Fermata Energy

How bidirectional V2X electric vehicle charging can lead to net carbon savings

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Executive summary

In 2024, the world saw record levels of electric vehicle (EV) sales, surpassing 17 million vehicles sold last year and 25% higher than 2023. Meanwhile, renewables such as solar PV, wind, and hydro are forecasted to deliver 46% of electricity generation by 2030, up from 30% in 2024.

These two trends — growing EV adoption and growing renewable generation — present an opportunity to accelerate both power sector and transportation decarbonization. Bidirectional vehicle-to-everthing (V2X) charging is the key to unlock this dual potential.

V2X introduces flexibility into power systems by using software algorithms — plus a combination of historical, real-time, and predictive price, carbon intensity, and EV driver behavior data — to plan when and how much an EV battery charges and/or discharges (feeding electricity back to a home, commercial building, or the power grid).

Standard smart charging can only minimize the emissions impact of adding EVs to the grid. V2X can go much further, by storing electric energy when renewables are in high supply and discharging this energy during peak times when the grid relies on fossil fuels.

For example, we show how a hypothetical EV driver in California could turn their EV into a net carbon sink. However, V2X systems are usually operated to maximize financial savings/earnings for customers.

Our analysis of the correlation between hourly electricity prices and grid carbon intensity in US grid regions shows that the correlation is not sufficient to use cost as a proxy for emissions.

If price and carbon signals don't align (or are not co-optimized), V2X could fail to live up to its full potential.

We offer four recommendations to unlock the full potential of V2X technology:

1. Enforce real-time emissions tracking systems using granular data from grid operators and other trusted data providers.
2. Develop incentive programs for carbon-responsive V2X, such as export rates or rebate programs that reward emissions reductions.
3. Educate consumers on carbon reduction potential, since market research shows that consumers value both the financial and environmental benefits of V2X.
4. Launch V2X pilot programs and partnerships spanning utilities, automotive manufacturers, governments, and energy companies to evaluate emissions benefits.

WHY V2X?

Introduction

In 2024 — and for the sixth year in a row — the world saw record levels of electric vehicle (EV) sales, surpassing 17 million vehicles sold last year and 25% higher than 2023. Meanwhile, also last year, solar PV + wind generation combined surpassed generation from hydro, with renewables forecasted to deliver 46% of electricity generation by 2030, up from 30% in 2024.

These two trends — growing EV adoption and growing renewable generation — present an opportunity to accelerate both power sector and transportation decarbonization. Bidirectional vehicle-to-everthing (V2X) charging is the key to unlock this dual potential.

OPPORTUNITY

The promise of EVs for emissions reductions

EVs naturally produce no tailpipe emissions. They also represent a substantial overall emissions decrease compared to internal combustion engine vehicles, even when taking into account charging EVs on heavier-polluting power grids as well as lifetime embodied emissions including their large batteries. Smart charging (i.e., preferentially charging the EV battery at times when grid electricity is cleaner and avoiding charging at times when power is dirtier) can further reduce EVs' emissions impact.

These qualities have made EVs popular among policymakers interested in automotive and trucking fleet-wide emissions reductions, air quality standards, and other goals. Associating regulations are frequently becoming more stringent.

In the European Union, emissions standards for passenger cars and light commercial vehicles are tightening from 115 gCO_2/km in 2024 to 95 gCO_2/km in 2025. In the United States, 17 states and the District of Columbia are following the lead of California and the state's California Air Resource Board (CARB). CARB's regulatory efforts include the Advanced Clean Cars II regulation (mandating 100% zero-emissions vehicle sales by 2035) as well as the Clean Miles Standard (which ratchets down emissions from ride-hailing services and transportation network companies from 257 gCO_2/passenger mile traveled in 2023 to 0 gCO_2/PMT by 2030).

OEMs may face hundreds of millions in fines for not meeting these and other emissions targets.

CHALLENGES

The challenges of an increasingly variable grid

As the renewables portion of the electricity generation mix has grown, as more grids in transition manage a diverse combination of power plants (retiring coal-fired units, natural gas, nuclear, wind, solar, etc.), and as electricity demand has grown and become peakier, new challenges have come to the forefront.

In particular, the timing of renewable generation does not always coincide with the timing of electricity demand. This is leading to oversupply challenges, when there's excess (i.e., surplus) renewable generation that essentially gets thrown away (i.e., curtailed). In Europe, by 2040 upwards of 310 TWh of renewable generation is at risk of curtailment. In the US in solar- and wind-rich regions, curtailment is growing in places like California and Texas, too.

Finding ways to integrate, store, and use this "lost" clean energy can help power grids further decarbonize and manage their increasing variability.

The role of bidirectional V2X charging

On both fronts — transportation emissions reductions and grid decarbonization — bidirectional V2X charging represents an exciting capability. V2X introduces flexibility into power systems by allowing EVs to store electricity and later feed it back… whether to a home, commercial building, or the power grid.

Such bidirectional charge / discharge capability, when coupled with price signals and awareness of the carbon intensity of the grid over time, becomes a powerful tool. Standard smart charging can only minimize the emissions impact of adding EVs to the grid. V2X can go much further, by storing electric energy when renewables are in high supply and discharging this energy during peak times when the grid relies on fossil fuels.

Today, V2X pilots around the world are already demonstrating significant financial earnings by intelligently responding to price signals, grid frequency, and utility demand response events. Much more is possible. For V2X technology to enable emissions reductions at scale, policies are needed to provide EV owners with the right financial incentives to align environmental and economic behavior. The first step is to track real-time emissions from EV charging.

For vehicle OEMs
V2X technology can help measure and reduce emissions further than standard EV charging technology, in turn helping achieve regulatory fleet-wide emissions standards as well as voluntary corporate decarbonization targets.

For grid operators
V2X unlocks the ability of EVs to respond as export-capable grid resources — individually and/or in aggregations such as virtual power plants (VPPs) — helping to offset system-wide peaks, reduce renewables curtailment, and a cleaner overall grid generation mix.

For EV drivers / owners / operators
V2X provides new value streams that lower EV total cost of ownership (TCO), support increased consumer adoption of EVs, and enable even better economics and carbon impacts for corporate and municipal fleets.

How V2X software works

V2X uses sophisticated software algorithms — plus a combination of historical, real-time, and predictive price, carbon intensity, and EV driver behavior data — to plan when and how much an EV battery charges and/or discharges.

V2X can optimize (or co-optimize) for lowest price to charge an EV, lowest emissions, greatest revenue for providing grid services, and other value streams. In all cases, V2X software typically also ensures that the vehicle battery has sufficient state-of-charge for the driver when they're ready to go.

OPTIMIZED CHARGING

Turning EV batteries into a net carbon sink

This bidirectional charging capability creates an exciting possibility for EV batteries: when optimized around a carbon signal, they can actually function as a net carbon sink. This could be true in two ways:

- **For the grid and the EV:** With V2X, EVs can be a full system-level net carbon sink if they displace more grid emissions during discharge to the grid (displace fossil-fueled generation) than the impact of the electricity used to charge them (charged on clean electricity) for the combined use of grid support plus driving energy.

- **Compared to a battery:** EVs with V2X can also reduce more carbon than stationary batteries. Even if both were charged on clean electricity and discharge to the gridduring times of higher marginal carbon intensity, with the V2X EV, the carbon reduction of your low carbon driving miles can exceed the carbon benefit of the stationary battery's higher availability to the grid.

To achieve these outcomes, the V2X optimization software needs to follow a carbon signal that indicates the marginal emissions intensity of grid-supplied electricity. We'll call this the carbon intensity (CI). To reduce emissions, function as a carbon sink, and create a net environmental benefit, V2X needs to charge during low CI times and discharge during high CI times.

Expressed as a mathematical formula, for V2X to act as a carbon sink, the following must hold:

$$[(\text{driving\_energy} + \text{V2X\_charged\_energy}) \times \text{charging\_CI}] - \text{V2X\_discharged\_energy} \times \text{discharging\_CI}) \le 0$$

$$\frac{\text{charging\_CI}}{\text{discharging\_CI}} \le \frac{\text{V2X\_discharged\_energy}}{\text{driving\_energy} + \text{V2X\_charged\_energy}}$$

EXAMPLE

A hypothetical EV driver

Here, we demonstrate an example use case of a passenger car in California, a grid system with high renewables penetration. Assume a passenger car EV with a usable battery capacity of 90 kWh and which is parked and plugged into its home charger overnight and other times when the vehicle isn't being driven.

At 3:00 am, as instructed by V2X software through automated algorithms, the car starts discharging electricity in the home for 2 hours until 5:00 am, discharging a total of 20 kWh of electricity. During this time, the carbon intensity of the California grid averaged 450 gCO_2/kWh. The V2X charger has 95% one-way efficiency.

Fermata Energy's V2X software ensures that the vehicle retains a usable state-of-charge of 70 kWh, which is more than sufficient to complete the morning and afternoon drop-off and pick-up of kids at school, covering 20 miles and using 7 kWh for each roundtrip.

When the vehicle returns home at 2:30 pm, Fermata Energy charges it from 2:30 to 5:00 pm, when solar production is in excess, with a carbon intensity of 0 gCO_2/kWh. During this charging session, the battery recoups 36.16 kWh (20/0.952 kWh discharged overnight, plus 14 kWh consumed during the daily driving). This returns the vehicle to the same state-of-charge at which it started the day.

For the day, the carbon impact of the vehicle was:

$$\text{Net carbon impact} = \text{induced emissions} - \text{avoided emissions}$$

$$\text{Net carbon impact} = (36.16\text{ kWh} * 0\text{ gCO}_2\text{/kWh}) - (20\text{ kWh} * 450\text{ gCO}_2\text{/kWh})$$

$$\textbf{Net carbon impact = -9 kgCO}_2$$

Estimating about 150 days per year with solar curtailment on the California grid, charging and discharging the vehicle like this, **the V2X EV can avoid 1.35 tonnes of CO_2 per year.**

DISCUSSION

When price and carbon signals don't align

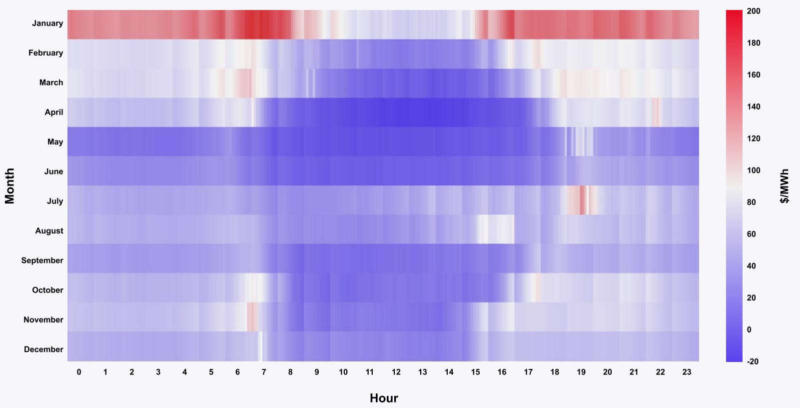
Today, V2X systems are usually operated to maximize financial savings / earnings for customers. But when V2X batteries are optimized for financial objectives, they may not actually be delivering on V2X technology's potential to enable more renewable energy grid integration and lower overall transportation and grid emissions.

If electricity prices were perfectly correlated with emissions, optimizing V2X for economic value would also maximize environmental value (i.e., minimize emissions). If higher electricity prices paired with higher grid carbon intensity, and vice versa, then saving money and saving carbon would be aligned. However, these two variables don't always correlate.

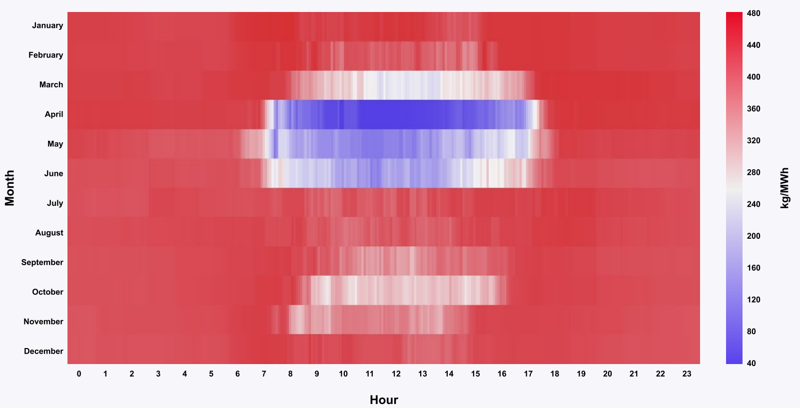
For example, in California, the most-efficient natural gas-fired power plants run around-the-clock and the less-efficient, more-polluting gas peakers run less often to meet demand peaks. In places like this, high prices typically correspond to times when the dirtier natural gas peaker plants are on the margin and setting system prices.

The California electricity market, which is heavily dependent on both solar and natural gas, also demonstrates another factor that influences the correlation of price and marginal emissions, which is renewable curtailment. California regularly has an excess of solar being generated during the day in the spring and early summer months. With insufficient transmission capacity to share it with neighbors, during these times electricity prices go negative and solar generators curtail their output to keep supply and demand in balance. During times of solar curtailment in a particular area, marginal emissions are zero because any additional electricity usage reduces curtailment (i.e., uses the surplus solar).

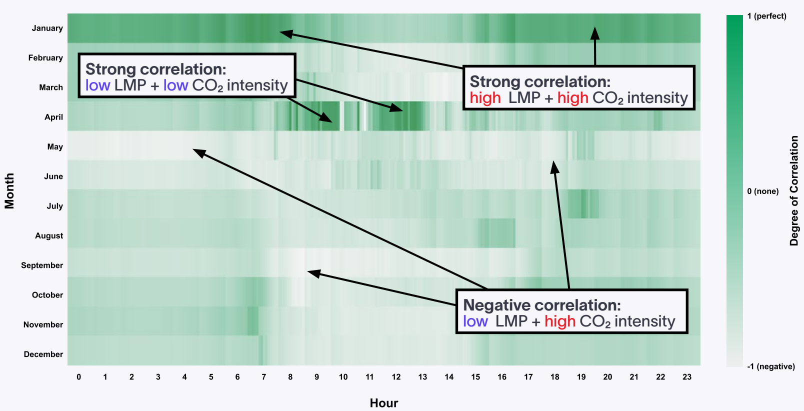
Locational marginal price (LMP)



Marginal CO_2 intensity



Correlation between LMP and marginal CO_2 intensity



In California in 2023, the best correlation between CI and wholesale prices of electricity was 0.76, which is strong. There is generally a positive correlation, but it drops significantly in certain months.

For another example, in other regions with low renewable energy penetration in the mix, and where there are multiple fossil fuel types such as both natural gas and coal, the correlation between price and emissions will be much worse and even sometimes inversely correlated.

The Midcontinent Independent System Operator (MISO) grid, for instance, still depends significantly on coal-fired generation in addition to natural gas. On a typical day, coal plants run all day for baseload demand, operating even during off-peak periods, while the relatively cleaner but more expensive gas-fired plants come online to meet increasing demand in the morning and the most expensive gas peaker plants come on in the afternoon.

This demonstrates a case where the cheapest electricity comes from the highest emitting source: coal. In multi-fuel grids, the correlation between prices and carbon intensity is therefore weak at best.

Thus, prices are not always correlated with CO_2 intensity. At least, the correlation is not sufficient to use cost as a proxy for emissions in short-term battery dispatch decisions.

Source: Fermata Energy analysis; WattTime; gridstatus.io

Recommendations

Due to the imperfect correlation between electricity price and carbon intensity, an EV owner might unintentionally contribute to higher emissions with V2X if their system is set up only to optimize based on prices. For V2X to contribute effectively to emissions reduction, it is therefore important to consider the grid's real-time emissions intensity rather than relying on electricity prices as a proxy.

Factoring in forecast marginal emissions, V2X optimization software would dispatch EVs to charge and discharge at times that minimize emissions as well as costs.

For certain customer sites, Fermata Energy can deliver CO_2 optimization without impacting the economics. For example, where a residential customer is on a time-of-use (TOU) rate with several hours corresponding to off-peak pricing, the algorithms can further refine when to charge and discharge with the off-peak window. In other cases, there may be a tradeoff, and Fermata Energy's platform offers V2X customers the choice of how to weigh one versus the other.

4 ways to unlock V2X potential

EV owners are more likely to follow carbon signals if the proper financial incentives are put in place. To unlock the full potential of V2X technology for reducing emissions and maximizing economic benefits, policymakers, grid operators, and consumers should consider the following recommendations:

1

Enforce Real-Time Emissions Tracking Systems

Real-time and forecast emissions data are now available on a highly granular basis, made possible by real-time reporting from grid operators around the world. The first step towards lower carbon emissions is analyzing the data. Some carbon credit programs such as California's Low Carbon Fuel Standard (LCFS) were designed before granular emissions tracking was made possible, and could be reformed to implement more accurate, hourly emissions tracking and monitoring of EV charging, including V2X discharging.

2

Develop Incentive Programs for Carbon-Responsive V2X

Incentives could include export rates for feeding energy back to the grid during critical times, rebate programs that reward emissions reductions, or ensuring V2X services are eligible and can access existing emissions trading programs. One example is the California Self-Generation Incentive Program (SGIP), under which battery storage assets are compensated proportionally to the volume of carbon they displace. We advocate for this program to become accessible to mobile storage, i.e. V2X, and expanded beyond California.

3

Educate Consumers on Carbon Reduction Potential

Consumers value both the financial and environmental benefits of V2X, according to many studies including a Fermata Energy user survey (2024) and a WattTime study (2020). Ensuring that consumers are aware of the potential carbon savings from V2X, and have the information at hand to make decisions, is essential to encourage sustainable energy behaviors.

4

Pilot Programs and Partnerships

Utilities, automotive manufacturers, governments, and energy companies should collaborate to establish V2X pilot programs that evaluate emissions impacts.

Conclusion

Standard smart charging can only minimize the emissions impact of adding EVs to the grid — i.e., minimize the carbon impact of mobility — whereas V2X technology can go beyond minimizing the impact of mobility by acting as a grid resource. By discharging to the grid during peak carbon intensity times and charging when renewables are abundant, V2X can further reduce reliance on fossil generators and reduce renewable waste, in turn helping accelerate the transition to renewable energy.

By carefully aligning incentives, educating consumers, and encouraging real-time emissions tracking, policymakers can maximize the environmental benefits of V2X, turning EVs into sustainable investments for fleets and consumers. With the right incentives, V2X technology can help OEMs and their customers comply with vehicle emissions targets even further than standard EV charging.

About the authors

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Fermata Energy

Fermata Energy is a premier provider of Vehicle-to-Everything (V2X) bidirectional charging solutions. Its V2X software platform optimizes and manages charging and discharging of EV batteries.

WattTime

WattTime is an environmental tech nonprofit that empowers all people, companies, policymakers, and countries to slash emissions and choose cleaner energy.