JIBAS

Journal of Insights in Basic and Applied Sciences

Volume 1, Issue 1, 2025, Pages: 01-09

Journal homepage: https://jibas.com.ly/index.php/jibas/en

Accelerating the Green Transition: An Experimental Study on the Integration of Renewable Energy with Electric Vehicle Infrastructure

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تسريع التحول الأخضر: دراسة تجريبية حول دمج الطاقة المتجددة في البنية التحتية للسيارات الكهربائية

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Received: March 17, 2025	Accepted: June 05, 2025	Published: July 06, 2025

Abstract

The rapid growth of electric vehicles (EVs) presents both opportunities and challenges for decarbonizing transport. Integrating clean renewables into EV charging infrastructure can greatly enhance environmental benefits. This study reviews experiments and case studies of renewable energy (especially hydropower) powering EV charging networks globally. We examine real-world examples: from a Polish hydropower-EV analysis and a Korean PV/storage charging station study, to U.S. and European pilot projects using hydropower directly for EV charging. Global data show EV adoption surging (≈40 million EVs by 2023), requiring massive charging expansion (US needs ~182,000 DC fast and 1,070,000 L2 ports by 2030). We compare energy mixes: hydropower still supplies ~47% of global renewable generation, but in coal-heavy grids (e.g. Poland) EV charging may raise grid emissions. Analyses using HOMER and grid models confirm that adding renewables (PV, wind, hydro) to EV stations cuts CO_2 but raises costs. Coordinated EV charging control and hydropower dispatch can absorb solar/wind variability and reduce curtailment. Policy and practice must align EV rollout with new green generation. This paper concludes that coupling EV infrastructure with renewable supply (especially dispatchable hydro) is technically feasible and vital for deep decarbonization.

Keywords: Electric vehicles, renewable integration, hydropower, EV charging infrastructure, grid stability, real-world case studies.

الملخص

يُمثّل النمو السريع للمركبات الكهربائية فرصًا وتحدياتٍ في آنٍ واحدٍ لخفض انبعاثات الكربون في قطاع النقل. ويمكن لدمج مصادر الطاقة المتجددة النظيفة في البنية التحتية لشحن المركبات الكهربائية أن يُعزز بشكل كبير الفوائد البيئية. تستعرض هذه الدراسة تجارب ودراسات حالة حول استخدام الطاقة المتجددة (وخاصةً الطاقة الكهرومائية) في شبكات شحن المركبات الكهربائية عالميًا. ونستعرض أمثلةً واقعيةً: بدءًا من تحليل الطاقة الكهرومائية والمركبات الكهربائية في بولندا، ودراسةً كوريةً لمحطات شحن الخلايا الكهروضوئية/التخزين، وصولًا إلى مشاريع تجريبية أمريكية وأوروبية تستخدم الطاقة الكهرومائية مباشرةً لشحن المركبات الكهربائية. تُظهر البيانات العالمية ارتفاعًا كبيرًا في اعتماد المركبات الكهربائية (حوالي 40 مليون مركبة كهربائية بحلول عام 2023)، مما يتطلب توسعًا هائلًا في الشحن) تحتاج الولايات المتحدة إلى حوالي 182,000 تيار مستمر سريع و1,070,000 منفذ L2 بحلول عام 2030). وتُقارن مزيج الطاقة: لا تزال الطاقة الكهرومائية تُوفر حوالي 47% من توليد الطاقة المتجددة عالميًا، ولكن في الشبكات التي تعتمد

بكثافة على الفحم (مثل بولندا)، قد يُؤدي شحن المركبات الكهربائية إلى زيادة انبعاثات الشبكة. تؤكد التحليلات باستخدام نموذج هومر (HOMER)ونماذج الشبكة أن إضافة مصادر الطاقة المتجددة (الطاقة الشمسية، وطاقة الرياح، والطاقة الكهرومائية) إلى محطات السيارات الكهربائية يُخفّض انبعاثات ثاني أكسيد الكربون، ولكنه يرفع التكاليف. ويمكن للتحكم المنسق في شحن السيارات الكهربائية وتوزيع الطاقة الكهرومائية استيعاب تقلبات الطاقة الشمسية/الرياح، والحد من تقليصها. يجب أن تُوائِم السياسات والممارسات نشر السيارات الكهربائية مع الجيل الأخضر الجديد. وتخلص هذه الورقة إلى أن ربط البنية التحتية للسيارات الكهربائية بإمدادات الطاقة المتجددة (وخاصةً الطاقة الكهرومائية القابلة للتوزيع) أمرٌ ممكن تقنيًا وضروري لإزالة الكربون بشكل جذري.

الكلمات المفتاحية: السيارات الكهربائية، تكامل مصادر الطاقة المتجددة، الطاقة الكهرومائية، البنية التحتية لشحن السيارات الكهربائية، استقرار الشبكة، دراسات حالة واقعية.

Introduction

Electric vehicle adoption is accelerating worldwide. In 2023 nearly 14 million new electric cars were sold, bringing the global EV fleet to ~40 million. This boom in EVs (≈18% of new car sales) means electricity demand for transport is rising rapidly. To maximize climate benefits, that charging must draw on clean energy. Integrating renewables with EV infrastructure is thus critical. For example, in regions still relying on coal plants, high EV penetration can shift emissions from tailpipes to power plants. Globally, hydropower remains the largest renewable source (≈47% of renewable generation), offering a dispatchable resource to support EV charging when sun or wind are insufficient. This paper examines experimental studies and practical case examples of linking EV charging and renewable energy (especially hydropower). We synthesize published models, pilot projects, and data analyses to assess how renewable- powered EV stations can reduce emissions and improve grid flexibility.

Energy Mix and EV Demand: Motivations for Integration

The environmental payoff of EVs depends on the underlying grid mix. In some countries, electricity is still mostly coal and gas. For instance, in Poland over 80% of generation came from fossil fuels by 2020. Only ~2% of Poland's output was hydropower (Brown, et al., 2024). Figure 1 highlights this imbalance.

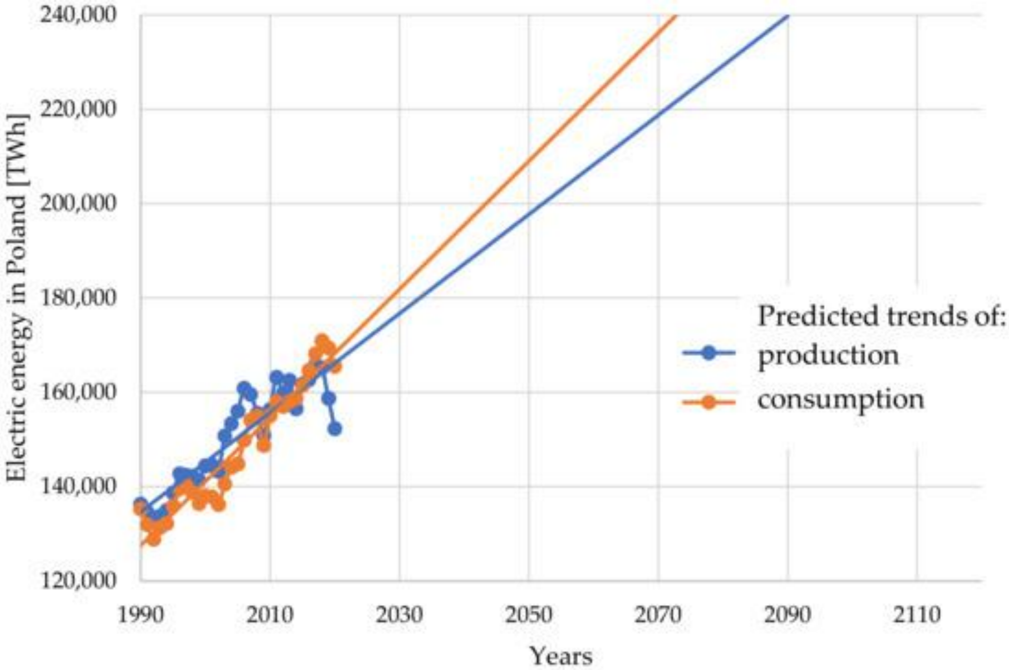

Figure 1 . Poland's electricity production and consumption (1990-2020). Coal and gas dominate supply,

This shows Poland's national production vs consumption. Roughly 80% of Polish electricity came from lignite, coal or natural gas by 2020. Only a few percent was hydropower or other renewables. If EV charging relies on this mix, CO_2 and pollutant emissions remain high. In a coal-heavy grid, shifting vehicles from fuel to electric means coal plants must burn more fuel to meet the extra demand. Thus adding renewables to the charging network is vital to truly cut emissions.

Planned renewables can help. Figure 2 compares hydropower and total renewable generation to overall output in Poland from 2000-2020.

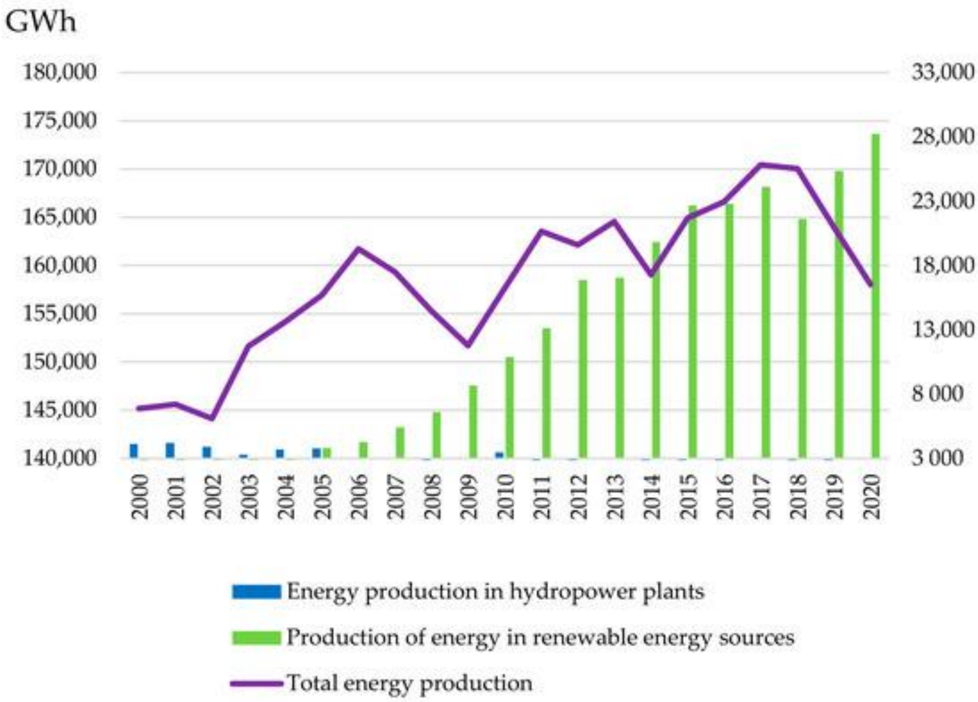

Figure 2 Poland's renewable generation vs total (2000-2020). Hydropower (dark blue) was a tiny share.

Poland's small hydropower output is evident - only about 1.8% of total energy. Total renewables (wind, solar, biomass) reached ≈10% of generation, but nearly all renewable growth came from wind and solar. Hydropower remained minimal. Expanding hydro (e.g. adding small dams on the Vistula River) could raise local green power supply. Figure 3 illustrates demand growth.

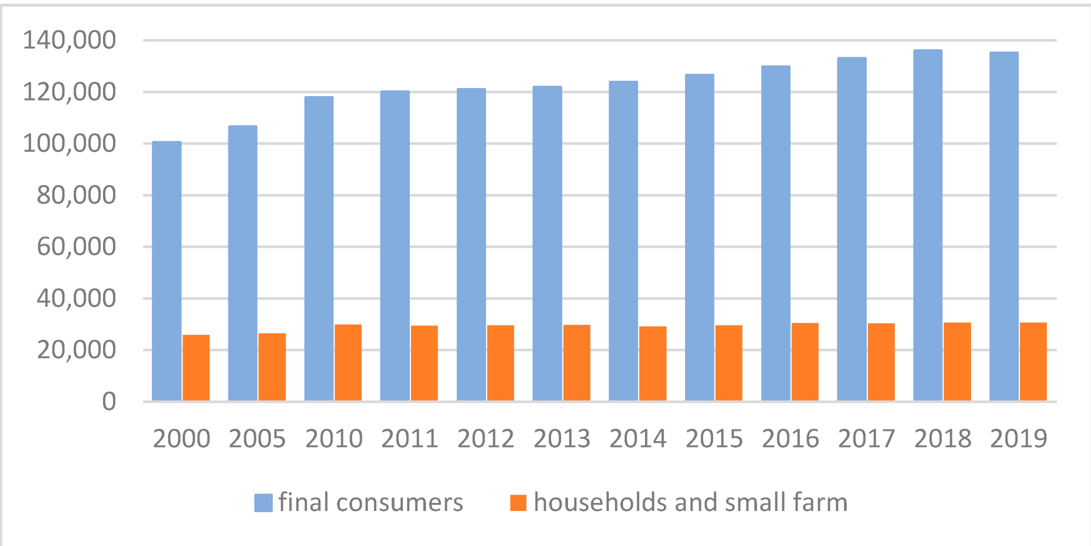

Figure 3 Poland's electricity production (blue) and consumption (orange), 2000-2020 with projections to 2100. Demand is rising sharply

Figure 3 projects that electricity demand will grow substantially. Models suggest that if EVs form a large share of vehicles, required generation jumps dramatically. One study found that charging 3.2 million EVs would add ~80 TWh/year to demand. In Poland's context, adding millions of EVs could force a 66% increase in output, requiring several new large power plants (Brown, et al., 2024).

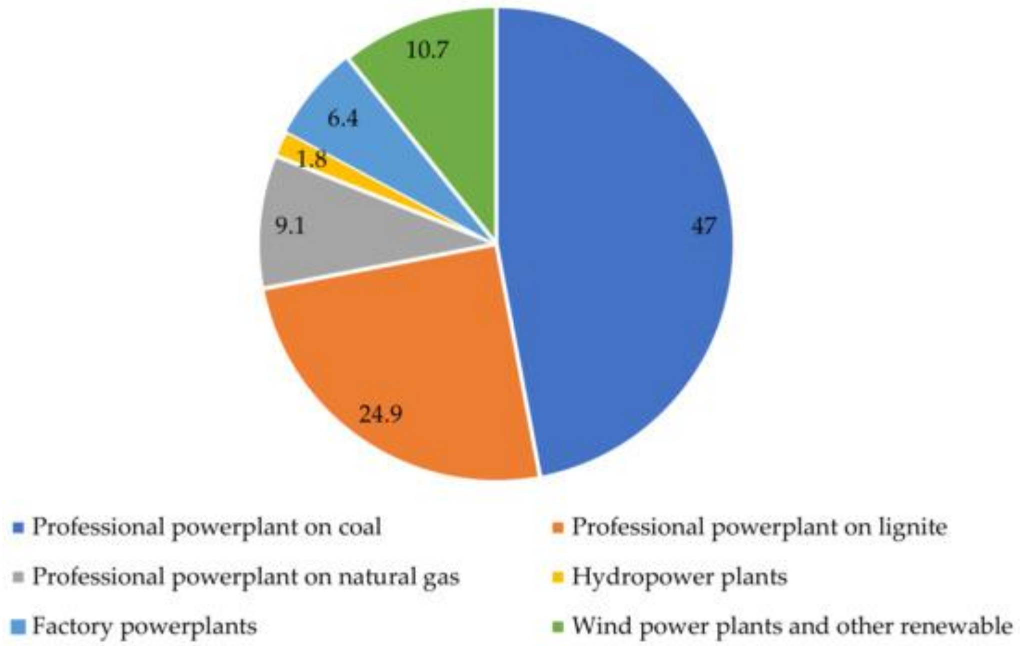

Figure 4 Poland's generation by fuel in 2020. Coal = 72%, gas = 9%, renewables ≈10%.

About 72% of Poland's power came from coal and ~9% from gas. Less than 10% was renewables (mostly wind/solar). Hydropower was negligible. Clearly, without adding renewable capacity, EV charging will burden the fossil generators. Figure 4 emphasizes the need for clean supply to meet new EV demand.

Hydropower and Renewable Potential

Hydropower can play a key role because it is dispatchable. However, Poland underuses its hydro potential. Only about 21.6% of its technical hydro resource is tapped. Plans are in place to add dozens of small projects on rivers (see Figure 5).

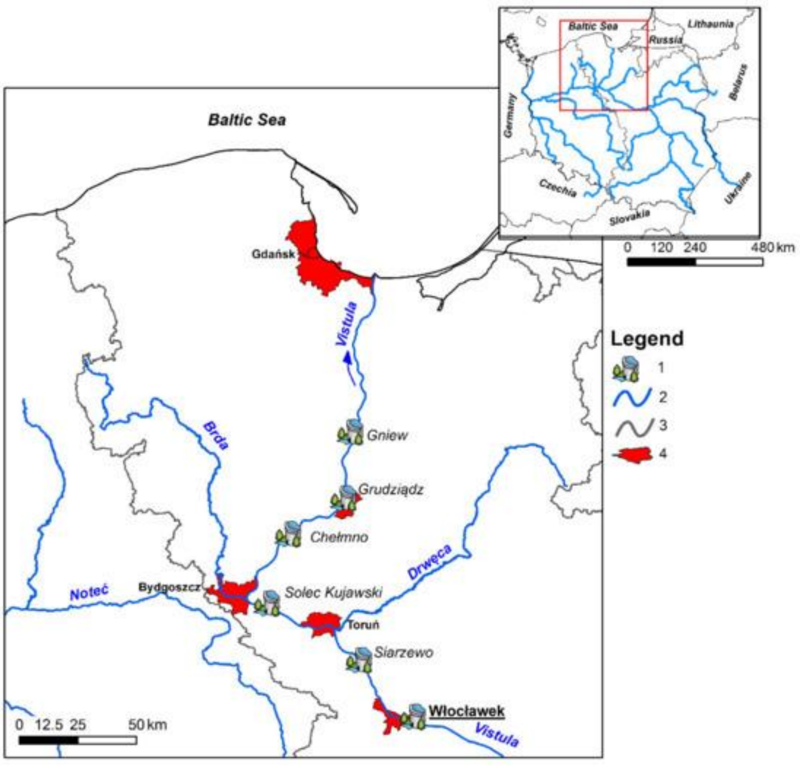

Figure 5 Planned hydropower stations on the lower Vistula River in Poland. (Legend: planned plants = 1) (Kubiak-Wójcicka, Polak, & Szczęch, 2022)

This map proposed hydropower plants on the Vistula River. Over 50 sites were planned, indicating large unused capacity. Realizing even some of these could deliver gigawatts of carbon-free power for EV charging and other uses. Figure 6 shows one example:

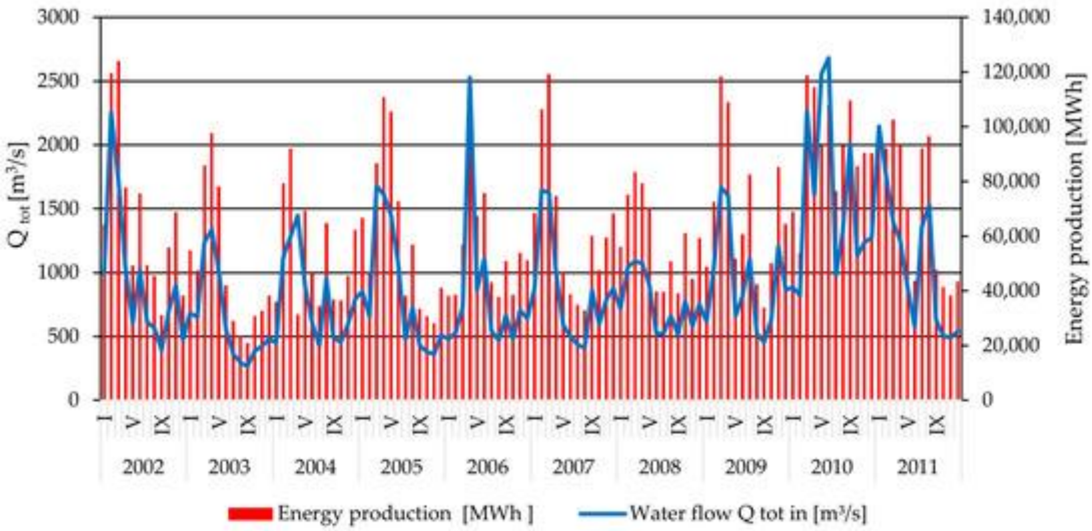

Figure 6 Output of Włocławek hydropower plant (2002-2011)afdc.energy.gov. It generated ~70 GWh/year on average.

This fig highlights the production of the 162 MW Włocławek dam. It averaged ~70 GWh per year - roughly 0.07 TWh. By contrast, total Polish generation is ≈160 TWh/year. Thus a single large plant yields only a fraction of national demand. Figure 7 compares aggregate hydropower to Włocławek.

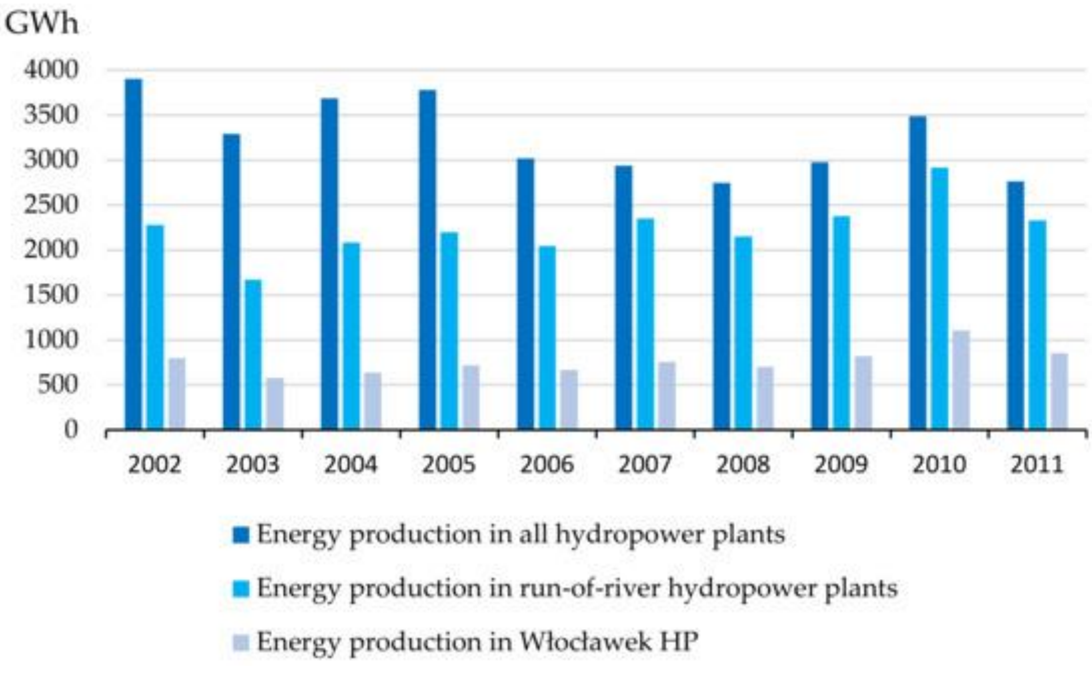

Figure 7 Poland’s total hydropower vs Włocławek (2002-2011). Total hydro (blue) is still <6 TWh/year, small versus demand.

Even combined, all Polish hydro produced <6 TWh/year (2002-2011). That was only ≈1.76% of total generation. This underscores that expanding hydro and other renewables is needed to meet EV-related load growth without relying on coal. Globally, hydro remains the backbone of renewables, providing nearly half of renewable electricity. In modernizing grids, coupling EVs with hydro-based microgrids or pumped storage can improve flexibility.

Global EV Charging Infrastructure Trends

Meeting EV demand requires huge charging networks. In the U.S., for example, a projected 33 million EVs by 2030 would need roughly 182,000 DC fast chargers (≥150 kW) and over 1,070,000 Level-2 chargers.

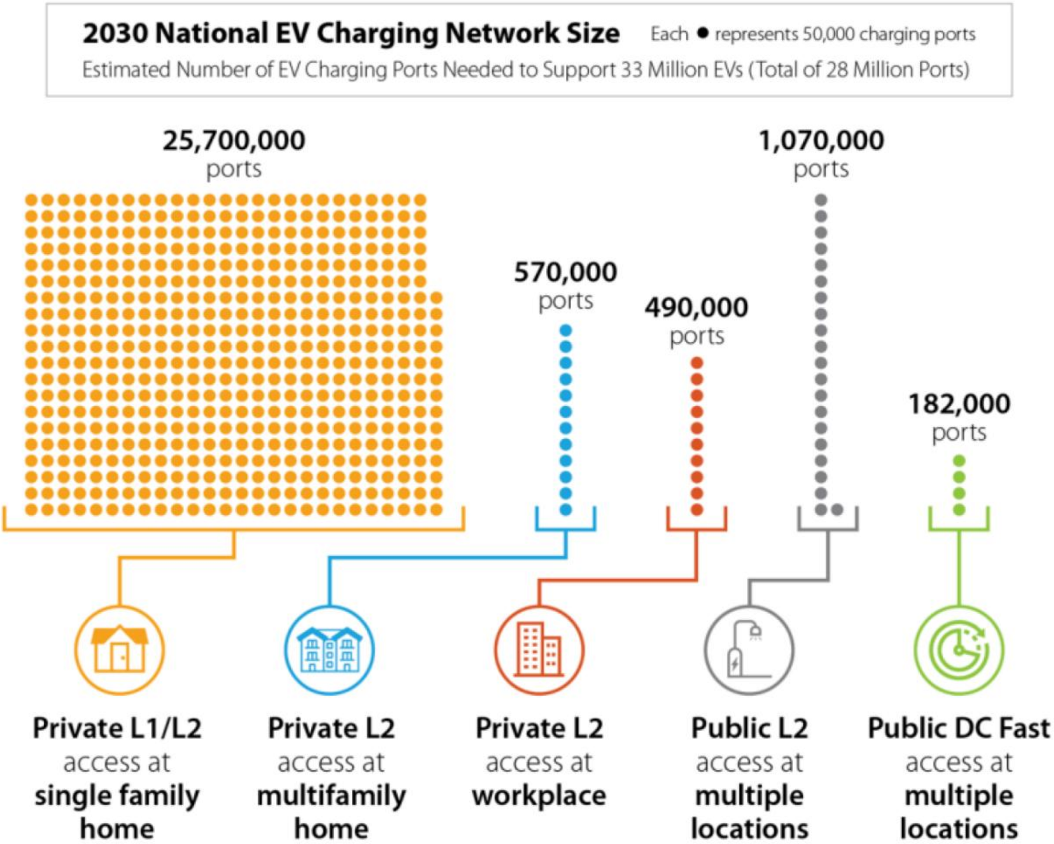

Figure 8 Estimated 2030 U.S. EV charging network (ports by location). Homes and workplaces dominate L1/L2; many public DCFC are needed.

This above fig shows that by 2030 most EV charging will occur at home or workplace L1/L2 outlets, but a large number of public DC fast chargers will also be needed to support highway and fleet use. Indeed, a major DOE analysis found only 13-14% of the required charging ports were installed by 2024 (Brown, et al., 2024). The gap underscores the infrastructure scale-up challenge.

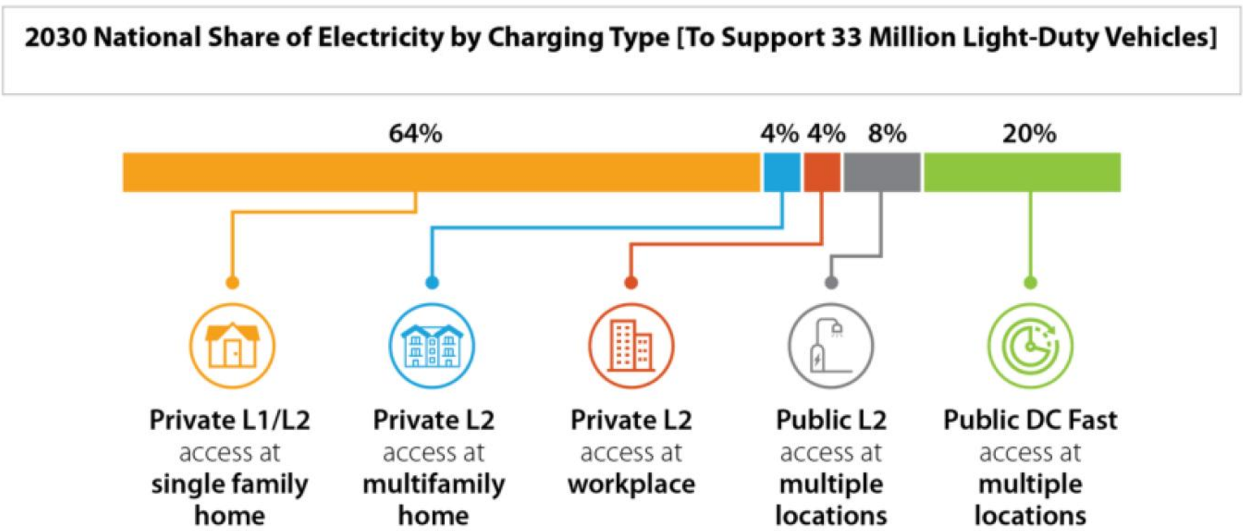

Figure 9 Predicted 2030 share of EV charging electricity by mode (Brown, et al., 2024). ~80% from L1/L2 (mostly residential), 20% from DCFC (public fast).

By 2030, roughly 80% of EV charging energy is expected to come from Level-1/L2 chargers (mainly at home) and only ~20% from public fast-chargers. This highlights that while fast chargers are critical for long trips, most EV charging will be residential. Such home charging could more easily be tied to local renewables (e.g. rooftop solar). But fleet and public charging require grid integration.

The scale of this growth means integration with renewables is both a challenge and an opportunity. Left unaddressed, charging millions of EVs on a fossil-heavy grid could slow emissions reductions. Yet smart integration allows EVs to act as controllable loads or storage, soaking up excess renewable generation. The literature emphasizes *vehicle-to-grid* (V2G) and smart charging to balance supply and demand. For example, optimizing EV charging schedules with time-of-use pricing can align charging with periods of high renewable output.

Case Studies of Renewable-EV Integration

- **Poland - Hydropower Analysis**

The Energies (2022) case study of Poland quantified how EV charging interacts with Polish power mix. It showed that moving to all EVs would require up to 80 TWh/yr more electricity, stressing a coal-dominated grid. The authors explored adding hydro capacity on the Vistula. They concluded that even with new hydro plants, EV charging would likely increase emissions unless paired with broader decarbonization (Hydro Review Content Directors., 2022). This underscores that national plans must synchronise EV adoption with grid greenification.

- **Korea - Solar/Battery EV Station**

In Korea, Ihm et al. (2023) designed a solar-plus-storage system for a real EV charging station. Using HOMER modeling with actual load data, they tested scenarios with 0-100% renewables. They found that a PV array plus battery (PV/ESS) was most economical, given local weather. A 25% renewable share minimized cost and emissions in their site.

As REF grew, capital costs rose (more solar/batteries) while grid energy purchases fell, lowering O&M costs. Total present cost increased sharply beyond ~50% REF. Crucially, every increase in renewables cut CO_2 emissions. At 100% REF, annual CO_2 reached zero (offset by renewables). This case shows economic trade-offs: a fully green system is cleanest but most expensive. Practical designs may target partial REF to balance cost and emissions.

- **China - EV Charging as Grid Resource**

Yu et al. (2025) modeled an integrated wind-solar-hydro system coordinating with EV charging stations (Ihm et al., 2023). In their Chinese power grid case study, heavy solar/wind introduced variability. They proposed using EV charging load and hydropower together for peak regulation. In a two-layer optimization, EV stations could shift charging to times of surplus wind/solar, while hydropower ramped up/down for deeper peak support. The result was 47% less renewable curtailment (wasted energy) compared to no EV control.

The figures show that when EV charging participates, overall curtailment of wind/solar drops significantly (International Energy Agency., 2024). Hydropower output also smooths out (Figure 12): with EVs adjusting load, hydro units need fewer sharp ramps. The study concludes that EV charging stations can act as flexible demand, coordinating with hydropower to stabilize grids with high renewables.

Real-World Demonstrations

Practical pilots have begun to implement these ideas. In New York, PlugIn Stations Online (PISO) demonstrated a direct hydro-EV charger hookup. They connected a 160-kW hydropower generator from Valatie Falls directly to a Level-2 charger (8 kW output). The system provided ~25 miles of EV range per hour using 100% hydroelectricity. This "proof-of-concept" showed a small hydro plant could continuously power EV charging on-site with zero grid emissions. The PISO president noted this represents the "feasibility of utilizing clean power and small hydro to transport people".

In Switzerland, Juice Technology AG established Juice Power AG to fuel EV chargers using hydro. They tapped two hydropower stations (11.6 MW Frisal and 43.4 MW Eglisau) to supply charging. The CEO emphasized that EVs, chargers, and energy must be an integrated system powered by low-emission sources (Hydro Review Content Directors., 2022). These industry examples illustrate viable models: using existing hydro assets to guarantee green charging.

Another pilot in Tasmania involved Hydro Tasmania's fleet charging. The company, which produces 90% of its electricity from hydro, now charges its electric vehicles entirely with on-site hydropower. They installed DC chargers at remote hydro stations, adapting to each site's constraints. This shows utility companies with hydro resources can quickly green EV fleets.

Table 1 summarizes key experiments.

Case	Renewable Source	EV Load	Key Finding	Ref
Poland (modeling)	Hydro (planned)	National EVs (forecast)	Coal grid needs 80 TWh more; hydro small share (~2%)	Kubiak-Wójcicka (2022)
Korea (HOMER study)	PV + Battery	Local EV station (89 kW peak)	25% REF (PV+ESS) minimized cost; emissions fall with REF	Ihm et al. (2023)
China (optimization)	Wind, solar, hydro	Regional grid + EV parks	EVs help absorb PV/wind, reduce curtailment by ~47%	Yu et al. (2025)
New York (demo)	Small hydro (160 kW)	Single Level-2 charger (8 kW)	100% clean charging, ~25 mi/hr with hydro	Doll (2023)
Switzerland (implementation)	Hydro (55 MW total)	Public chargers	High-capacity hydro can fully power EV stations	Hydro Review (2022)

These cases show both challenges and solutions. Models predict large costs for full renewables, but pilots prove technical feasibility.

Discussion

The reviewed studies indicate that integrating renewable generation with EV charging yields clear environmental gains but requires careful system design. Modeling results agree that higher renewable fractions at charging sites cut carbon emissions - but also increase capital cost (Hydro Review Content Directors., 2022). This trade-off implies mixed solutions: partial renewables plus grid as backup may be optimal economically while still reducing emissions substantially.

Hydropower offers special advantages: it can operate on demand and "ride through" periods with low solar or wind. Coordinating EV charging schedules with hydropower dispatch (including pumped storage) provides peak shaving capacity. In China's case, adding smart charging reduced renewable curtailment by nearly half. This synergy could be especially valuable as variable renewables grow.

However, infrastructure and policy hurdles remain. Many regions have insufficient charging networks: e.g. the US had only ~5% of needed fast chargers as of 2024. Without incentives or mandates, EV owners may charge off-peak or with high carbon grids by default. Policies that co-locate renewables and charging (e.g. solar roofs on charging stations, hydro-powered charging hubs) can help. Dynamic pricing and V2G tariffs can further align charging with renewable availability.

Experimentation continues: pilot projects around the world are showing practical solutions. Manufacturers and utilities are trialing microgrids combining wind, solar and batteries with chargers. For example, some fast-charging corridors in Europe are being fitted with dedicated renewables and storage. These experiments will yield data on reliability, costs, and user acceptance.

Conclusion

Integrating renewable energy with EV infrastructure is essential for achieving the full environmental benefits of electrified transport. Our review shows that this integration is both necessary and technically feasible. Real-world cases demonstrate that small hydropower plants can directly charge EVs off-grid, and smart control of EV loads can stabilize grids with high wind/solar. Modeling studies support these findings: even partial renewable supply to charging stations significantly cuts CO_2 emissions.

To accelerate the green transition, planners should co-optimize EV deployment and clean generation. This means building new charging hubs with on-site renewables or securing green power purchase agreements for EV fleets. Policies should encourage time-shifting of charging to when renewable supply is abundant. Industry and governments can leverage hydropower's flexibility - in many regions, unused hydro or pumped storage can act as the backbone for green EV charging.

In summary, coupling EV infrastructure with renewable energy supply is a win-win: it promotes EV adoption while deepening decarbonization of the grid. As EVs proliferate, ensuring they charge from renewables (especially dispatchable sources like hydro) will magnify benefits. Future work should continue real-world trials and refine economic models to guide investments. By accelerating these green experiments, societies can move faster towards both transportation and power system sustainability.

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