12) represents existing HC enhancement studies comprising network parameters and methods.

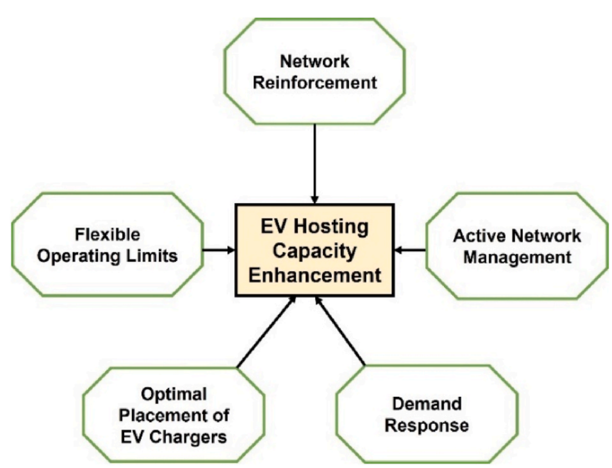


Fig. 8. EV hosting capacity enhancement strategies.

4.1. Active network management

The active network management approach is well-established in managing and optimizing distribution network operations in real-time or near real-time to enhance grid stability. These techniques are used in distribution networks to control voltage fluctuations, power loss, voltage imbalance, and protection issues [153]. Coordinated control techniques comprise energy storage systems, OLTC transformers, smart inverters, and switching capacitors [154]. In Ref. [155], Volt/Var control is considered an economical method for HC enhancement but may not address all violations with high DER penetration.

Another study explores phase shifting control in real UK residential networks with EV integration, reducing the Undervoltage probability, though it's not ideal for single-phase users [156].

In [90], authors suggest improving EV HC through voltage regulation, power factor control, and managing charger demand without considering customer benefits. Another study concentrates on controlling reactive power injection to maximize EV penetration in the IEEE-13 test network, primarily addressing voltage violations [81]. Authors in Ref. [55] recommend balancing PV exports and EV charging in a distribution network, employing smart charging technologies and PV curtailment. Another investigation [5] examined a distribution network featuring OLTC transformers and public charging stations to enhance PV HC. While several approaches proposed in existing studies, implementation complexities and high costs often hinder practicality in industries. Additionally, many distribution networks lack smart technologies, making it challenging to adopt those strategies solely based on theoretical validation.

4.2. Optimal placement methodologies

Random placement affects the distribution network by increasing the chance of violating constraints during DER integration [157]. Several DNSP-focused micro-level approaches are used in existing studies to allocate EV chargers in distribution networks and mitigate voltage violations and power losses [125]. However, managing residential chargers considering other performance constraints is essential. Also, most of the works are validated in test networks, which needs validation in real networks. The EV charger distribution should be done after assessing stochastic HC. Integration of diverse uncertainties and customer-centric solutions is required to promote EV adoption.

4.3. Flexible operating limits

In low-voltage networks, fixed export limits from residential PV systems were commonly used to control power exports from prosumers [158]. However, this approach often failed to maintain network integrity, resulting in prosumers receiving fewer benefits. Introducing V2G services could be too restrictive in such networks with fixed exports. Export management is crucial for network operators to enhance grid performance, especially during peak hours [11].

Uncontrolled exports from prosumers may negatively impact grid stability by causing voltage imbalances, thermal overloads, and overvoltage issues [96]. Flexible operating limits offer a solution by providing variable export options over time while monitoring performance constraints, described in Fig. 9. This approach can potentially strengthen the network and improve EV hosting capabilities [115]. However, it may not consider diverse capacities and nodal strength, which could discourage prosumers from investing in clean energy technologies. To address this, flexible solutions that are prosumer-centric and accommodate both export and import limits are essential to ensure that prosumers remain motivated to accept clean energy technologies.

4.4. Demand response

Demand response is a stakeholder-centric strategy for enhancing EV HC and actively managing consumption patterns, including EV charging in response to grid constraints [99]. Research at the California Institute of Technology and an industry 'PowerFlex Systems' proved that adaptive charging networks can resolve detrimental issues using a fixed limit for the EVCS [159]. In that project, they designed an adaptive charging scheduling system that provides a 300-kWh fixed power limit irrespective of the requested EV demand. Authors in Ref. [99] proposed a hierarchical two-level optimization framework for demand response by dynamic pricing schemes in a microgrid. A prosumer-focused ancillary service shows the potential to increase hosting capabilities in a study [160].

4.5. Network reconfiguration

This method has been widely practiced and investigated for improving grid resilience. Network upgradation requires improvement in distribution transformers, lines, and voltage regulators to accommodate growing loads. Integration of SCADA and AMI data in distribution system modeling provides clear visibility through the locational map of the network and enhanced HC [3]. In Ref. [161], authors suggest an increase of 1.4 cents/kWh tariff for infrastructure upgrades to support EV charging in a network serving 2–3 million customers. The rapid fluctuations in EV adoption rates and associated technologies make it challenging to estimate upgrade costs accurately. Detrimental impacts can be mitigated by allocating EV chargers in strong nodes and co-locating with renewable-based generators [157]. Reconfiguring urban distribution networks to enhance their strength is challenging due to complex interconnections among networks in densely populated areas. In a network reconfiguration method, authors presented optimal conductor replacement with different DER loading scenarios, which is expensive and time-consuming [162]. Hence, this approach should be used when other methods cannot ensure the distribution network's stability.

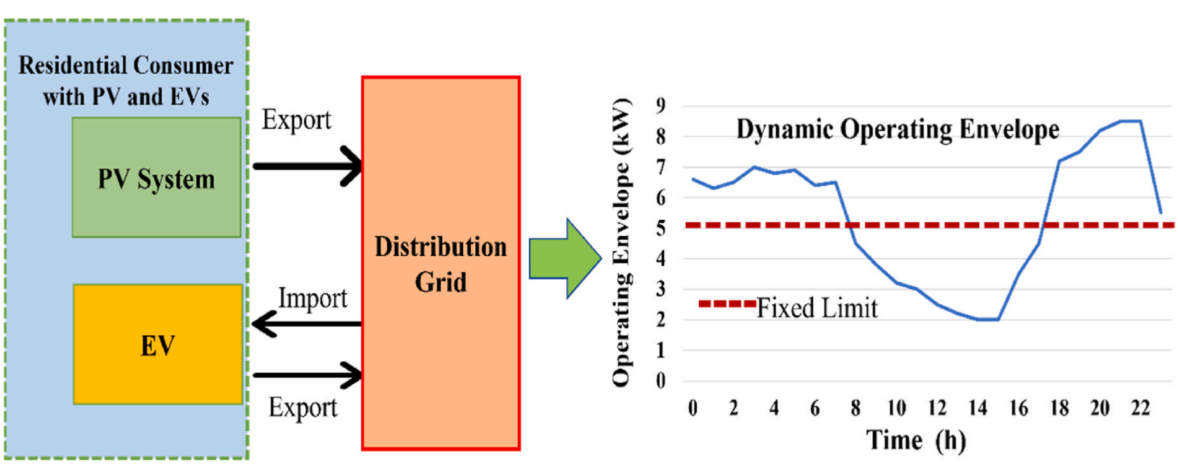


Fig. 9. Increasing EV hosting capacity using dynamic operating envelope technique.

5. Discussion

5.1. Summary of findings

Accurate measurement of techno-economic factors in EV HC calculations is essential for informed grid planning, resource allocation, and sustainable solutions for current and future needs. This section highlights several challenges and use cases that need to be considered during EV HC analysis. Table 13 shows the challenges for EV HC of the distribution system by use-case analysis.

The findings from existing research and industry reports regarding estimating and enhancing EV HC in distribution networks. The outcomes are outlined in the following.

- Considering single performance constraints, EV HC results may lead to inappropriate results. In most EV HC studies, voltage and thermal overloading limits are considered, where the inclusion of power loss, voltage imbalance, and protection is important.
- EV HC estimation methods should consider data needs, accuracy, computational complexities, and the uncertainties involved in EVs, loads, and rooftop PVs in distribution networks. This review proposes a hybrid fuzzy-MCS EVHC analysis method, as shown in Fig. 4, for logically incorporating uncertainties and scenarios for better accuracy.
- Based on the statistics of Fig. 5, most HC studies used a probabilistic approach for more accurate estimation, requiring a large computational burden. A few studies used a streamlined process requiring small cases and computational load. Hence, an innovative method considering the accuracy and computational burden is needed.
- As the EV penetration is evolving, the plugin uncertainties and market sales data might differ in regions; hence, it is necessary to analyze and cluster EV data before applying it to HC analysis.
- Worst-case scenarios are mostly reported in existing EV HC studies where other cases consideration is required for producing dynamic hosting capabilities in the distribution networks. The selection of cases affects accuracy and computational burden in EV HC simulation.
- The type and location of EV chargers in distribution networks affects EV HC, which should be considered in future studies.
- Regulatory limits of performance constraints differ in recent EV HC studies [90,96], which need standardization focusing on diverse charging levels and plugin uncertainties.
- Commercial tools usually employ iterative and streamlined approaches with limited performance constraints and worst-case scenarios, often resulting in inaccurate HC estimation. This study recommends using AI-enabled hybrid methods for faster and more accurate assessment.
- Scalability testing and validation in real distribution networks are essential, as existing studies predominantly work with standard test feeders.
- Industry projects investigated in this research mostly report PV HC in distribution networks, dealing with overvoltage issues. Besides, EV HC usually incurs undervoltage problems. Hence, EV HC estimation in renewable-rich distribution networks is crucial.
- Around 90% of DER projects in Australia dealt with EVCS installation, where HC estimation and enhancement projects are essential.
- The existing HC enhancement studies are divided into five key areas: network reconfiguration, active network management, optimal placement methodologies, flexible operating limits, and demand response.
- Network reconfiguration is the key enabler of EV HC augmentation, which depends on network structure in various settings such as urban, suburban, and remote areas. Instead of network reconfiguration, flexible operating limits and active network management play a key role in augmenting hosting capabilities in distribution networks.
- Adapting novel AI-based data-driven technologies with smart metering infrastructure is advantageous in managing EVs and DERs in distribution networks.
- Data privacy and security issues may remain crucial while deploying smart metering and multi-directional communication among customers, charging stations, and operators of distribution networks.

5.2. Future research directions

- **Availability of Datasets for EV Load Profile:** EV Hosting capacity calculation requires an EV load profile based on energy demand and plug-in uncertainties [94]. Many EV datasets are unsuitable for HC calculation, having fewer uncertainties and differences in demographic profile (population, area, weather, road conditions, driving behavior) and economic profile (annual income, charging tariff). In addition, privacy and legal issues must be considered before using the data related to network, customer loads, and renewable integration in HC calculation. Only a few synthetic datasets based on gasoline vehicles are available online for researchers and industry use [94]. Along with EV loads, household PVs and other non-linear loads are responsible for power quality problems; hence, incorporating real-time data using AMI and SCADA systems is essential [138]. Updating household load data in the distribution network databases improves data quality and leads to more accurate HC estimation [38].

- **Accuracy and Computational Time:** The accuracy and computational burden vary with the data quality, methods, and tools employed in HC assessment. In a few HC estimation studies, network topology, renewable resource data, and EV data are utilized considering the worst-case scenario and limited performance constraints, which affect accuracy [3,5,6,4]. Deterministic methods have less precision and small computational time for worst-case studies bounded by local regulation [37]. Besides, stochastic and streamlined processes have higher accuracy and significant computational

Table (13)
Challenges for EV HC analysis (use case analysis).

EV HC (Use case and benefits)	How will it work?	Challenges
Support EVs and DERs integration	❖ Identify the impacts and performance constraints ❖ Assessing HC without network upgradation. ❖ Considers uncertainties and charging strategies to comply with the standard.	❖ Real-distribution system data is required. ❖ The assumption and use of the conventional methodology ❖ Computational time and accuracy
Support advanced distribution grid-planning	❖ Considers growth of EV, renewables, and BESS ❖ Estimate the future network upgradation costs ❖ Includes commercial tools for HC analysis	❖ Regulatory standards may be incorporated. ❖ Data recording, forecasting, and HC enhancement technologies can be included. ❖ Scalability and validation testing are needed in different networks.
Support modernization of the distribution grid	❖ Strong cooperation among stakeholders ❖ Regular updates of EV and renewable portfolio ❖ Data visualization and smart network analysis	❖ It needs a long-term goal and roadmap ❖It requires a new business process and data governing operations to control capacities.

time due to simulating many scenarios [8,21,102]. Therefore, an efficient algorithm is necessary to improve accuracy and reduce computational time.

- **EV Clustering:** Research performed EV HC assessments only for selected EVs, although many are available in the markets [90,96]. Due to diverse EV models, the type of EVs integrated into the distribution network is uncertain. Therefore, it is crucial to classify EV groups from available models before proceeding with the HC estimation process.
- **Selection of Performance Indexes:** Voltage fluctuations, voltage unbalance, harmonics, thermal overloading of lines and transformers, power loss, and protection device coordination are considered in HC calculation [22,10,23,27,30,102,45,48]. Considering limited performance constraints may overlook violations in other indexes, which might be detrimental to distribution networks. In Ref. [34], the authors described both commonly applied parameters (voltage limits, thermal overloading, reverse power flow, rapid voltage changes, and voltage regulators operation) and advanced parameters (protection coordination and harmonics) are needed for HC analysis.
- **Scalability of the HC Analysis Method:** Conventional HC assessment methods are often applied in standard test networks [3,42]. Only a few are evaluated and benchmarked in the real-distribution network with limited constraints and scenarios. Hence, investigating the scalability of the EV HC estimation is needed to adapt to real-world problems.
- **Lack of Commercially Available Tools**: Distribution network planners are looking for suitable and commercially available tools for HC analysis. Table (8) mentions the commercially available tools employing iterative and streamlined approaches with accuracy and computational time problems. Some utility companies integrated AI and probabilistic methods with geospatial and societal data to determine hosting capacity. These are in the early development stages and require rigorous testing and validation before becoming commercially available. Fig. 10 shows the commercial tool development and enhancement phases, utilizing smart devices to balance accuracy and computational load.

- **Network Modernization with Integrated Renewables**: Modernizing the grid with AMI and SCADA plays a vital role in HC analysis, offering a clearer view of the grid strength in data-driven methods [117]. In addition, network reinforcement and grid modernization require significant investment and time for network operators needing a standardization and process improvement policy framework for managing EVs. Instead of using standalone PV systems, hybridizing renewables may reduce the intermittency and cost of energy in EVCS [18]. In integrated renewable-rich networks, effective management of Electric Vehicles (EVs) and renewables relies on network visibility, a goal attainable through deploying and exploring smart devices.

- **Optimal Placement of Charging Stations**: The worldwide increase in EV sales requires many charging stations, although these are insufficient. For instance, the Australian Capital Territory's state government has declared that 90% of transport vehicles will be EVs by 2030. Only five fast and twenty-nine regular charging stations have been established [163]. This insufficiency compels the EV owners to use residential charging, reducing the overall HC in LV residential networks. Also, the location and availabilities of charging stations should be convenient for EV users to foster transport electrification and grid HC [157].
- **Dynamic operating limits for HC enhancement**: Dynamic export limits for prosumers from PV or V2G positively impact managing load demand and improving HC. However, defining flexible export limits based on stakeholder benefits is essential to foster energy-transferring technologies and HC enhancement instead of expensive network reconfiguration [99]. However, defining flexible export limits based on stakeholder benefits is critical to enable energy-transferring technologies and HC enhancement instead of costly network reconfiguration.

5.3. Practical implications and limitations

The practical implications of this study extend beyond distribution networks to include other stakeholders such as EVCS owners, customers, and policymakers. As the EV deployment is in the early stages, grid planners and policymakers may utilize this study to develop strategic planning for large-scale penetration. The DNSPs can enhance resilience by knowing conventional hosting capacity and optimizing investments in network augmentation. Also, understanding network HC, EVCS placement, and scheduling can be developed. The innovative HC expansion solutions are proposed in this review, offering substantial techno-economic and environmental benefits to the stakeholders. This study suggests active network management, flexible operating limits, and demand response programs as post-network reinforcement measures to enhance EV HC, potentially promoting transport electrification. The future research directions highlighted in this review will be valuable for researchers and industries dealing with the EV hosting challenges in distribution networks.

This study primarily focuses on EV integration within distribution

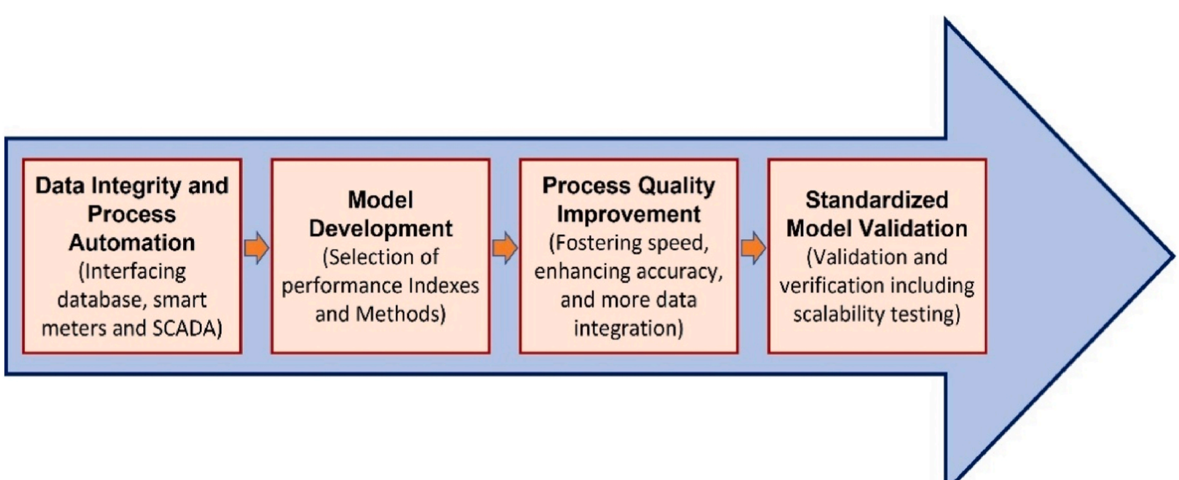


Fig. 10. Future enhancement process for commercial tool in HC Analysis.

networks while acknowledging the influence of other clean energy technologies on hosting capacity. Although EV integration involves diverse stakeholders, this review is mostly limited to distribution network operators and customers. This review paper limits the studies from literature and industry reports on hosting capacity spanning 2014 to 2023 using Google Scholar and Scopus web searches. Also, industrial HC projects in a few international and Australian contexts are summarized in this paper, acknowledging that these findings may not precisely reflect the situation in other countries. This study considers the technical aspects of EV HC, excluding economic and environmental impacts. Additionally, it has a limited temporal and geographic scope when reviewing relevant HC studies and projects.

6. Conclusion

This review provides a systematic overview of two key aspects: the conventional methods and the role of AI technologies in estimating and enhancing the EV hosting capabilities in distribution networks. While reviewing HC assessment strategies in existing literature, it was observed that researchers primarily focused on a limited set of performance indicators, often resulting in inaccurate calculations. In this study, a thorough literature review is conducted to determine key performance constraints, including voltage fluctuations, voltage unbalance, power quality issues, transformer overloading, reverse power flow, and fault-current protection, to provide a more comprehensive and accurate assessment of EV HC in distribution networks. It is also observed that the speed and accuracy of the EV HC analysis depend on scenario selection and uncertainty modeling. AI technologies (data-driven approach) with traditional methods in HC calculation show reduced computational time and enhanced accuracy. Although advanced methodology undoubtedly improves computational efficiency regarding execution time and accuracy, meeting data requirements (residential loads, diverse EV profiles, household renewables, and battery storage systems) for HC calculations is a significant challenge.

This study highlights international and Australian HC projects, primarily focusing on PV penetrations, where EV HC projects are essential for planning transport electrification. In addition, region-specific EV HC analysis in renewable-rich networks is crucial due to having diversity in EV models, charging facilities, and network topologies in different regions.

Several promising solutions for enhancing EV HC are outlined in this study, consisting of active network management, flexible operating limits, demand response, optimal placement methods, and network reconfiguration. The need for stakeholder-centric solutions is encouraged in this research to foster clean energy technologies in distribution networks. Also, the use of smart devices in network infrastructure to improve visibility and HC is discussed in this review.

Finally, the future research scopes for EV HC analysis in the distribution networks are discussed, emphasizing sensitivity analysis, selection of multiple constraints, reliable tools, realistic EV data, and use of hybrid renewables. With the concurrent PV-EV integration in residential distribution networks, there is a growing need for combined HC analysis in future studies. In future studies, it is also essential to consider customer data privacy, legal issues, and policy framework while deriving hosting capacity. This study does not consider economic and environmental factors in EV HC analysis. The authors expect this review will be beneficial in identifying the research gaps and development constraints for the researchers and distribution grid planners, providing up-to-date information on EV HC calculation.

CRediT author statement

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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.

Data availability

No data was used for the research described in the article.

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