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MACK INSTITUTE
for INNOVATION MANAGEMENT

PROGRAM on VEHICLE
and MOBILITY INNOVATION

New Paths for Solving Emergent Problems of the Electric Vehicle (EV) Sector

MIT Mobility Forum, November 11, 2022

By: Prof. John Paul MacDuffie, Management Department
Director, Program for Vehicle and Mobility Innovation (PVMI)
Mack Institute for Innovation Management

PVMI: Its Roots in IMVP

The roots of the Program on Vehicle and Mobili are in the International Motor Vehicle Program (IMV MIT.

"IMVP is an international network of faculty researchers delivering knowledge and insig tomotive industry."

"IMVP organizes international teams of r porative research on topics throughout the automotive valu

PVMI is the new name and provides the new direction for the IMVP network, and Wharton's Mack Institute of Innovation Management is its new home

Electrification

Connectivity

"A Once-in-a Century Transformation"

Autonomy

Shared Mobility Services

Disruptive Technologies/Business Models: What Impact of CASE (separately and together)?

- **C:** "Connected car" – within-vehicle network; vehicle-to-vehicle (V2V); vehicle-to-infrastructure (V2I); infotainment services
- **A:** Autonomous vehicle – "driver assist" (Levels 1 & 2) to "primary vehicle control" (Level 3) to "full vehicle control" (Levels 4 and 5)
- **S:** Shared -- New mobility services, w/high asset utilization strategies (car-sharing/ ride-hailing) that reduce vehicle ownership
- **E:** Electric vehicles (BEVs) and recharging via electricity (from varied sources)

Many Identify Barriers to Diffusion of EVs

Goal: Achieving cost and performance parity with legacy ICEV technology

First, overcome these barriers:

- Need for battery innovations (range, cost, supply chain)
- Access to charging infrastructure
- Affordability

These Barriers Look Different Today Than 20, 10, 5 or even 3 Years Ago

- We've moved beyond questions of "whether" & "chicken and egg" debates
- Now the questions are "when and "how" -- around a set of still-thorny but more tractable problems.
- Expanding EV supply and multiple forces affecting EV demand are creating favorable conditions for a **swarm of innovations**
- Some are highly visible, others behind the scenes, from both private & public sectors
- ***Taken as a whole, they yield promising paths for addressing these problems***

Disruptive Technologies Often Only Demonstrate Their Biggest Impact After a Swarm of Related Innovations

- For EVs, these innovations are occurring in:
  - Batteries → physical innovations, e.g., new chemistries; new extraction approaches; new vehicle integration concepts; deglobalized supply chains; circular recycling
  - Charging → electrification for decarbonization; new sources of electricity; public policies favoring clean energy; both decentralized and centralized grid enhancements; smart grid tools/incentives; multi-mode 'refueling'
  - Affordability → public policy to speed cost parity; used EV and PHEV markets; physical innovations tied to vehicle market segments; more multi-mode mobility options; P2P vehicle sharing; remove "dirty" products

Battery Innovations

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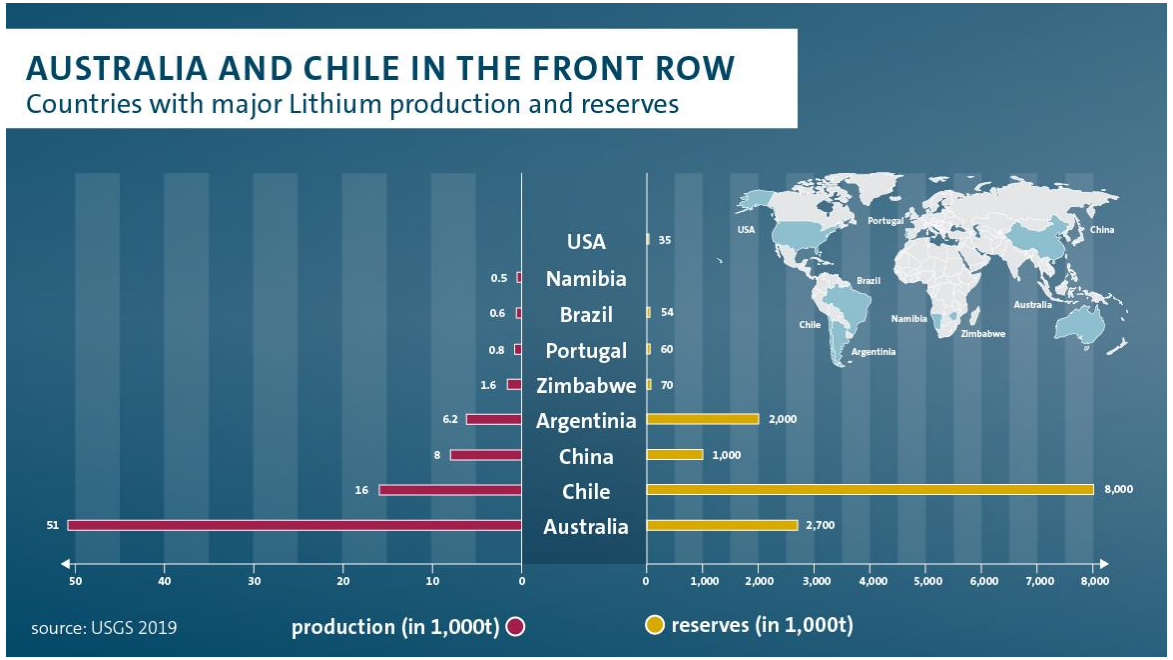
Headlines On Shortages of EV Battery Materials Grow More Alarmed

- **COBALT** → Scarce, Concentrated (nearly 50% in Congo) Where Mining Is Linked to Human Rights Abuses
- **NICKEL**→ Scarce, Concentrated (over 50% in Australia, Indonesia, South Africa, Russia and Canada), New Formulations Use More Nickel
- **GRAPHITE** → Not Scarce But Concentrated: "China accounts for about 60% of natural graphite production capacity and 90% of the synthetic variety" (Fortune)
- **LITHIUM** → Not Scarce, Supply Lags Demand Considerably, Price Up Dramatically (400-600% increase since January 2022), Surface Mining Method Has Negative Environmental Impacts

Dominant battery chemistry is NMC (Nickel Manganese Cobalt) with Lithium (Li-ion in all chemistries for now) – and Graphite for anodes

LITHIUM PRODUCTION AND RESERVES BY COUNTRY (USGS 2019)



Meanwhile, A Swarm of Physical Innovations in Batteries and Their Components – Plus Software

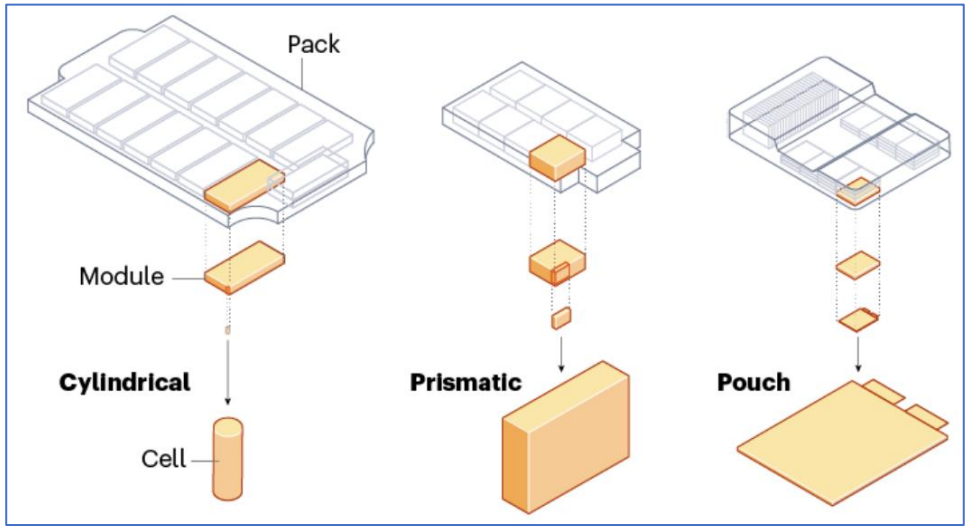
- Looking beyond cells
- Chemistry variants
- Packaging innovations
- Platform flexibility
- Battery management software (BMS)

Looking Beyond Cells

Evolution of Panasonic's cells for Tesla

Innovations in cell design and manufacturing continue but:

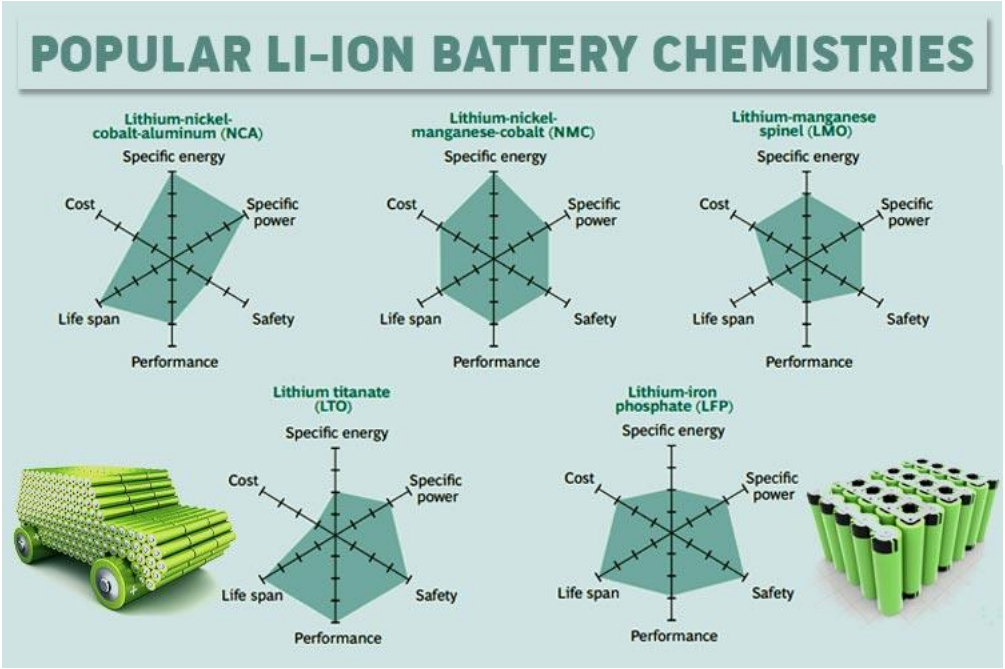
- Battery chemistries are now important strategically
- Innovations in combining cells into modules and packs offer alternate paths to improvement
- OEMs developing packaging innovations, battery platforms to support broad product portfolios
- All are boosting vertical integration for batteries*
- Employment impact: 2/3 of OEMs build battery modules and packs in their own plants*



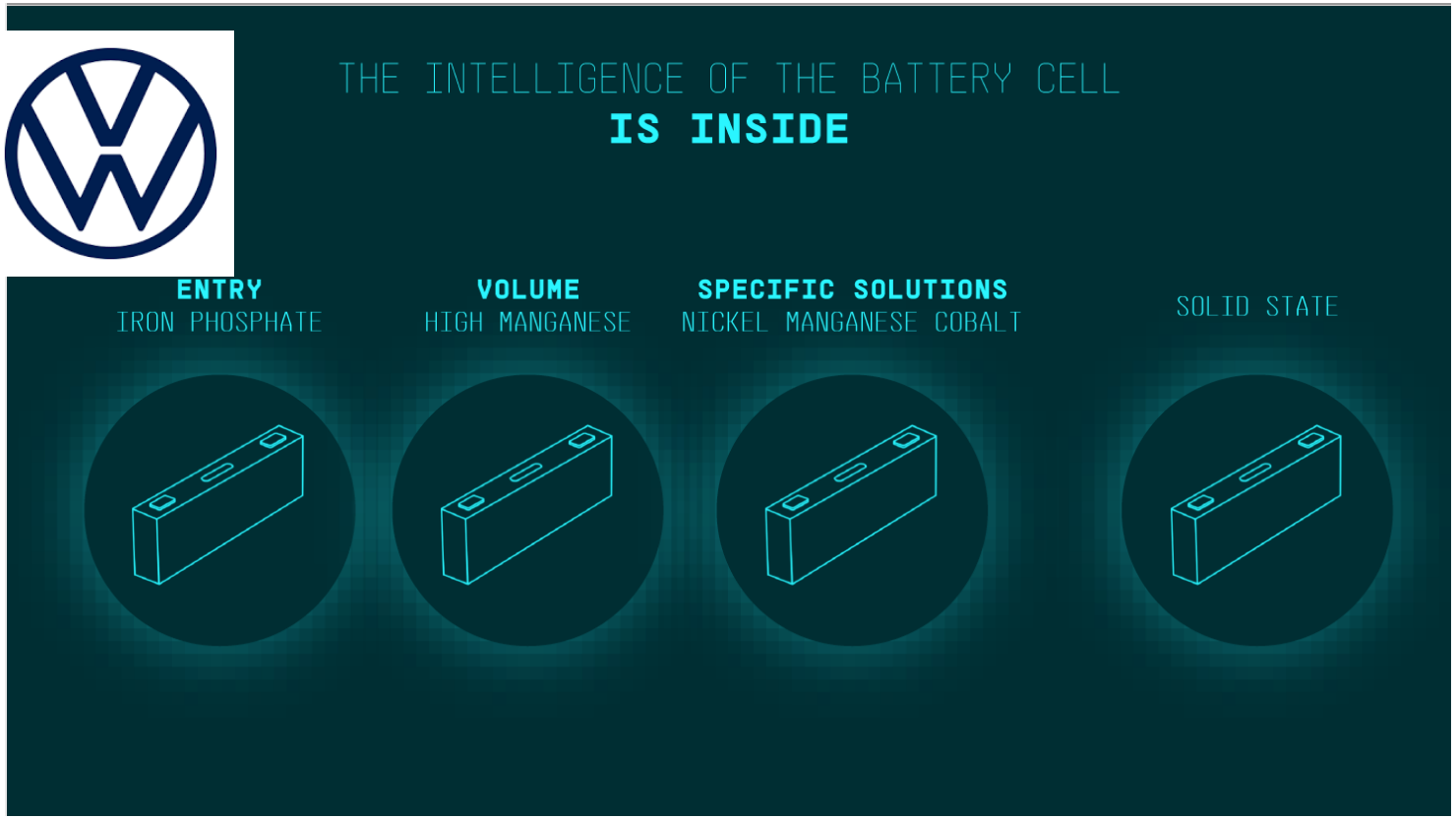
Different cell designs are put into battery modules and packs of different shapes

*Source: Alochet, MacDuffie, & Midler, 2022

Different Battery Chemistries Offer Tradeoffs - and Supply Chain Solutions



Many chemistries that avoid or reduce need for cobalt (especially) and nickel

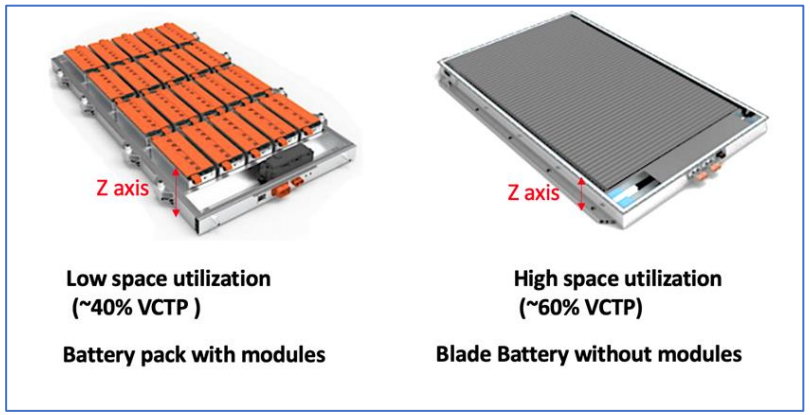


LFP **LMO, LMNO** **NMC** **2025-30**

LG Chem's new formulation: from 6-2-2- to 8-1-1

Packaging Innovations Are Crucial to Support New Battery Chemistries

- Battery makers are eliminating modules in cell-to-pack designs
- OEMs are experimenting with packing cells directly into the chassis (cell-to-chassis)
- Both save weight, processing steps, and increase power density, helping support new battery chemistries
- Great way to avoid the "weight spiral"

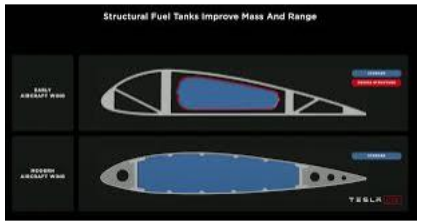


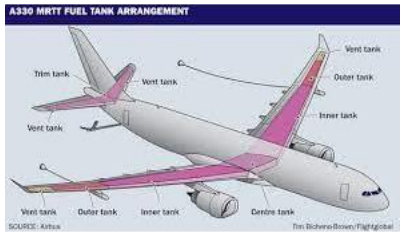
BYD's cell-to-pack design (no modules)

Cell-to-chassis integrates battery into structure

Cell-to-Chassis = Structure with a Double Function

- Analogy that Tesla uses: Like using airplane wings to hold fuel
- First step: Design the fuel tanks in the shape of the wings
- Analogous step: Design the chassis with a battery pack-shaped cavity
- Next innovation: New glues that add structural strength to adhesive bonds that keep cells and plates together



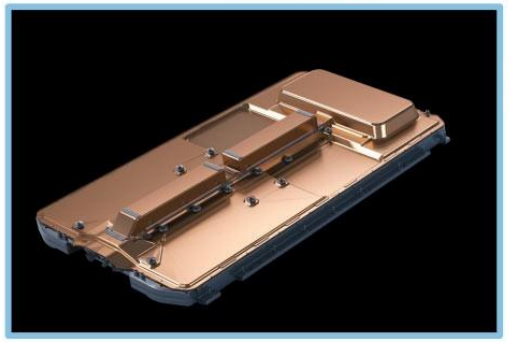


"The ultimate battery pack would be one that consists of 100 percent active material. That is, every part of the battery pack stores and releases energy," Euan McTurk

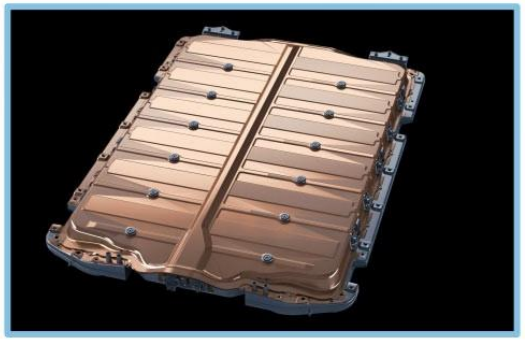
Battery Platforms Offer Flexibility to Support Broad Product Portfolio

Ultium Module Flexibility

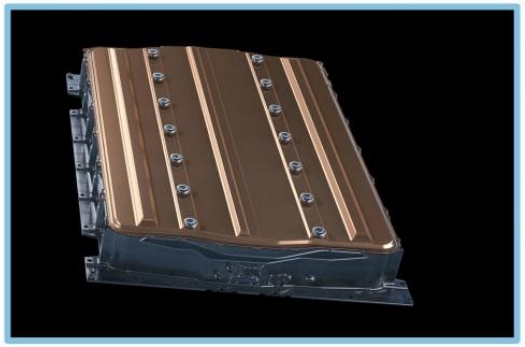
Performance



Crossover



Truck / SUV



- Battery packs are custom tailored for energy and range

- Packs can contain 6, 8, 10, 12 modules, or can be double stacked to hold up to 24 modules

Cell-to-Chassis and Configurable Platforms Solve Some Problems and Create Others

- Replacing faulty cells will be far more difficult w/cell-to-chassis
- Idiosyncratic pack shapes won't fit in other models→

  Loss of scale economies? Less repair or replacement flexibility?
- Limits range of "second-life" applications when the car is scrapped
- Larger battery sizes in cell-to-pack and cell-to-chassis designs may limit them to grid-storage applications

Battery Management System (BMS): “DNA of EVs”

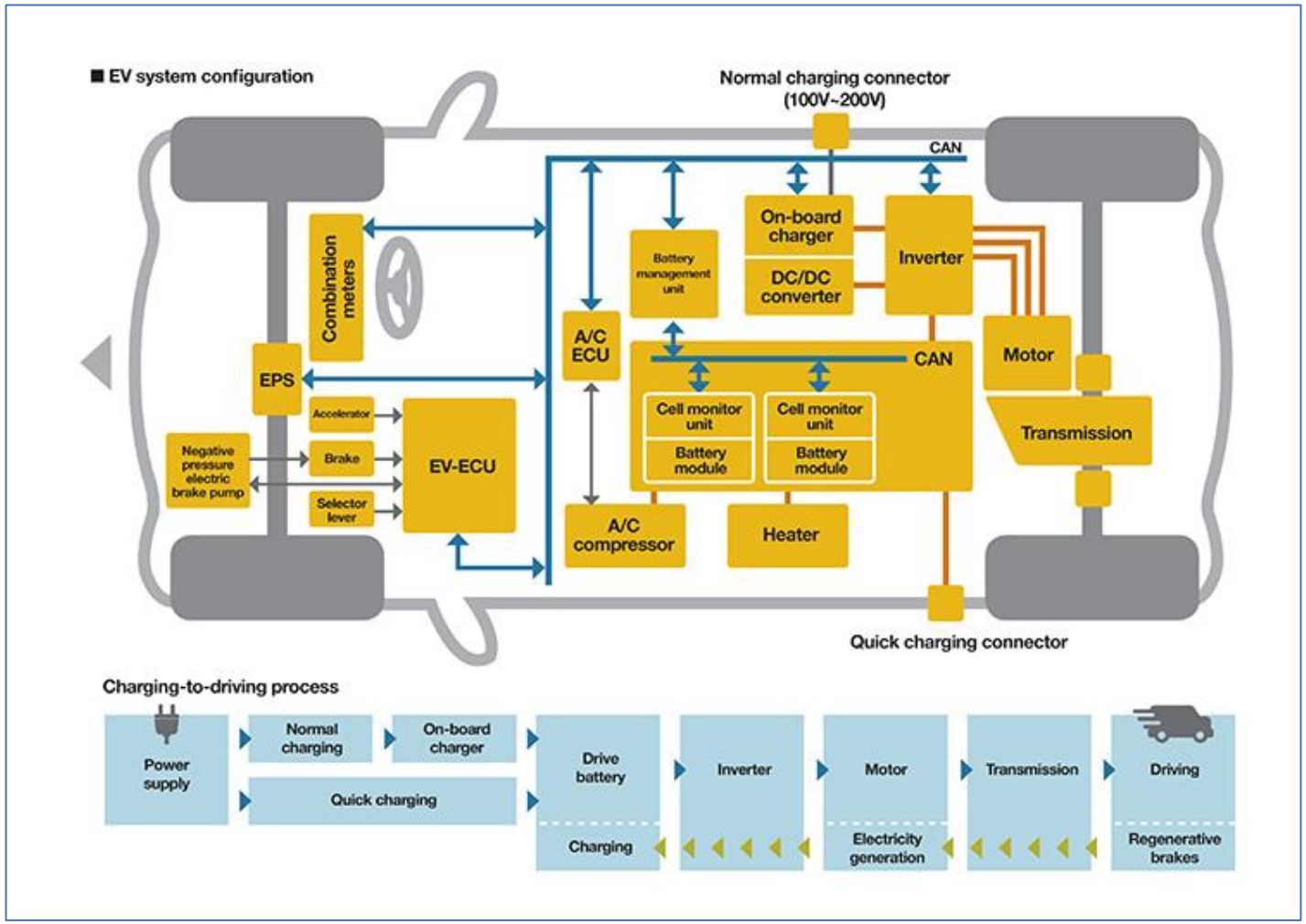
Monitors parameters of individual cells and overall battery pack

Controls charging and discharging rates and timing

Regulates thermal conditions (affects safety and efficiency)

Evaluates overall capability, over time and in different operating conditions

Enacts different driving modes (performance; eco; towing)



Leapmotor's "Intelligent Power System"

"We integrate our electric motors, gearboxes and MCUs into our proprietary electric drive system, Heracles. We expect to mass-produce a more advanced oil-cooling electric drive system, PanGu, which features an industry-leading maximum efficiency up to 94.6%. We develop our own battery pack and battery management technologies. With the delivery of the C01 in the third quarter of 2022, we expect to become the world's first pure-play EV company to apply cell-to-chassis ("CTC") technology in mass production."

- Vertical integration of the entire e-drive train; battery pack and BMS; and now cell-to-chassis
- This is the same approach being taken by most incumbent OEMs and *de novo* EV startups

Who Does What in Battery Manufacturing

(Alochet, MacDuffie, & Midler, 2022)

Nearly all OEMs (incumbent ICEV and *de novo* BEV), buy cells.

In contrast, 2/3 of OEMs make battery modules and packs at or near EV assembly plants

These assembly jobs can be done by existing workers, after training

1/3 ally with one battery partner

OEMs do Battery Management System (BMS) on their own or write specs for software specialist

	Design Perimeter			
Automakers	Cell	Module	Battery pack	BMS
BMW	Buy	Make	Make	?
BYD	Make	Make	Make	Make
Daimler	Buy and Ally	Make	Make	Ally-to-make
Ford USA	Buy	Make	Make	Ally-to-make
Ford Europe	Ally with an automaker	Ally with an automaker	Ally with an automaker	Ally with an automaker
Geely – Geometry pure EV brand	Ally with a battery maker	Ally with a battery maker	Ally with a battery maker	?
GM USA	Ally	Make	Make	Ally-to-make
GM China	Buy	Buy	Buy	Buy
Honda but USA	Ally with a battery maker	Ally with a battery maker	Ally with a battery maker	Ally with a battery maker
Honda USA	Ally with an automaker	Ally with an automaker	Ally with an automaker	Ally with an automaker
Hozon	Ally with a battery maker	Ally with a battery maker	Ally with a battery maker	Ally with a battery maker
Hyundai / Kya	Buy	Make (through Mobis, a wholly-owned subsidiary)	Make (through Mobis, a wholly-owned subsidiary)	Make (through Mobis, a wholly-owned subsidiary)
Lucid Motors	Buy	Make	Make	Make
NIO	Ally	None	Ally-to-make	Ally-to-make
Nissan but China	Ally with a battery maker	Ally with a battery maker	Ally with a battery maker	?
Nissan China	Buy	Buy	Buy	?
Renault Group Europe	Buy *and Ally*	Make	Make	Ally-to-make
Renault Group China	Buy	Buy	Buy	Ally-to-make
SAIC – MG brand	Ally with a battery maker	Ally with a battery maker	Ally with a battery maker	Ally with a battery maker
Stellantis	Buy and Ally	Make	Make	Ally-to-make
Tesla USA	Ally	Make	Make	Ally-to-make
Tesla China	Buy	Make	Make	
Toyota	Ally with battery makers	Ally with battery makers	Ally with battery makers	Ally with battery makers
VW	Buy, Ally and Ally to Make	Make	Make	Ally-to-make
Xpeng	Buy and Ally	Make	Make	?

Taken As a Whole: LFP Can Replace NMC

LFP (Lithium Ferro-Phosphate) was applied first in scooters and small EVs.

*"The big Chinese battery makers (BYD, CATL and Lishen — each one larger by itself than any other battery company that's not in China) -- have been making LFP cells for 10 years."**

For a time, displaced by NMC (Nickel Manganese Cobalt) – but no longer.

LFP Advantages: Cheaper (non-scarce) materials, more recharging cycles, much safer (no fires), low toxicity

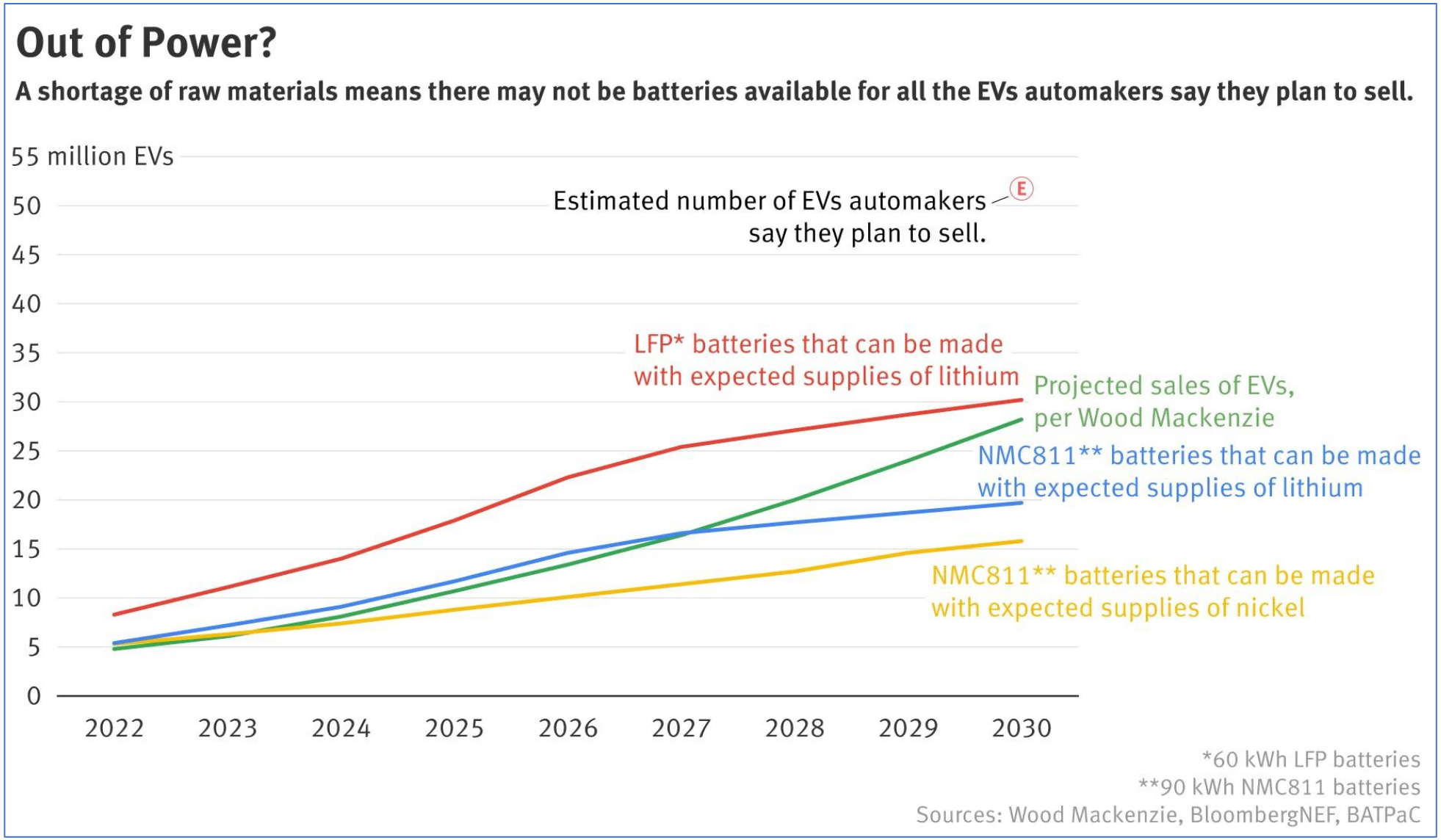
LFP Disadvantage of lower energy density at cell level can be offset by:

Packaging innovations (cell-to-pack; cell-to-chassis) that boost energy density

BMS adjustments (less acceleration speed, slower HVAC temperature adjustments, less range) that reduce energy demand

* Lou Schick, director of investments at Clean Energy Ventures

Shortage of Raw Materials Not Easily Solved…



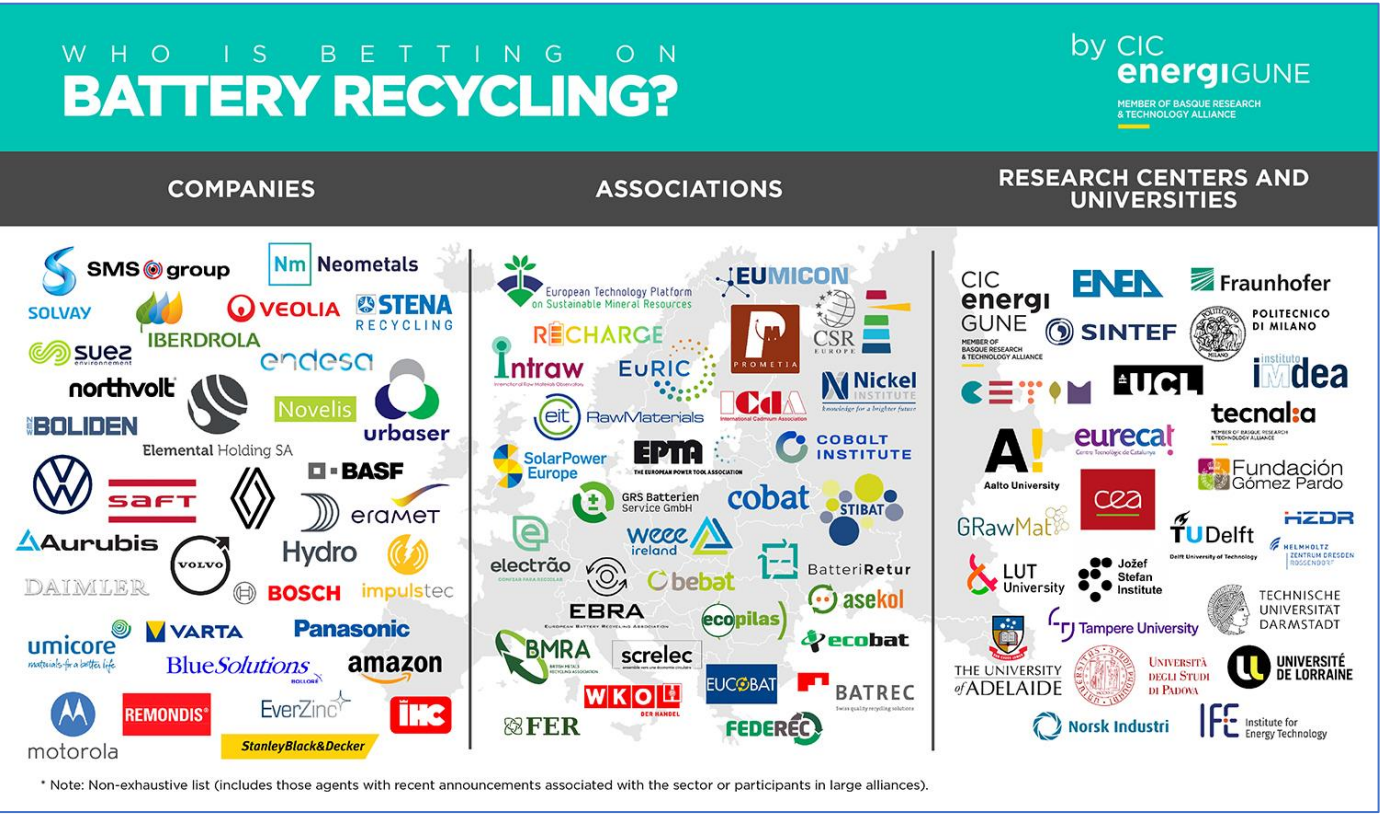
…But Shortages Drive Expanded Supply, Substitutive Innovations, and More Recycling

- Lithium production is just scratching the surface of available reserves
- New methods of lithium extraction are gaining ground (e.g., direct extraction from brine rather than evaporation)
- NMC (Nickel Manganese Cobalt) is shifting from 6-2-2 to 8-1-1
- LFP (Lithium Ferro (Iron) Phosphate) avoids nickel and cobalt altogether
- Economics of battery recycling grow more attractive as raw material prices increase – boost for “circular economy” investments and public support

Mining of Minerals for EVs Is, To Date, Small Scale

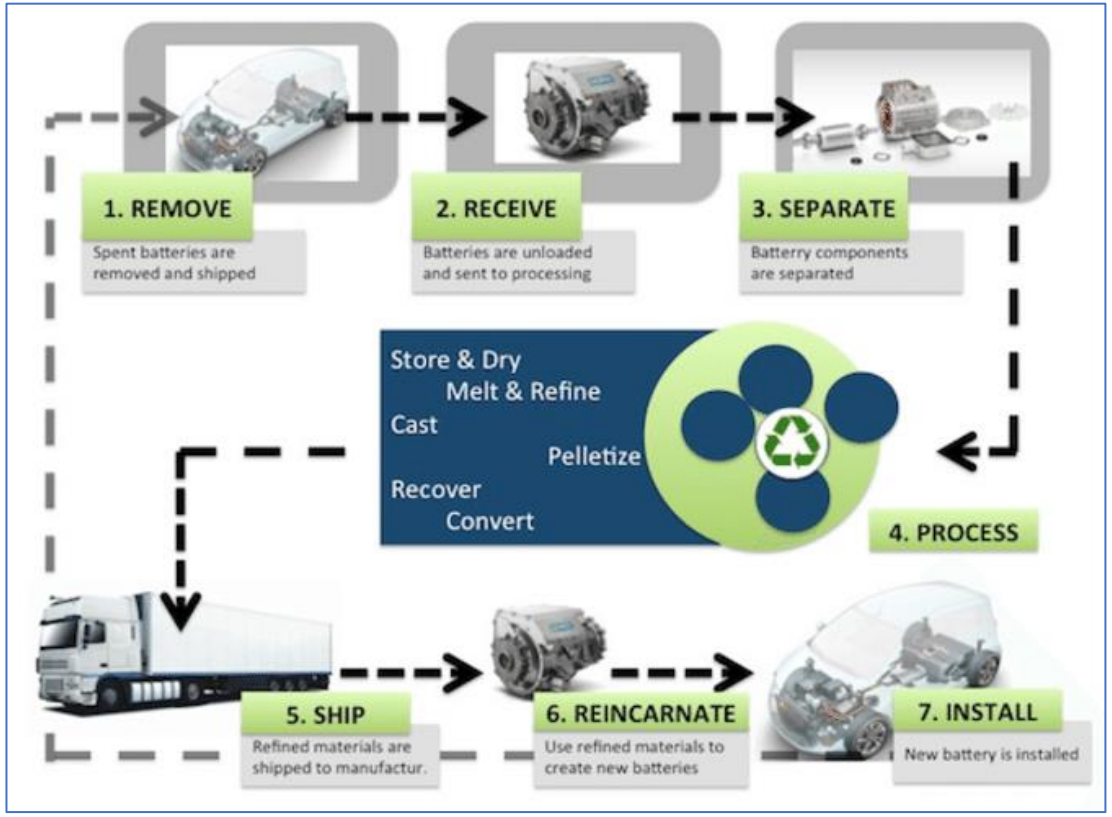
Investment Is Pouring Into EV Recycling

Lots of Players



* Note: Non-exhaustive list (includes those agents with recent announcements associated with the sector or participants in large alliances).

A Emerging Value Chain



Higher raw material prices drives more investment in recycling.

If recycling capacity grows sufficiently, it helps reduce dependence of EV industry on new mining.

Charging Innovations

Disruptive Technologies Often Only Demonstrate Their Biggest Impact After a Swarm of Related Innovations

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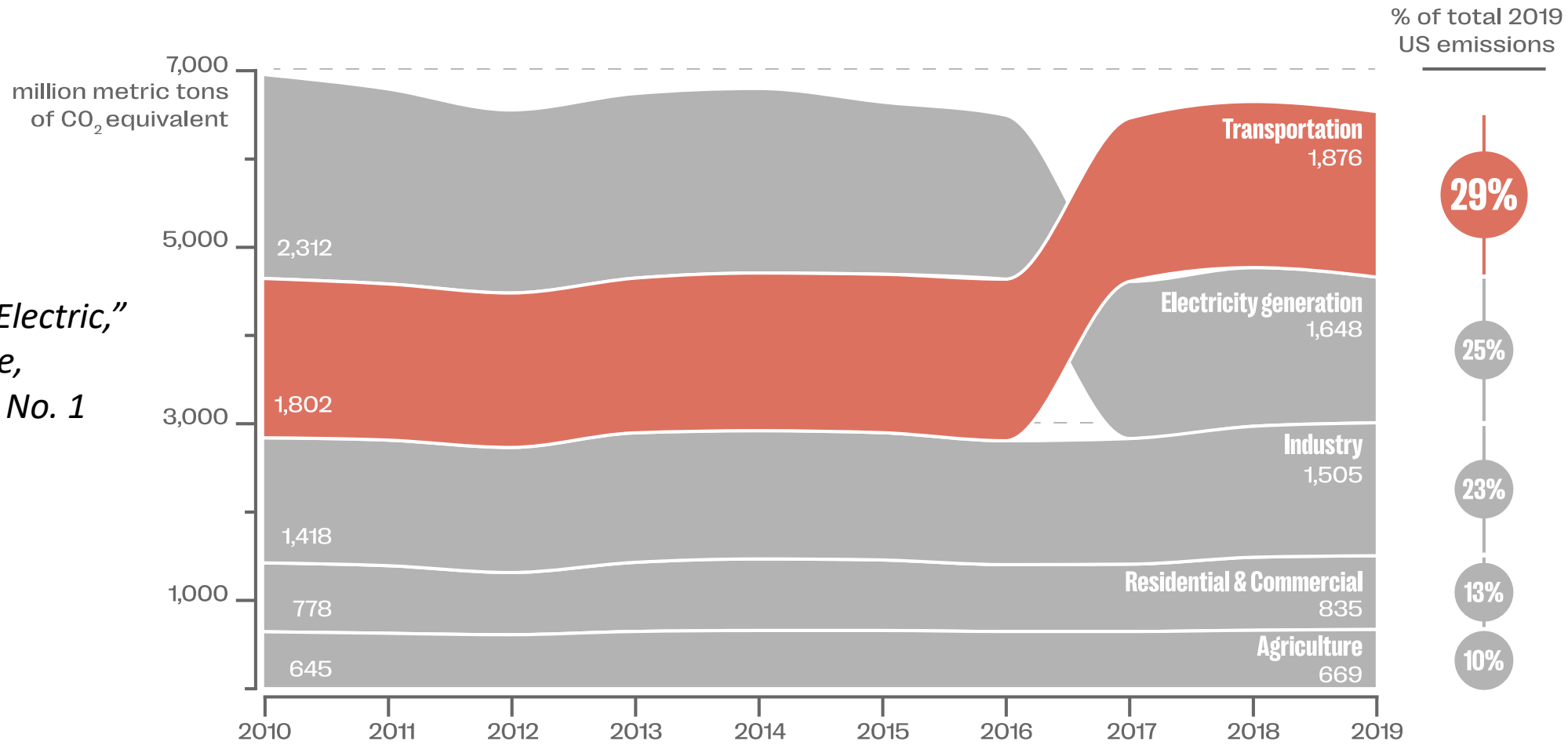
  - Charging → electrification for decarbonization; new sources of electricity; public policies favoring clean energy; multi-mode 'refueling'; both decentralized and centralized grid enhancements; smart grid tools/ incentives
  - Affordability → public policy to speed cost parity; used EV and PHEV markets; physical innovations tied to vehicle market segments; more multi-mode mobility options; P2P vehicle sharing; remove "dirty" products

Electrification Is Urgently Needed for Transportation

FIGURE 1.1

Transportation is the Leading Source of Greenhouse Gas Emissions in the US

"Mobility Becomes Electric," J.P. MacDuffie, report for Engine No. 1



Source: EPA Greenhouse Gas Inventory Explorer

Drop in Price of Alterative Sources of Electricity Has Dramatically Changes the Playing Field

- “In 2009-10, solar PV cost 10x what they cost now - and onshore wind farms cost 3x what they cost now.”
- “Put differently, 90% drop in solar PVs -- and in cost per kWH of lithium-ion batteries. 70% decline in the cost of wind.”
- “That changes the playing field for climate policy. What it would cost to have 10x the political will - that is what we unlocked by driving down solar PV and Li-ion costs by factor of 10.”
- “10x easier to take action for a given amount of political will.”
- **“All before the new U.S. legislation. (Infrastructure Bill; CHIPS Act; Inflation Reduction Act)”**

Jesse Jenkins, NetZero Project, Princeton on Ezra Klein podcast, 9/20/22

Q: “How Do These New Bills Make Scaling Clean Energy Easier?”

- “Focuses on making clean energy cheaper” - subsidies via tax credits, rebates for weatherizing, loans to towns. “Put thumb on the scale for clean vs dirty energy.”
- “Many countries subsidized deployment of those technologies when they were expensive and created the early markets that drove innovation and cost declines.”
- **“Not pricing carbon but decarbonizing energy production. Economists want product prices to represent their true cost. But making fossil fuels more expensive is politically impossible.”**
- “Alternative is less economically efficient but much more likely to succeed. Cleaner energy develops public goods – less emissions, less air pollution, better public health, fewer extreme weather event – hence worth subsidizing.”
- “Move cost of clean energy off households and onto the progressive tax structure of the federal government - 15% corporate tax plus go after tax cheats.”

Jesse Jenkins, NetZero Project, Princeton on Ezra Klein podcast, 9/20/22

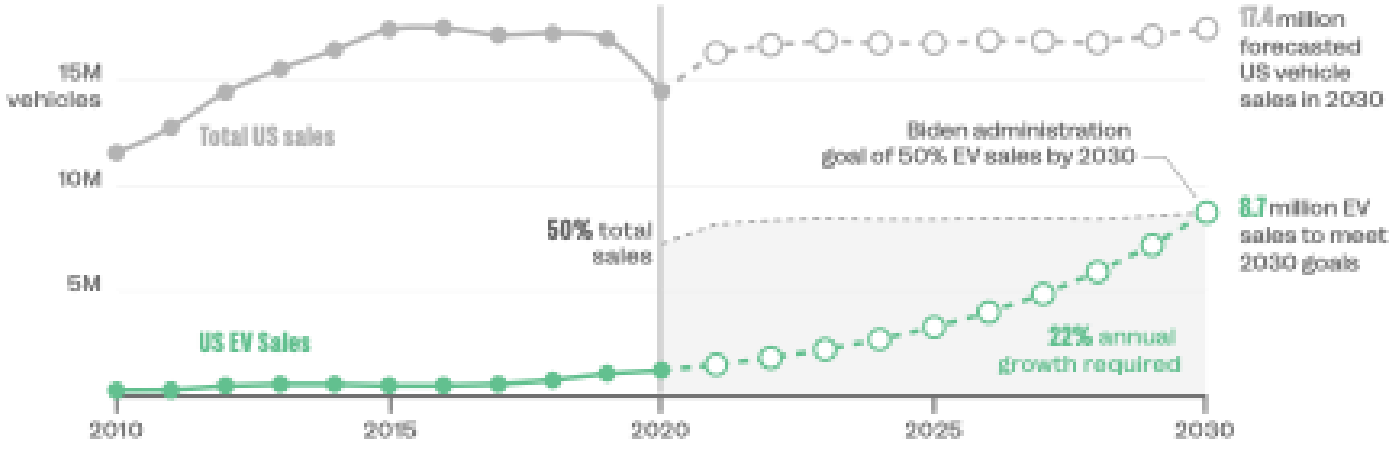
Between now and 2030. increasing diffusion of BEVs is the surest path to electrifying transportation

"Mobility Becomes Electric,"
J.P. MacDuffie,
report for Engine No. 1

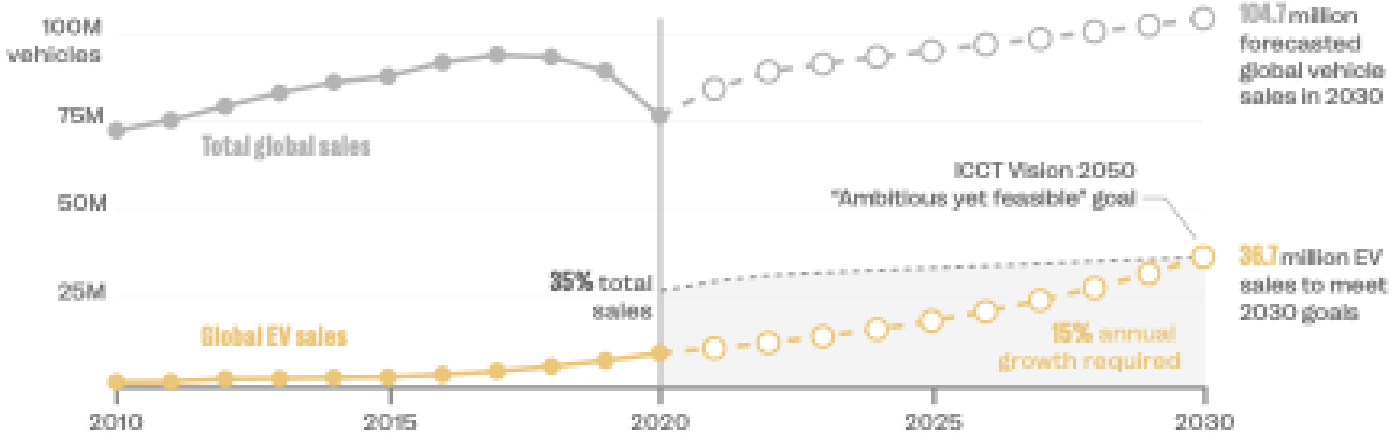
FIGURE 3.1

Aggressive Growth in EV Sales is Required to Meet 2030 Goals

A) US forecast for light vehicle sales and requirements to hit Biden Administration goal of 50% EV sales by 2030

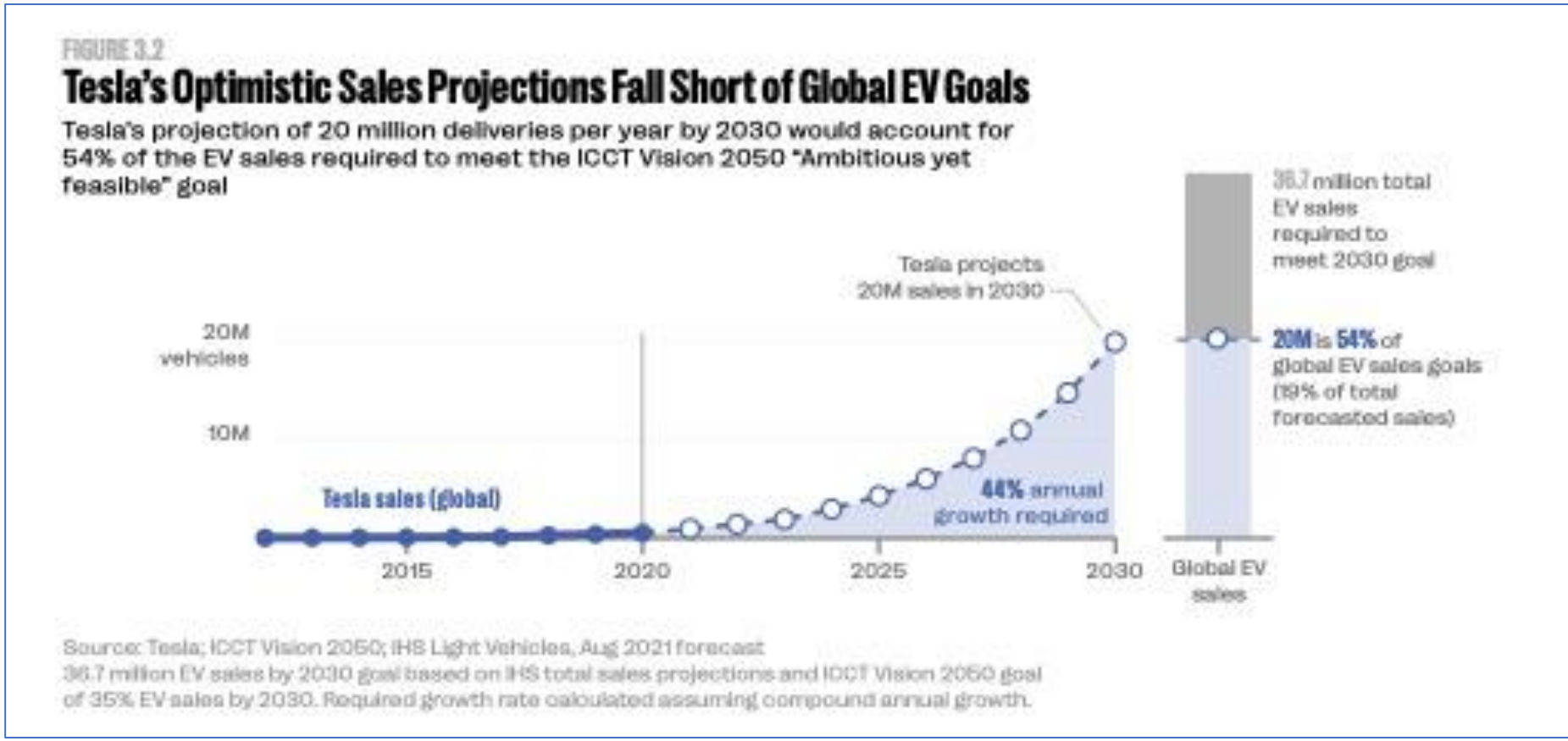


B) Global forecast for light vehicle sales and requirements to hit ICCT Vision 2050 "Ambitious yet feasible" goal for global EV sales in 2030



Source: EV-Volumes; IHS Light Vehicle Sales, Aug 2021 forecast; US Bureau of Economic Analysis; ICCT Vision 2050
Required growth rate calculated assuming compound annual growth.

“The Tesla Is Not Enough”: Incumbent Automotive OEMs Are Needed To Speed the EV Future



“Mobility Becomes Electric,”
J.P. MacDuffie,
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Tesla’s most optimistic forecast is selling 20 million/year by 2030.
That’s double the current size of Toyota or VW.
And would still only be 1 out of 5 vehicles sold annually worldwide.

Charging Infrastructure Is Now An Urgent Matter – And, in the U.S., Has Gained New Subsidies

Home

Actor: Homeowner; Landlord

Charging Hours: Overnight

Charging Duration: 8-12 hours

Financed by: EV Owner

Other Benefits: Home Grid System

Subsidized!

Around Town

Actor: Municipalities; Businesses

Charging Hours: Daytime

Charging Duration: 0.5-8 hours

Financed by: Charger Lease/Purchase

Other Benefits: "Customer" Perk

Subsidized!

Highway

Actor: Federal Government

Charging Hours: Road Trips!

Charging Duration: 0.5-1 hour

Financed by: Federal Government

Other Benefits: Range Anxiety

Subsidized!

Many Grid Investments and Enhancements Are Needed – and Smarter Grid Policy – e.g.,

- How to apply incentives for off-peak EV charging based on actual charging time?
- Need to distinguish between electricity used to charge an EV and power used simultaneously for other purposes by the same customer – *aka* load disaggregation.
- Con Edison and GM are working together on accurate smart meter measures of this.
- Reliable load disaggregation encourages participation in off-peak EV charging incentive programs. Con Edison, 10/12/22

- At what times should EV owners be encouraged to charge?
- In California, not at home.
- Cheapest prices for electricity from wind and solar are late morning and early afternoon.
- Nighttime requires storage.
- Best to incentivize daytime charging – while at work or around town. Stanford U News, 9/22/22

Ideas and Politics Will Matter

- As (if) electrification for home and transportation is understood, accepted, and supported, home charging for EVs will become subsumed in a broader idea of developing a decentralized smart grid – and support will grow
- As (if) electrification for home and transportation is also linked to visible cost savings, new and good jobs, support will grow
- Electrification – and all climate policies – can be politicized
- Jurisdictional disputes (municipal, state, federal) over installing charging infrastructure and grid enhancements can also be a barrier
- The hope: streamlined & facilitated permitting; training for the new jobs; and visible changes in the built infrastructure will build political support

Affordability Innovations

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Affordability Is One Aspect of Accessibility (and What I Cover Here)

- Accessibility to EVs is a broader question than affordable prices.
- Urban vs. suburban vs. rural is another crucial dimension.
- Accessibility is heavily intertwined with charging infrastructure; affordability is less so
- Indeed, one key affordability issue is ”gateway” access to BEVs through PHEVs – can be charged but also has ICE backup when needed
- I emphasize the growth/evolution of used EV vehicle markets, BEV and PHEV

With Lower Operational Costs, Primary Barrier is Front-End Purchase

- EVs have lower “fuel” price; lower operational expenses and maintenance needs --> lower lifetime ownership costs than ICEVs
- Purchase prices for EVs have stayed high – and current high demand and limited supply limits price competition
- Current tax credits only apply when filing your taxes – and no longer apply to the most popular models
- EV “sticker shock” when seeking to purchase is high

Inflation Reduction Act Subsidies Are Well-Designed to Help (Though Not Immediately)

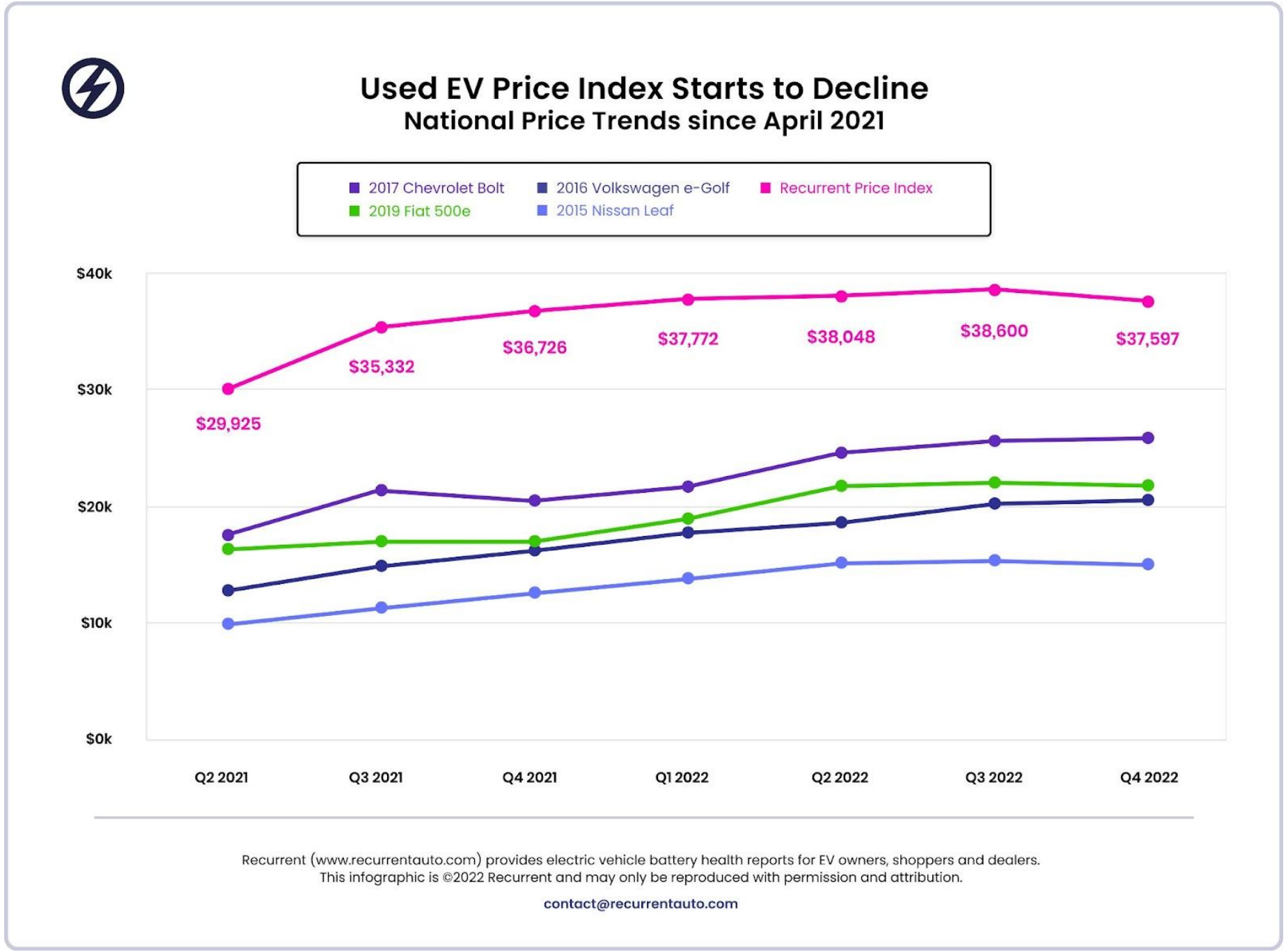
- Allows point-of-sale incentives
- Removes vehicles-per-manufacturer cap.
- Creates purchase price and income limits:
- Extends the tax credit to pre-owned EVs.
- **PHEVs are included** - important because they can be owned by people without ready access to charging

Inflation Reduction Act Subsidies Are Well-Designed to Help (Though Not Immediately)

- Allows point-of-sale incentives starting in 2024. Purchasers will be able to apply the credit (up to $7,500) at the dealership, reducing sticker shock.
- Removes 200,000 vehicle-per-manufacturer cap. Brings back the tax credit for some popular and affordable EVs, which should attract new buyers.
- Creates income and purchase price limits:
  - SUVs, vans, and pickup trucks priced under $80,000, and all others (e.g. sedans) under $55,000.
  - For new vehicles, AGI cap on purchaser income: $150K for individuals; $300K for a joint filer.
- Extends the tax credit to pre-owned EVs.
  - Purchase price can not exceed $25,000
  - Model year must be at least two years earlier than the calendar year of the purchase
  - Tax credit for 30% of the sale price up to $4,000.
  - The AGI cap for pre-owned EVs is $75,000 for individuals and $150,000 for a joint filer.
- **PHEVs are included** - important because they can be owned by people without ready access to charging

Used EV Market Will Grow

- Used vehicles are already the most common purchase of income-constrained buyers
- Longevity of modern vehicles (average of 13-14 years in U.S.) means potential for multiple owners
- With mostly older Tesla models available, used EV prices are high
- Proliferation of new EV models will, in time, provide lower-price options
- Used EV tax credit (in IRA) won’t cover many models at first
- PHEVs will get the tax credits, boosting this type of hybrid (over HEV)

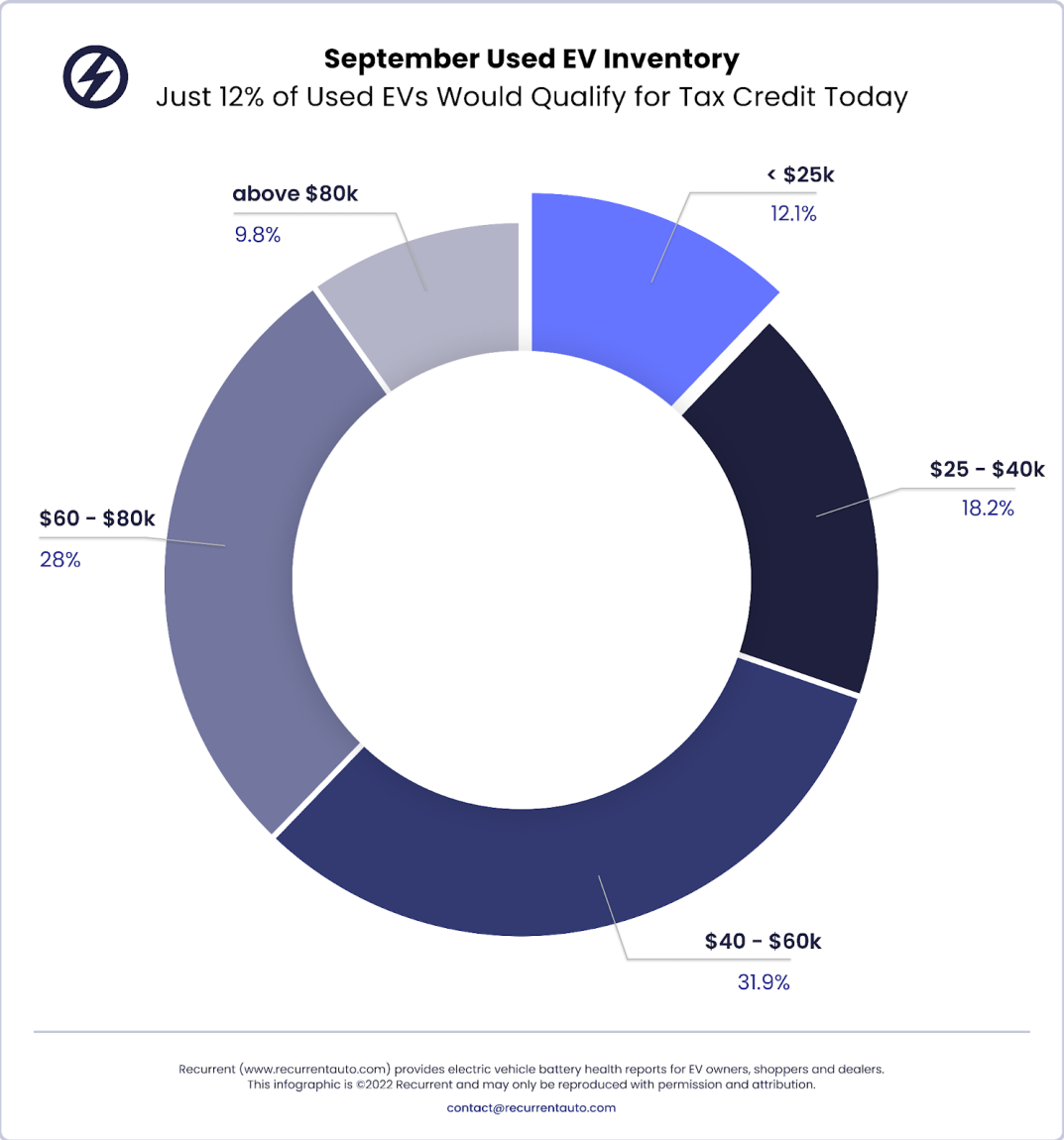


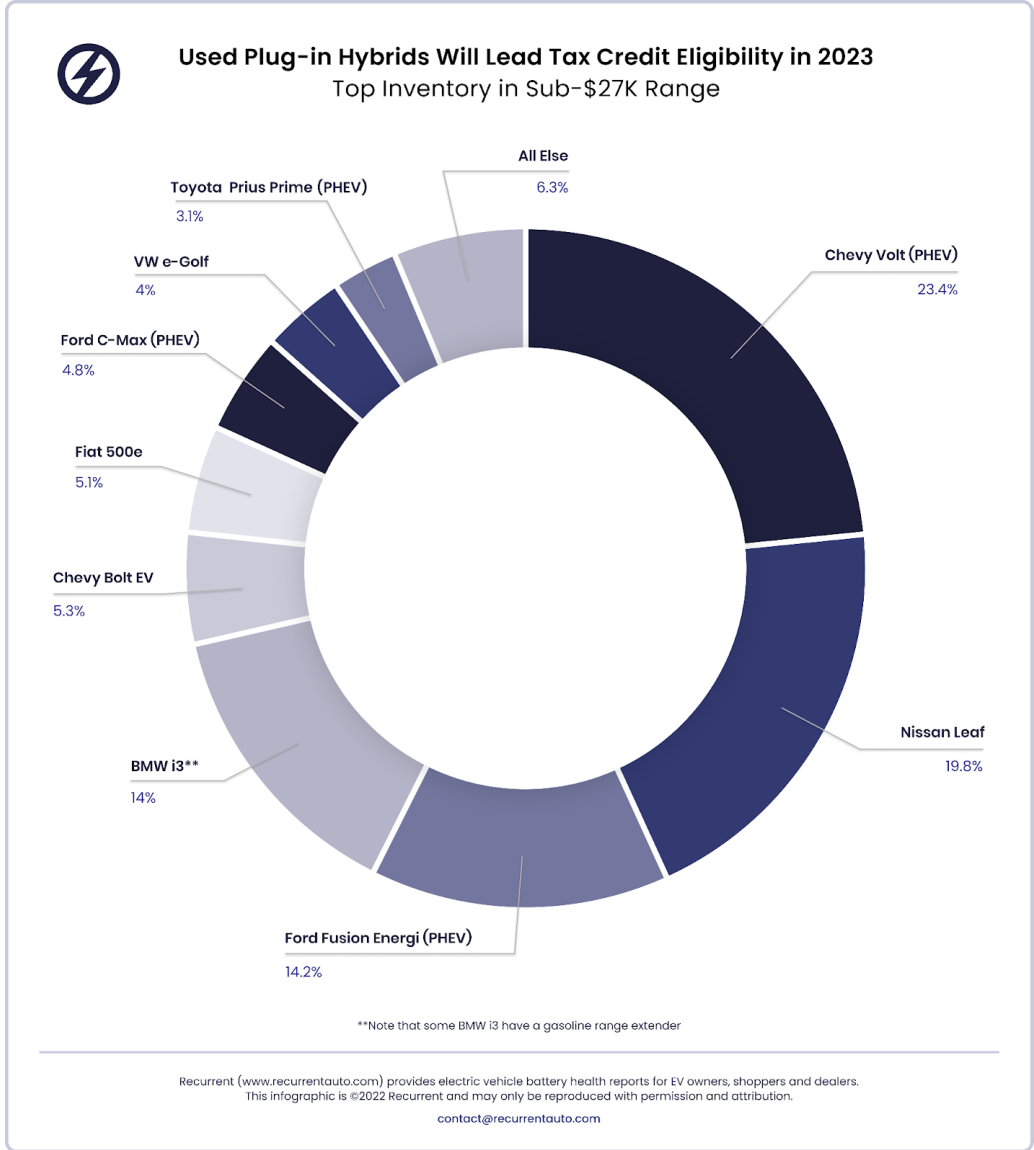
Recurrent Price Index Includes:

- 2017 Chevy Bolt
- 2017 BMW i3
- 2017 Tesla Model S
- 2018 BMW 530e
- 2018 Nissan LEAF
- 2018 Honda Clarity
- 2019 Audi e-tron
- 2019 Tesla Model 3
- 2019 VW e-golf

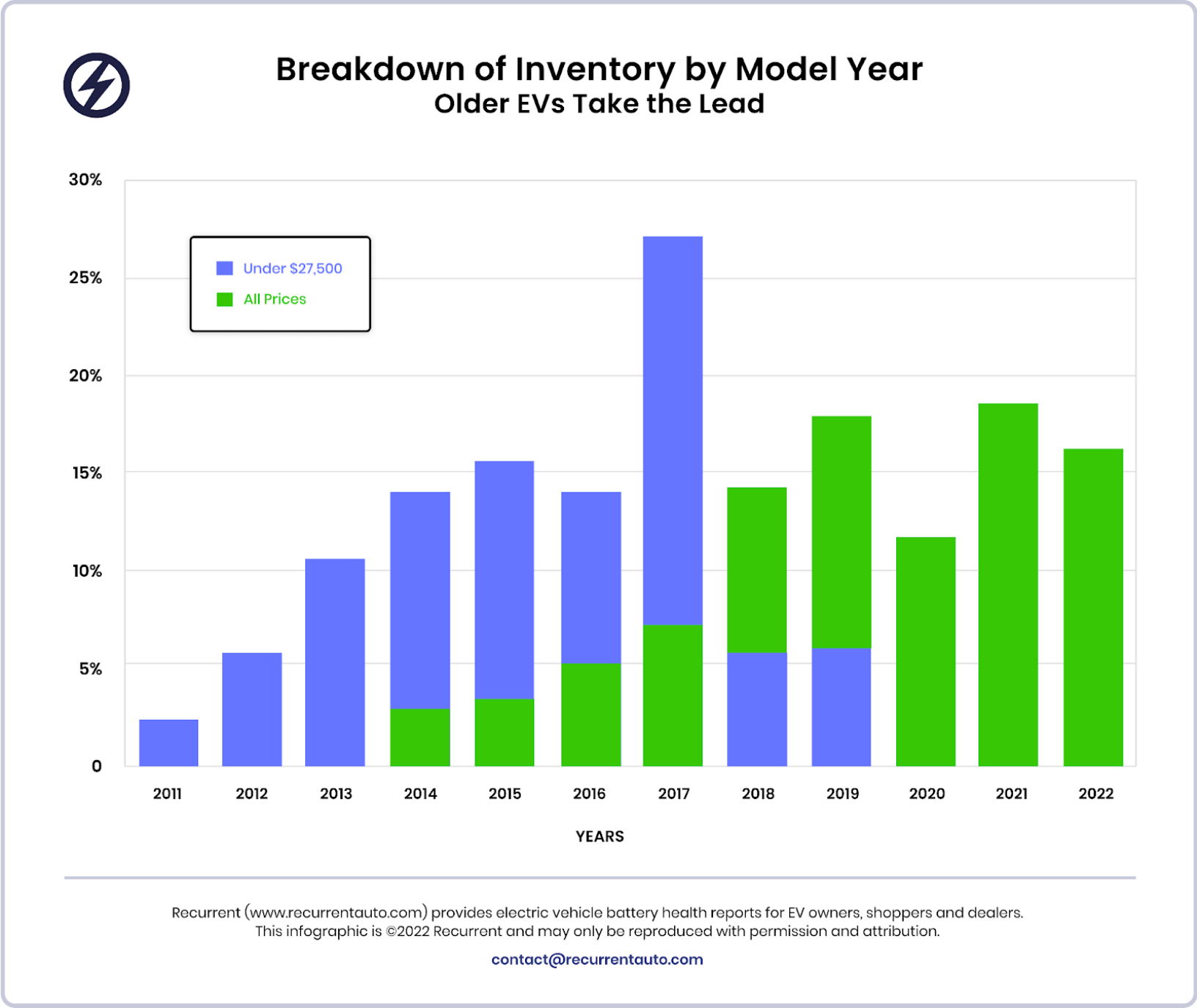
Recurrent.com, Q4 2022 report

Few Current Used EVs (12%) Will Be immediately Eligible for the Tax Credit



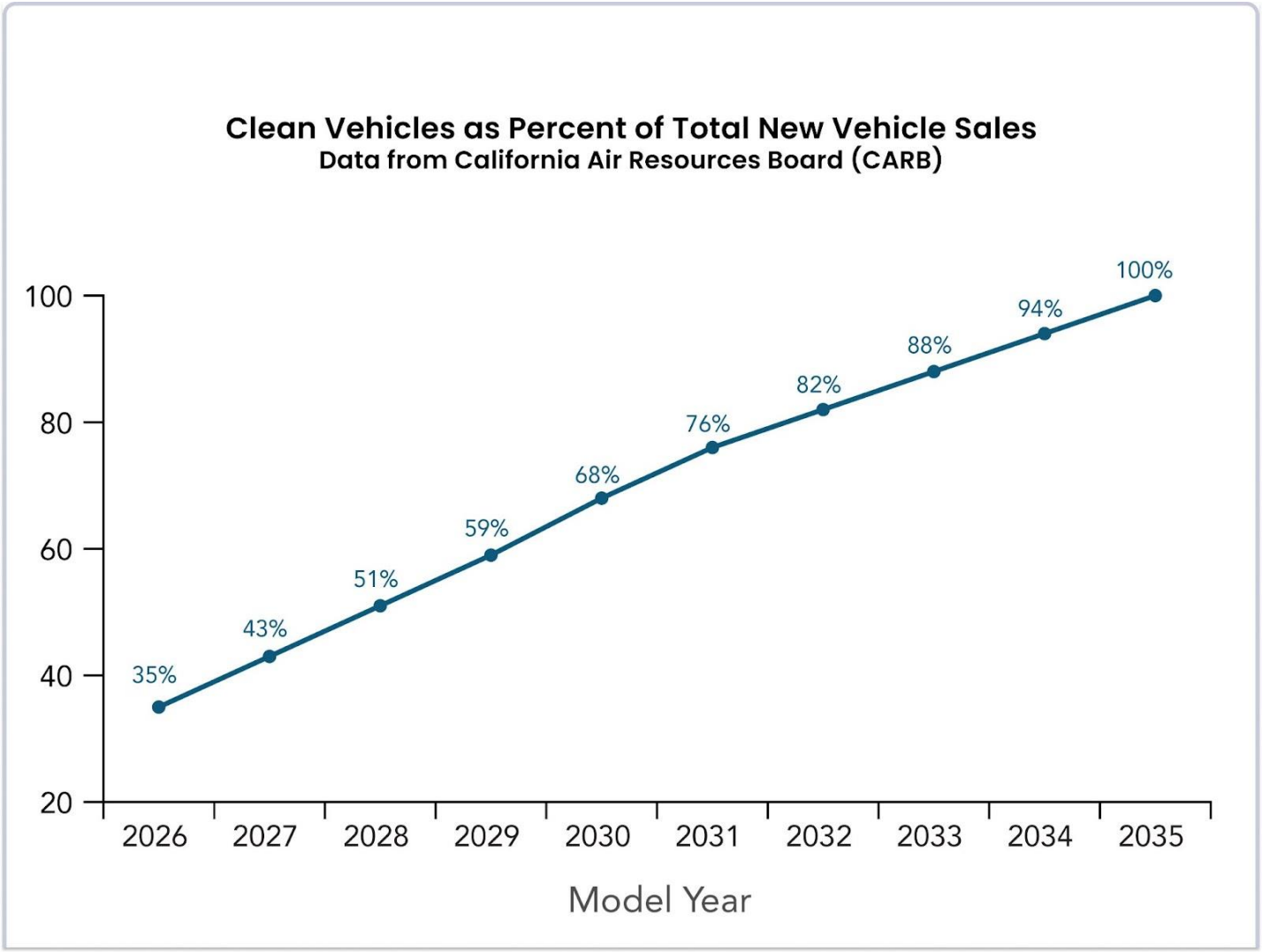


To get federal tax credit, used EV purchase price must be under $27,500 (blue bar)



Recurrent.com, Q4 2022 report

Mandates at State Level Will Boost EV Sales – and (Soon) Supply of Used EVs



California's mandate is the most ambitious/ aggressive

Other states that follow CA's standards for emissions may choose similar mandates

Politically complex – but could speed transition to electrification and path to more affordable EVs

Other trends that will help w/ affordability

- LFP batteries work well in smaller vehicles – and can be cheaper
- Imports of smaller and cheaper EVs may grow (though won't qualify for full tax credits under current rules)
- China very much wants its EV manufacturers to be global exporters (though current US-China dynamics may impose constraints)
- Peer-to-Peer business models – private owners renting out their vehicles for use – could make EVs more affordable (Tesla promises this)
- Urban dwellers with many low-emissions mobility options – e-bikes, e-scooters, EV taxis – may buy a small EV/PHEV (or forego ownership)

The Most Affordable Vehicles Will Continue to Be Used ICEVs

- Problematic because they have the most emissions, lower miles per gallon, less safety equipment
- “Cash for clunkers” programs to get the oldest, dirtiest vehicles off the road have a mixed history
- Well-designed policies could be critical to speeding the transition to affordable EVs for those currently relying on these vehicles
- For a thoughtful examination of what these polices would be, see a recent study by MIT System Dynamics faculty here

SUMMARY

Staying Alert to the Swarm of Innovations Underway Will Help Identify the Paths Forward

- We've moved beyond questions of "whether" & "chicken and egg" debates
- Now the questions are "when and "how" -- around a set of still-thorny but more tractable problems.
- Expanding EV supply and multiple forces affecting EV demand are creating favorable conditions for a swarm of innovations
- Some are highly visible, others behind the scenes, from both private & public sectors
- *In my view, taken as a whole, they yield promising paths for addressing these problems*

Innovations Will Support EV Momentum – and Also Reveal New Problems

- New problems are also tractable but involve tough tradeoffs:
  - Batteries → more battery-vehicle integration and some new chemistries make second-life applications and recycling for raw materials more difficult
  - Charging → jurisdictional and permitting complexity that slows rollout of multi-mode refueling options, constraining demand
  - Affordability → used ICEVs will be a primary choice for many due to affordability; removal of the dirtiest will help; value of PHEVs as gateway to BEVs (esp. used) but supply is (will be) low

Questions?