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Comparison of Low-Carbon Transport Strategies in California and Europe

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Institute of Transportation Studies, University of California, Davis

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16. Abstract
A rapid transition to a near-zero-emission transportation system in California and Europe will require rapid uptake of transportation technologies, changes in transportation services, and investments in associated infrastructure. These in turn require policy innovations. This report compares California and EU policies across three broad areas: 1) greenhouse gas (GHG) targets for 2030 to 2050; 2) progress on reducing GHG emissions from different transportation modes; and 3) current strategies and policies to achieve targets. Differences by region and across major modes are identified. Strategies cover electrification, uptake of hydrogen, aviation and shipping fuels, and modal shifts. Policies include regulatory requirements (fuel economy and CO2 standards, fuel standards); incentive programs, including taxation, feebates, and others; direct investment programs; equity considerations and environmental justice-related initiatives. In both geographies, a range of impactful policies are in place. However, these fall short of guaranteeing that targets will be met, and more actions will likely be needed. Some possibilities are presented, with a particular focus on pricing strategies.

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Glossary

ACC	Advanced Clean Cars (title of a CARB regulation)
ACF	Advanced Clean Fleets [rule]
ACT	Advanced Clean Trucks [rule]
BET	battery-electric truck
CAFE	Corporate Average Fuel Economy
CAGR	compounded annual growth rate
CVRP	Clean Vehicle Rebate Project
EU	European Union
GHG	greenhouse gas
ICE	internal combustion engine
ICEV	internal combustion engine vehicle
LCFS	Low Carbon Fuel Standard
LDV	light-duty vehicle
LEV	Low-Emission Vehicle (title of a CARB regulation)
MDHV	medium- and heavy-duty vehicle
PHEV	plug-in hybrid electric vehicle
SAF	sustainable aviation fuel
VMT	vehicle miles traveled
ZET	zero-emission truck
ZEV	zero emission vehicle (ZEV is a global term that encompasses battery electric and fuel-cell electric vehicles It often includes plug-in hybrid vehicles as well).
ZLEV	zero- and low-emission vehicles

Executive Summary

Achieving a near-zero CO_2 transportation system within California by 2045 will be challenging but is needed as part of reaching the state's broader goal of carbon neutrality by that year. A rapid transition will require a revolution in the rate of uptake of transportation technologies, the way transportation services are provided, and associated infrastructure. New policies will also be needed to bring these technologies and services to bear and to ensure economic viability. Like California, Europe has ambitious decarbonization goals. These two regions can learn from each other in terms of their targets, policy plans, and on-going progress and challenges. It should be noted that some policies in California discussed here are currently contested or restricted by the Federal government, but are still relevant to the discussion.

As part of this review, we compare California and the EU (and its member states) across three broad areas:

1. Transportation greenhouse gas (GHG) targets for 2030 to 2050 and how the pathways to various targets vary over time, in absolute terms and percentage or per capita values.
2. Progress on reducing GHG emissions from different transportation modes; recent modal trends in per capita access and utilization; demographic, economic and transportation indicators.
3. Current strategies and policies, and their impacts; review of initiatives and strategies, (such as whether electrification goals dominate; role of hydrogen, electrified roadways, aviation targets, focus on mode shifts to lower emissions, etc.). Policies include regulatory requirements (fuel economy and CO_2 standards, fuel standards); fiscal and non-fiscal incentive programs including taxation; direct investment programs; equity considerations and environmental justice-related initiatives.

Light Duty Vehicles

- California could better understand European taxation policies for internal combustion engine (ICE) vehicles (based on CO_2 emissions and other vehicle parameters, and – in some cases –integrating equity-related conditions) to generate sustainable revenue flows for EV rebate programs, including for smaller, more affordable, EVs.
- Targeted rebates towards low- and middle-income consumers will be crucial for California (which could also include incentives for retrofits) and EU countries to manage the accelerated transition to ZEVs by 2035.
- EU countries could include household income limits for new EV purchase incentive eligibility, taking lessons from California's Clean Vehicle Rebate Program (CVRP) and conditional access to incentives based on income, already used in specific programmes such as the social leasing in France.
- The phase-down of purchase incentives for plug-in hybrid electric vehicles (PHEVs) remains a key consideration, given growing evidence from Europe of limitations in PHEV electric driving use.

Germany has begun to phase-out rebates for PHEVs and reduce overall incentives for zero-emission vehicles (ZEVs) from 2024 onwards. California is also revamping its incentive program with a focus on battery electric vehicles (BEVs) for low- and middle-income buyers.

Medium and Heavy-Duty Vehicles

- Europe and California have already adopted a range of policies, including regulatory and pricing approaches, to promote the transition to low- and zero-emission medium- and heavy-duty vehicles.
- While California has relied primarily on increasing sales and purchase requirements of ZEVs (so-called "ZEV mandates"), Europe is relying primarily on vehicle CO_2 regulations to help promote ZEV adoption. In the EU, important complementary policies include minimum deployment requirements for charging points and hydrogen refueling stations, the possibility for road usage charges for lorries and buses to be differentiated based on CO_2 and pollutant emission performances, and a generally higher level of taxation on fossil fuels.
- Both regions acknowledge the need for vehicle price incentives to achieve total cost of ownership (TCO) parity (or better) with diesel trucks. This will help with adoption rates, as will improvements in charging infrastructure and cost. In Europe, pricing policy happens at the member state level and these policies can vary considerably within and between jurisdictions. This is also true in California, with some incentives differentiated by district. Also, California has different incentive systems than other states in the US and can be considered as equivalent to a single EU member state in that regard.
- The two markets are linked by the need to bring down zero-emission truck (ZET) prices, which will occur over time and with increasing sales volume. In cases where the same vehicles—or even the same manufacturers—operate in both regions, the manufacturers leverage scale across the US and EU markets.

Aviation and Maritime

- Include aviation and maritime in 'Cap and Trade' programs in California and allocate revenues for sustainable aviation fuels (SAFs) sustainable shipping fuels, low carbon fuel infrastructure, and fleet modernization investments.
- Introduce an overall sector-specific cap on aviation and maritime emissions within California (intra-state), in line with the state net zero goals.
- Explore a regional initiative to address aviation and maritime emissions with other states authorized to adopt California's emissions standards (Section 177 states) or states with the Low Carbon Fuel Standard (LCFS).
- Monitoring, reporting and verification framework for CO_2 and non-CO_2 emissions for both aviation and shipping (at least for travel within California and eventually trips originating from California). Such a framework can potentially lead to legislative action on emission mitigation.

Conclusions

A number of specific recommendations are provided in the last section of the document. Overall, we find that while both California and Europe have put in place significant, often strong, policies to help achieve their GHG reduction targets for transportation, there are further steps that could be taken, and the two geographies could learn from each other and probably adopt a number of policies already adopted by the other. Additional and ongoing comparisons, leading to discussions between policy makers in the two geographies, might yield important new initiatives and policy innovations. The situation in 2026 is dynamic and further comparisons may best be reserved for a time when the US has a clear, new direction on promoting the uptake of zero-emission vehicles.

Contents

1. Introduction

Achieving a near-zero CO_2 transportation system within California will be challenging but is needed as part of reaching the state's goal of carbon neutrality by 2045 (CARB, 2022). Forty percent (40%) of in-state greenhouse gas (GHG) emissions come from vehicle exhaust, and this percentage is even higher if one considers well-to-wheel emissions—i.e, from fuel production or extraction, refinement, delivery, etc. (CGII, 2025). The key transportation modes contributing to these emissions are household light-duty vehicles (LDVs), commercial trucks, buses, rail, aviation, and shipping. While there are unique inter- and intra-modal differences, potentially mature technologies are available today to achieve low-carbon goals for each mode. A rapid transition will require a revolution in the rate of uptake of transportation technologies, the way transportation services are provided, and associated infrastructure. New policies will also be needed to bring these technologies and services to bear and to ensure economic viability. Like California, Europe has ambitious decarbonization goals, and the two regions can learn from each other in terms of their targets, policy plans, and on-going progress and challenges.

California is often seen as a world leader in low-carbon transportation policies, including 100% zero-emission vehicle (ZEV) mandates, vehicle and infrastructure incentives, and the Low-Carbon Fuel Standard (LCFS). However, these policies are likely not enough to achieve net zero goals by 2045, as highlighted in the 2022 Scoping Plan by the California Air Resources Board (CARB, 2022). The Plan highlights some key additional policies, such as a ZEV mandate for trucks, having a dominant share of sustainable aviation fuels, reduction in vehicle miles traveled (VMT), and mode-shift. The Scoping Plan will serve as an important roadmap document, but California would also benefit from additional analysis of other national sustainable transportation strategies, especially from leading European countries (such as the UK, Germany, and France) and the EU overall, that can be contextualized for California.

In the EU, the adopted "Green Deal" can be seen to draw parallels with the California Scoping Plan. The European Green Deal is outlined in a communication, released by the European Commission in 2019. It defines a growth strategy to transform the EU into a fair and prosperous society, with a modern, resource-efficient, and competitive economy; no net emissions of greenhouse gases in 2050; and decoupling of economic growth from resource use (European Commission, 2019). The same communication refers to the importance of an inclusive and just transition allowing the EU to protect, conserve, and enhance its natural resources , as well as the health and well-being of citizens from environment-related risks and impacts.

As part of this review, we compare California and EU policies across three broad areas:

1. **Targets:** Review of transportation GHG targets at the level of the EU (and specific member states), for 2030 to 2050; how the targets compare to those in California, and how the pathways to various targets vary over time, in absolute terms and percentage or per capita values.

2. **Progress** on reducing GHG emissions from different transportation modes; recent modal trends and per capita access and utilization; comparing demographic, economic and transportation indicators across the EU and member states to California.
3. **Current strategies and policies**, and their impacts; overall review of initiatives and strategies, (such as whether electrification goals dominate; role of hydrogen, electrified roadways, aviation targets, focus on mode shifts to lower emissions, etc.). Policies include regulatory requirements (fuel economy and CO_2 standards, fuel standards); fiscal and non-fiscal incentive programs including taxation; direct investment programs; equity considerations and environmental justice-related initiatives.

Since policies can change almost on a daily basis, there may be policy changes in both California and the EU after this paper is published that alter the current situation. There is, in particular, a situation in California at the time of publication where the Federal government has restricted California's ability to implement some key regulatory policies, such as Advanced Clean Cars II and Advanced Clean Trucks. We still report on these policies and consider them in the context of what the EU has focused on, and what additional policies might make sense for California.

The paper is organized as follows. First, we lay out the European policy landscape, then focus on California's policies and plans. This is followed by a comparison of the two with a detailed look at road transportation. Finally, we extend the analysis and comparisons to cover aviation and shipping.

2. Overview of European Transport, Energy and Climate Policy

The European Green Deal was formally adopted in 2020. A set of targets and strategies to support it, including a 55% reduction in CO_2 by 2030 (“Fit For 55”), was adopted in phases during 2021–23 (European Union, 2021). The Green Deal sets the vision and foundation for the EU’s overall climate strategy and legislation. Its vision is grounded in scientific evidence regarding risks associated with climate change and biodiversity loss. These are not limited to the EU but have global relevance and lessons for California as well.

The European Green Deal (European Union, 2019) communication includes an initial roadmap of the key policies and measures to mainstream sustainability. These include:

- The proposal for the first European ‘Climate Law’.
- The application of effective carbon pricing across the economy, including for transport modes (aviation and shipping) not previously subject to it.
- Tools meant to handle the risk of carbon leakage (including through a carbon border adjustment mechanism, for selected sectors).
- Measures fostering a green and digital transformation of transportation.
- Support for renewable electricity and smart infrastructure to ensure access to cheap and low-carbon energy, strengthened further following the Russia-Ukraine conflict, with the ‘RepowerEU’ plan.
- The promotion of a circular economy as a way to ensure resource efficiency and long-term economic competitiveness.
- The enhancement of energy efficiency in buildings and transport and the deployment of alternative energy infrastructure.
- A reorientation of agricultural policy towards climate action.
- The establishment of a Just Transition Fund to support the economic diversification and reconversion of territories that are most impacted by the transition towards climate-neutrality. This fund would complement other funds focused on cohesion and the Social Climate Fund to mitigate social inequalities, leveraging a specific carbon pricing mechanism for buildings and transport.
- The development of a revised sustainable finance strategy, including a taxonomy for classifying environmentally sustainable activities and stronger disclosure requirements for companies and financial institutions.

- The revision of State aid guidelines to a cost-effective transition to climate neutrality by 2050; this includes facilitating the phasing-out of fossil fuels and considers the economic impact of COVID-19 and the Russia-Ukraine conflict.
- The mobilization of research funding, education, and training to increase deployment and demonstration of climate-aligned technologies.
- The use of the EU's diplomatic and financial tools to ensure that: (i) green alliances are part of its relations with other countries; (ii) trade policy is used to engage with partners on climate and environmental action; and (iii) the global financial system supports sustainable growth.

2.1 European Climate Law and "Fit for 55" package

The Climate Law, established in 2021, followed the strategic lead already included in the European Green Deal communication. It requires the European Union to achieve carbon neutrality by 2050 and to reduce GHG emissions by 2030 to 55% of the 1990 levels (European Union, 2021). It was followed by the proposal of the "Fit for 55" package, which refers to the reduction of GHG emissions by 2030 by at least 55% of the 1990 levels. This feature was included in the impact assessment of the Climate Law, and it is by now largely enacted as a series of binding legislative instruments, unlikely to be reversed.[1]

The framing conditions that led to the adoption of the Climate Law and the "Fit for 55" package are grounded in scientific evidence from the assessments of the Intergovernmental Panel on Climate Change (IPCC) and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). They illustrate the need to rapidly step-up climate action, continue the transition to a climate-neutral economy and address biodiversity loss.

2.2 European Sustainable and Smart Mobility Strategy

The European Sustainable and Smart Mobility Strategy also follows the European Green Deal communication. It specifies in greater detail the basis upon which the EU transport system can achieve its green and digital transformation, with the stated objective of becoming more resilient to future crises (European Commission, 2020).

The Strategy makes explicit reference to goals such as: the market readiness of zero-emission large aircraft by 2035; at least 30 million zero-emission cars to be in operation on European roads by 2030; nearly all cars, vans,

[1] Its reversal would need new legislative proposals by the EU Commission, followed by negotiations/agreement to be reached in the EU Council and a majority vote in the EU Parliament. Changes could also be possible in the context of revision clauses of the different legislative mechanisms, but they would also need political majorities in the EU institutions to be approved.

buses, and new heavy-duty vehicles to be zero-emission by 2050; zero-emission marine vessels to be market-ready by 2030; and scheduled collective travel for journeys under 500 km to be carbon neutral.

It also mentions clearly, amongst other priorities, the importance of supporting research and innovation on competitive, sustainable, and circular products (implicitly including transport vehicles and fuels), and incentivizing their demand by end-use.

Its impact assessment (European Commission, 2020) is indeed a key reference for the determination of the nature of the proposals included in the ‘Fit for 55’ package regarding transport and mobility.

3. Overview of California Climate Action

The California Global Warming Solutions Act of 2006, otherwise known as Assembly Bill (AB) 32 was a legislative landmark that set the stage for a multi-year program to reduce GHG emissions in the state. The Scoping Plan has since been developed every five years since 2008, providing a review of GHG emissions by sectors and the pathway to achieve climate targets. As shown in **Figure 1**, the 2022 Scoping Plan for Achieving Carbon Neutrality (2022 Scoping Plan) lays out a path to achieve targets for carbon neutrality and reduce GHG emissions by 85% below 1990 levels by 2045. The Scoping Plan estimates 40% of the GHG emissions from transportation, followed by industry (21%), and power (14%).

California has relied on a three-pillar approach to reduce GHG emissions: incentives, regulations, and carbon pricing. As part of its 2030 GHG reduction target pathway, the state has implemented key policies and continues to strengthen them. These include, among others, the Renewables Portfolio Standard, Advanced Clean Cars Rule, Advanced Clean Trucks Rule, Low Carbon Fuel Standard, promotion of a green hydrogen ecosystem (ARCHES, 2023), Short-lived Climate Pollutant Strategy, mobile source measures to achieve federal air quality targets, and a Cap-and-Trade Program.

The 2022 Scoping Plan highlights the need to invest in new and upcoming clean technologies while aiming to avoid stranded assets. The Plan also calls for a regular review to identify and solve any market and implementation barriers. It also includes modeling and analyses of emissions, economics, air quality, health, jobs, and public health. As in the European Green Deal, this analysis is critical to assess trade-offs and inform strategies for balancing climate legislation and a just and equitable transition pathway.

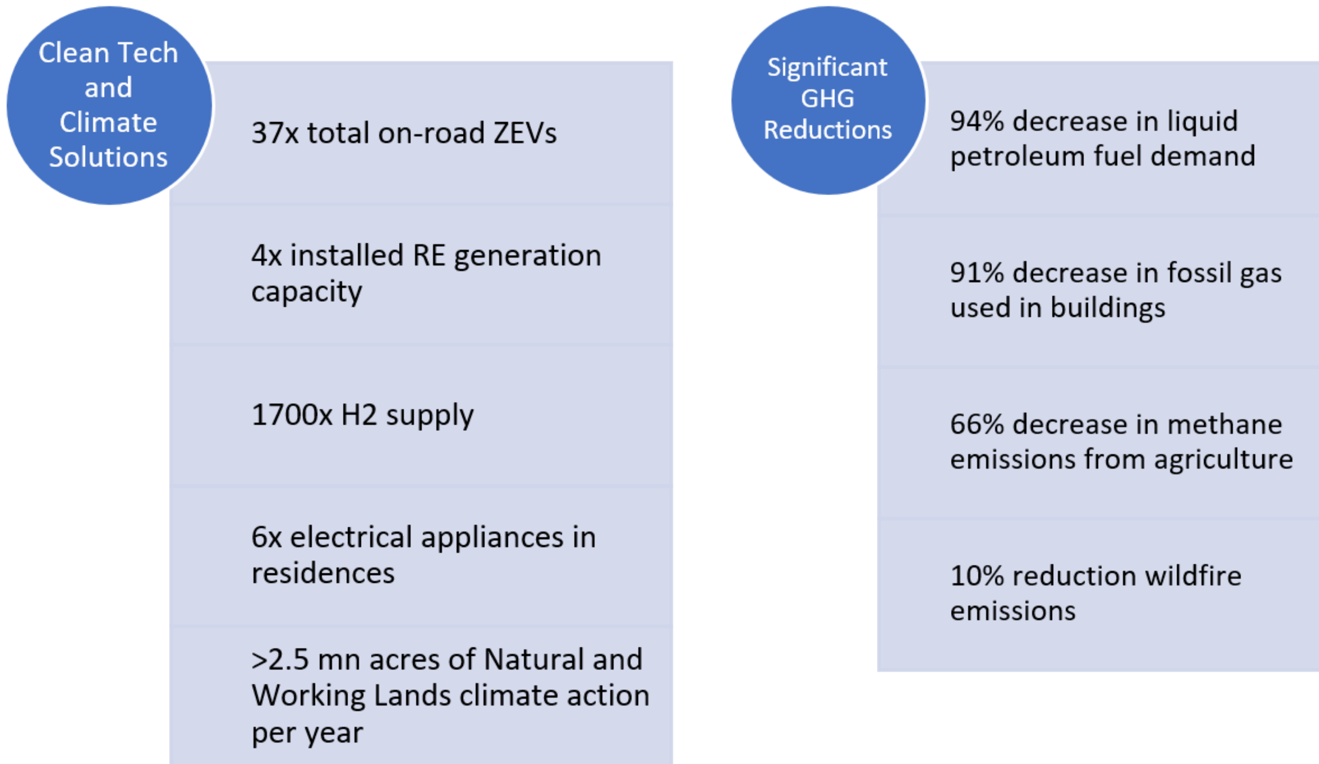

Figure 1. Overview Framework of the California 2022 Scoping Plan.

3.1 Climate Legislation in California

The California Global Warming Solutions Act of 2006 (AB32) required the "State Air Resources Board to reduce statewide emissions of greenhouse gases to at least the 1990 emissions level by 2020 and to maintain and continue reductions thereafter". In 2016, the Senate Bill (SB) 32 added a further amendment requiring that the California Air Resources Board (CARB) shall ensure that statewide greenhouse gas emissions are reduced to at least 40 percent below the 1990 statewide greenhouse gas emissions level no later than December 31, 2030.

While SB32 set the GHG emission reduction target for 2030, California's climate goals were further strengthened by a more recent legislation passed in 2022, known as the California Climate Crisis Act (AB 1279). The Act stated two clear policies for the State of California:

- Achieve net zero greenhouse gas emissions as soon as possible, but no later than 2045, and to achieve and maintain net negative greenhouse gas emissions thereafter.
- Ensure that by 2045, statewide anthropogenic greenhouse gas emissions are reduced to at least 85 percent below the statewide 1990 greenhouse gas emissions level.

The Act further requires CARB to evaluate the feasibility and trade-offs of achieving the above stated policy goals and report to the legislature by December 31, 2035.

California has passed various other legislation addressing statewide emissions, with major policies being passed in 2022. Some of the key policies enacted include: the SB 1383 (2016), which set 2030 targets for Short Lived Climate Pollutants (SLCPs); SB 905 (2022), which establishes a Carbon Capture, Removal, Utilization and Storage Program; SB 1020 (2022), which established interim clean electricity targets (90% of all retail electricity sales by 2035 and 100% by 2045 should be renewable or zero emission); and SB 1075, which requires CARB to evaluate the role of hydrogen in California.

3.2 California's Clean Transportation Strategy

The primary objective of California's ZEV program when it began in 1990 was to reduce local air pollution by controlling and regulating emissions, beginning with tailpipe emissions from passenger cars and trucks In 1990, CARB adopted its first Low-Emission Vehicle (LEV) regulations with the LEV-I package, expanding these into a second-generation iteration with the LEV-II regulations passed in 2004, which introduced stricter criteria pollutant emission standards]. In the same year, CARB adopted the Pavley regulations to target automobile greenhouse gas emissions. In 2012, California began another landmark innovative vehicle emission control strategy with its Advanced Clean Cars (ACC) Program, introducing ACC-I which included the new LEV III criteria pollutant and greenhouse gas emissions standards as well as a new ZEV regulation requiring specific numbers of PHEV and ZEV sales from auto manufacturers. As of 2023, CARB approved the ACC-II regulations, which are set to establish the latest LEV-IV emissions reductions as well as an updated ZEV regulation that will require automakers to have electric vehicles make-up 100% of new LDV sales by 2035. In addition to the LDV regulations, California passed the Advanced Clean Trucks (ACT) and Advanced Clean Fleets (ACF) Rule in 2022-2023, to transition the medium and heavy-duty vehicles (MHDVs) segment to ZEVs. The ACT rule requires all Class 2b-8 vehicles sold in California to be ZEVs from 2036, while the ACF rule requires all fleets operating across California to transition to ZEVs by 2045 wherever feasible. Both the ACT and ACC Programs have been suspended due to Federal intervention, but still represent important policies that deserve to be included in comparisons with EU policies, and are part of California's planning going forward.

4. Comparing California and EU Policies and Progress on Clean Road Transportation

Given the broad and ambitious set of policies that have been enacted in both the EU and California, it is useful to compare them in some detail to understand how they are similar or different, and possible lessons for California from EU policies.

4.1 Decarbonizing Light-Duty Vehicles

In this section, we compare California and EU policies on clean road transportation, with a focus on LDVs, also considering that both markets have a target of 100% ZEV sales among LDVs by 2035.

From 2015 to 2025, annual LDV sales in the EU have been stable at around 12.6 million, with an outlying peak of 14.7 million sales in 2019. On the other hand, LDV sales in California during the same period have had a stable sales of 1.7 million on average annually, with a peak of 1.9 million sales in 2018 (**Figure 2)**.

California had a head-start on the EU with regards to EV adoption because of the State's earlier adoption of ZEV regulations, dating back to the 1990s. The EV sales CAGR from 2015 to 2025 was 38% in the EU and 22% in California (**Figure 2**). In 2025, EVs made up 23% of new LDV sales in California and 25% in the EU. The EU saw a significant jump in EV sales share in 2020 and then again in 2025, getting ahead of California in 2025. This was driven by an increase in both battery electric vehicle (BEVs) and plug-in hybrid electric vehicle (PHEV) sales and it is largely imputable to a step change in regulatory requirements for CO_2 emissions/km of new vehicles, in 2020 (a similar circumstance in 2025). The EV sales share in California had an inflection point in 2022, reaching 20.5% sales share compared to 19.6% in the EU. This was driven, in part, by changes in the US federal EV tax incentives and the California EV purchase subsidies, as well as the California ZEV mandates for LDVs. The withdrawal of the same federal US subsidies in September 2025 led to a marginal decline in EV sales in California.

In both markets, BEVs and PHEVs had similar market shares up to 2018, after which there was a clear inflection point in BEV sales. While PHEV sales share has remained at 3% in California, it is significantly higher in the EU at 8.5% 2025.

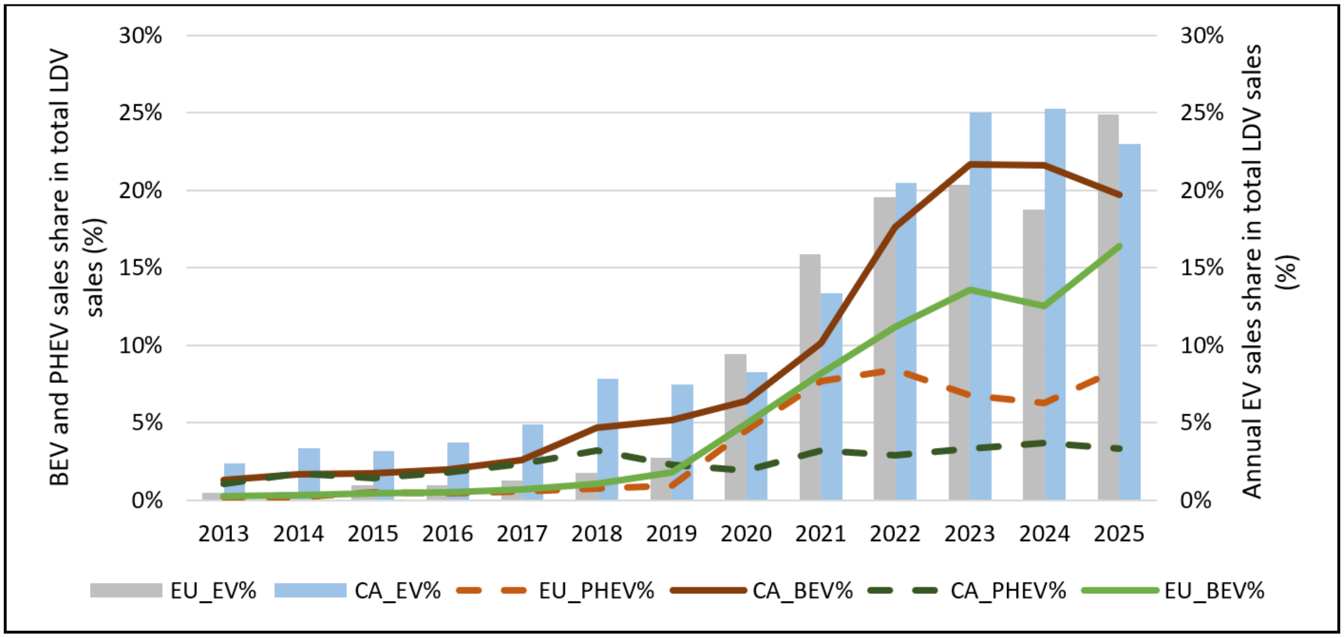

Figure 2. EV Sales Trend in California and EU27 Between 2013 – 2025.

Table 1. Comparison of Key LDV ZEV-Oriented Policies and Their Current Status in the EU and California.

Policy	**European Union**	**California**
Targets	100% new ZEV sales by 2035	100% new ZEV sales by 2035
Definition of ZEVs	Any vehicle with zero emissions of CO_2 from the tailpipe; these include battery electric vehicles, fuel-cell and other hydrogen powered vehicles	Includes BEV, PHEV and FCEV; H_2 internal combustion engines currently not included
Fuel Economy (CO_2 regulations)	0 g/km in 2035; interim targets of 93 g/km in 2025 and 49 g/km by 2030 (WLTP)	Follows US EPA regulation: 112 g/km (179 g/mi) in 2025 & 101 g/km (161 g/mi) by 2030
Criteria Emission Standards	Euro 7, with an expanded scope in terms of particle number, for particulate matter	Low NOx and PM rules limit emissions to very low levels that vary by vehicle type. Ultra-low NOx rule pending.

Policy	European Union	California
Incentive Mechanism for ZEVs	From 2025 to 2029, relaxation of a manufacturer's specific emission target, if its share of new zero- and low-emission vehicles (i.e., with emissions between 0 and 50 g CO_2/km WLTP) registered in a given year exceeds 25% for cars and 17% for vans (eco-innovation credits capped at 7 g/km in 2023 and progressively phased out with increased stringency of CO_2 emissions/km)	ZEV Credit trading mechanism based on annual manufacturer ZEV sales requirements; with the ZEV sales mandate going to 100% from 2026 to 2035
Penalty Mechanism for excess emissions	€95 per g/km of target exceedance and per vehicle if average CO_2 emissions of manufacturer's fleet exceed its specific emission target	$5000 per ZEV Credit deficit

WLTP, Worldwide harmonized Light vehicles Test Procedure

Another key difference between Europe and California is in the design of the ZEV credit systems. California has a direct credit system with tradable credits among automotive manufacturers as part of its ZEV sales mandate regulation (Advanced Clean Cars Rule). The EV sales credits provisioned in the federal US EPA GHG or Corporate Average Fuel Economy (CAFE) requirements also apply concurrently. In contrast, the ZEV credits in the EU are integrated into the CAFE compliance measures.

While certain rule-making, such as CAFE standards, emission criteria, and phase-outs of internal combustion engine vehicles (ICEV) are set at the EU level, each of the member countries within the EU has their own rulemaking for vehicle taxation, fuel taxes, and EV purchase incentives. Thus, it is also important to understand some of the underlying country level policies in the EU that are potentially impacting EV sales. We compare California to the top two LDV producers within the EU—Germany (DE) and France (FR)—who are also among leading automotive producers globally. As can be seen in **Figure 3**, France and Germany are close to California in terms of their EV shares in 2022 (~23-25%), with Germany racing ahead to 28% in 2025.

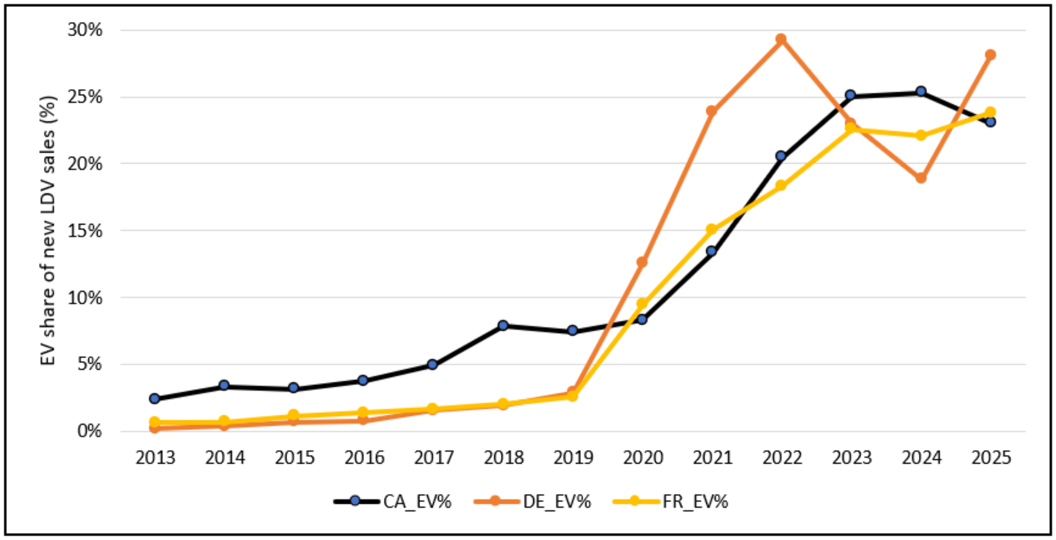

Figure 3. EV Sales Share Trend in California and Select EU27 Countries.

Before comparing the policies between California, France, and Germany, we contextualize the transition so far in terms of the EVs that have sold in these markets by segment and price, to understand the impact of policies in each of the regions on EV adoption.

In California (**Figure 4**), 17 models made up 80% of the sales up to 2023, of which 12 models are BEVs, and the remaining PHEVs. More than half (52%) of the sales in California in this period came from just two models, the Tesla Model Y and Model 3. The weighted average base MSRP of 80% of the EVs sold in California for 2023 was around USD 46,783.

In France (**Figure 5**), 53 models made up about 80% of the sales up to 2023, of which 28 models are BEVs and the remaining PHEVs. Unlike California, model availability and sales distribution in France spans a wider range of vehicle manufacturers. While Tesla models made up more than half the sales in California, in France, the Tesla Model Y (7.5%) and Model 3 (3.7%) make up only 11.2% of the EV sales. The weighted average base MSRP of the 80% of EVs sold in France for 2023 was around EUR 38,929 (or USD 41,265; EUR/USD = 1.06).

In Germany (**Figure 6**), 60 models made up about 80% of the EV sales in the period until 2023, of which 44 models were BEVs. This is similar to California, where over 70% of the models sold were BEVs (as compared to France, where BEVs are about 53% of the models sold). The highest selling is the Tesla Model Y with a share of 9%, followed by VW ID.4 (4.4%) and ID.3 (3.9%). The weighted average base MSRP of the 80% of EVs sold in Germany for 2023 was around EUR 49,214 (or USD 52,167; EUR/USD = 1.06).

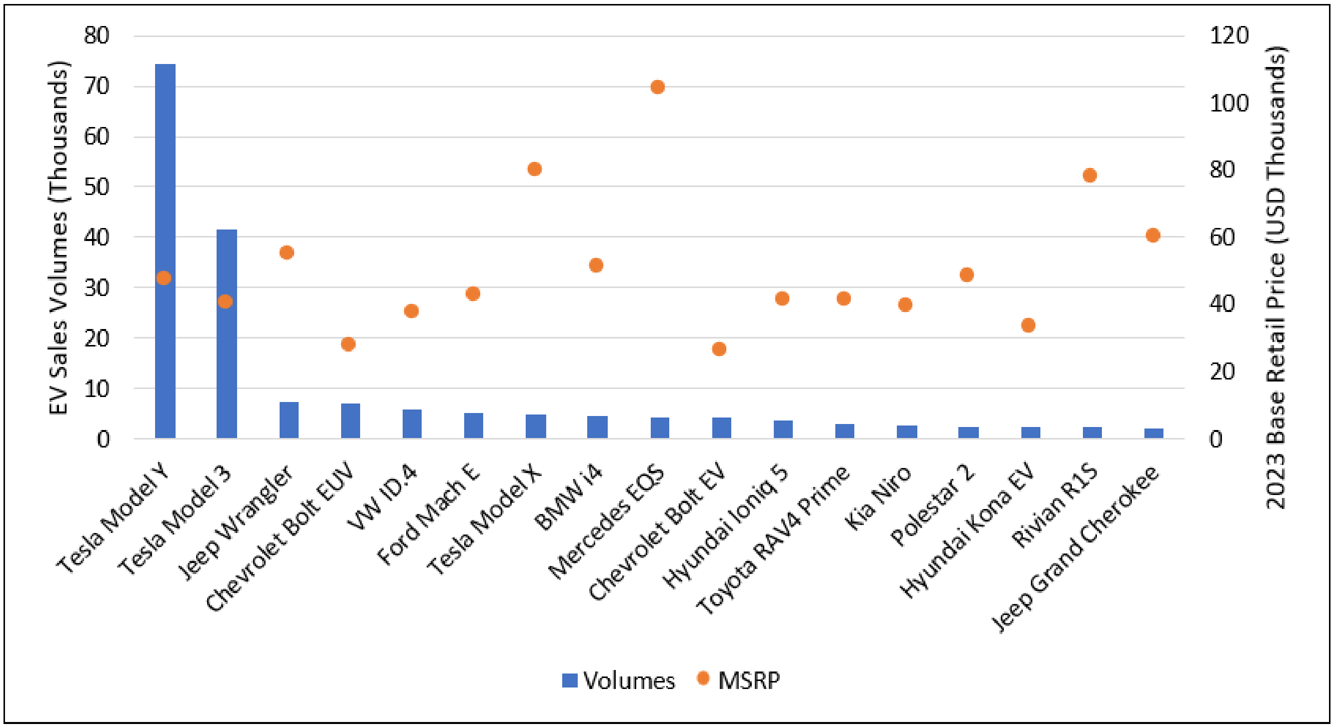

Figure 4. Majority EV Sales by Model and Price in California (2023).

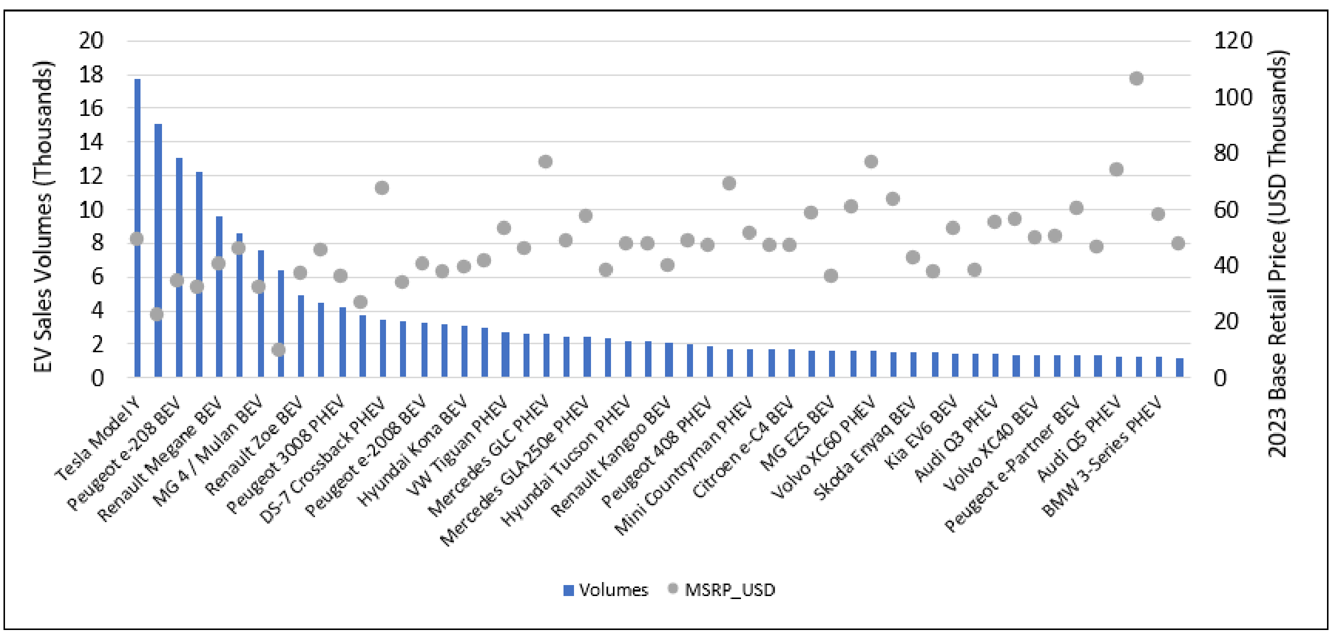

Figure 5. Majority EV Sales by Model and Price in France (2023).

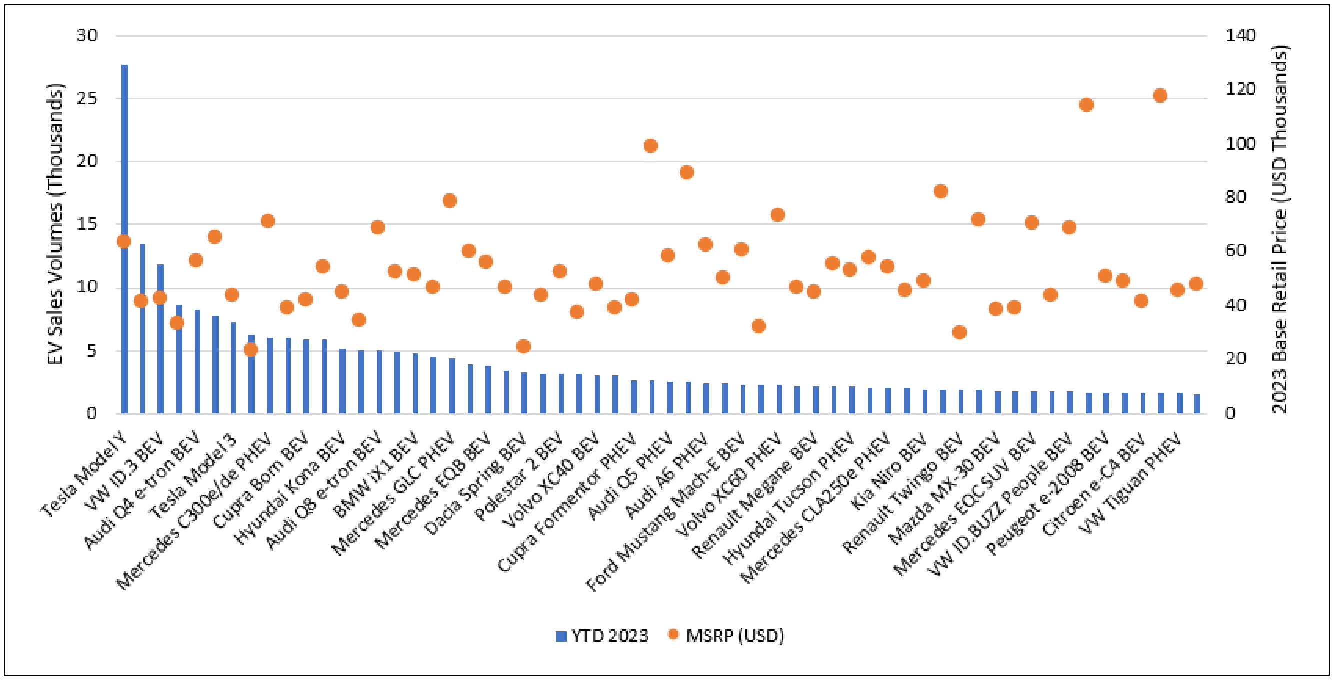

Figure 6. Majority EV Sales by Model and Price in Germany (2023).

Given the context of these sales figures, **Table 2** shows the regulations and incentives around EV purchases in these regions.

Table 2. Comparison of EV Purchase Incentives and ICE Taxation in France, Germany, and California.

Region	EV Purchase Incentive	EV Incentive Eligibility	ICE Taxation	Fuel Price (average for November 2023)
California	**BEV:** \$2000 - \$7500 **PHEV:** \$1000 - \$6000 **FCEV:** \$4500 - \$7500 (incl. increased rebate for low-income households). These are in addition to the US Federal EV tax rebate of up to \$7500	Base MSRP ≤ \$60,000 for SUVs/Vans; Base MSRP ≤ \$45,000 for cars	Tax rate varies by vehicle type and price, but typically 10-12% of transaction price; can lead to higher taxes on (more expensive) EVs than similar ICEs.	\$160.88 /100 litres of Gasoline (SP95: E10); with taxes being ~13% of final price
France	From €4000 to 7000 for cars, €5000 to 8000 for light commercial vehicles), €3000 for companies. PHEVs excluded.	Conditionality of access to credits based on income and cost of the vehicle (less than €47000 for cars). Conditionality also based on an upper weight limit (2.4 t) and specific environment-related parameters ("score environmental"), including aspects related with life-cycle emissions of vehicle and battery manufacturing, differentiated based on carbon intensity across different global regions.	(20% VAT + CO_2-based malus starting at 117 g CO_2/km in 2024, from €50 (for 188 g CO_2/km) to €60000 at 193 g CO_2/km	€163.47 /100 litres of Gasoline (SP95: E10); with taxes being ~58% of final price
Germany	**BEV / FCEV:** €4500 – €6750 Rebates subject to price cap	Higher incentive if Net List Price ≤ €40,000; else, lower incentive (capped at € 65,000)	(19% VAT + CO_2-based malus > 95g/km + engine capacity-based tax per 100cc) on purchase + annual registration	€166.96 /100 litres of Gasoline (SP95: E10); with taxes being ~59% of final price

The average range of upfront purchase incentives for EVs are similar across the three regions with a notable difference that both France and Germany has ended any subsidies on PHEVs as of 2023. These decisions also reflect evidence from on-board data recordings in the EU that PHEVs tend to be used in all-electric mode far less often than expected. In California, the sum of federal and state incentives for an EV are likely higher than in the other regions. One key difference is that California—unlike France, Germany, and most EU countries—includes upper limits on household income for incentive eligibility. France provides an additional €3000 as a purchase incentive for buyers below a certain income tax threshold (and also introduced a “social leasing” scheme, temporarily suspended due to its success), has no upper limit on incentive eligibility, but applies a vehicle price and weight cap to access the incentives, in addition to conditions based on the carbon intensity of vehicle and battery components. California and the US federal incentives also had a vehicle price cap. Starting in 2024, all three regions will have thresholds for vehicle prices, above which certain incentives are not available: vehicles above EUR 60 000 EUR or US dollars will not qualify for any incentives, 45,000–60,000 will qualify for lower incentives; and ‹45,000 will qualify for higher incentives. As seen in **Figure 7**, France and Germany have more models contributing to EV sales, but about a third of the models in these two countries and about a quarter of the models in California are in the price range of $/€ 45,000–60,000.

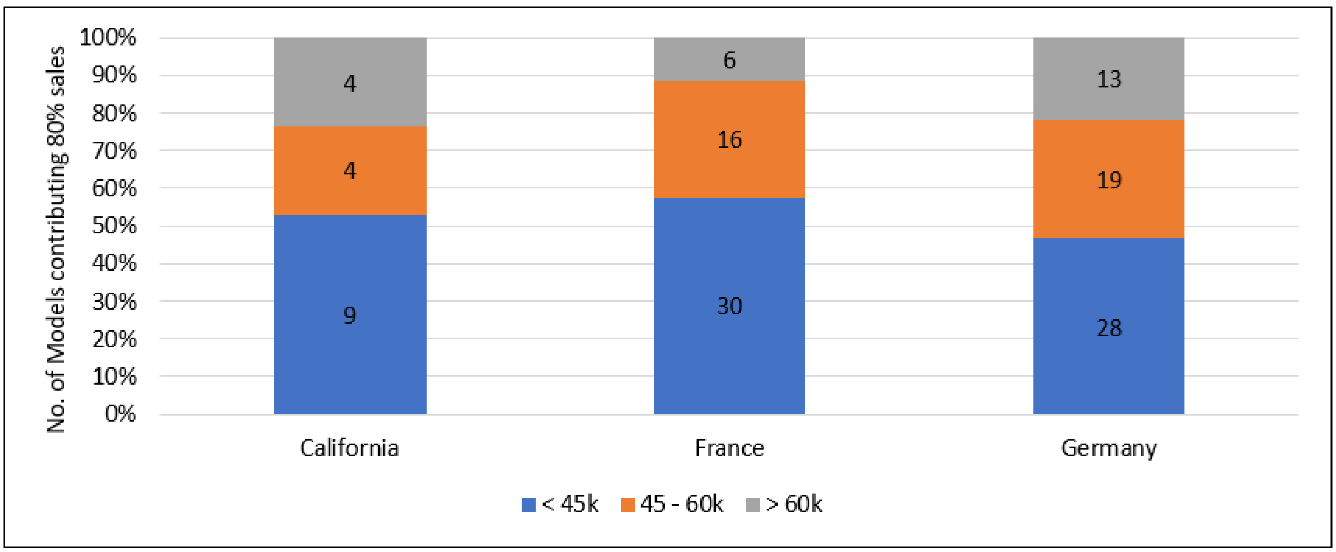

Figure 7. Majority EV Models by Price Ranges (2023).

The ICE taxation system in France and Germany is designed to create strong disincentives among buyers and is based on CO_2 emissions, and other vehicle parameters such as weight or engine size. This mechanism helps generate revenue beyond the vehicle purchase tax (VAT), supporting an EV rebate program with greater certainty of funds that are less dependent on annual legislative and budgetary allocations. In contrast, California’s EV programs are funded through legislative and annual budgetary allocations, which often get exhausted before the year ends. As California accelerates EV deployment to meet its 100% new sales target by 2035, it will likely require continued financial support for end-users, especially middle and low income consumers.

In December 2023, California, citing lack of funds, ended the Clean Vehicle Rebate Project (CVRP), which had been the primary EV incentive program in the state. The CVRP has funded over half a million EVs on California roads with a total rebate spending of over $1.2 billion since its inception in 2010. The program is being reformed to focus on low- and middle-income consumers to transition to EVs and will be merged with the existing Clean Cars 4 All program. The significant state budget deficit for 2024 has elevated concerns of availability of budgetary funds to finance the incentive program. A policy framework such as the EU can be replicated in California to ensure sustainable revenues to support the EV transition.

Table 3. Comparison of Equity-Based EV Programs Across France, Germany, and California.

<table>
<tr><th>Region</th><th>Used EV Incentive</th><th>Scrappage Incentive</th><th>2/3-Wheelers and Quadricycles</th><th>Other Equity-Incentives</th></tr>
<tr><td>California</td><td colspan="2">Up to $9,500 for purchase of new or used PHEV or ZEV including scrappage of previous vehicle</td><td>$750 for e–2-Wheeler</td><td>Clean Cars for All program rebate of $7500 – 9500 for low/middle income to replace older vehicles with new/used hybrids, PHEV/ZEV</td></tr>
<tr><td>France</td><td>Same as scrappage incentives (also applicable to used BEVs or FCEVs)</td><td>From EUR 0 to 5000 for BEV/FCEVs depending on income; EUR 1000 to 3000 additional for household location in a low-emission zone</td><td>€900</td><td>Same as scrappage incentives for BEVs or FCEVs; also possible for PHEVs (from EUR 0 to 3000)</td></tr>
</table>

4.1.1 Key Considerations

- California could better understand ICE taxation policies (based on CO_2 and other vehicle parameters) in EU countries to generate sustainable revenue flows for EV rebate programs, especially important from an equity perspective.
- Targeted rebates towards low- and middle-income consumers will be a key foundation for both California and EU countries to accelerate an equitable transition to ZEVs by 2035. These will need to be accompanied by a contextual increase in the offer of smaller and cheaper ZEVs. Policies limiting the scope for ZEV incentives based on weight and capping them based on vehicle price can also help steer production in this direction.
- The use of an environmental score, based on the French model for the eligibility of ZEV purchase incentives (adding to income, vehicle weight, and a price cap), can offer interesting opportunities for

California and EU countries to foster a diversification of ZEV supply chains, while also bringing climate and environmental benefits. The same model can be extended to other social and sustainability criteria.

- EU countries could include household income limits for new EV purchase incentive eligibility, taking lessons from California's CVRP.
- Since 2024, Germany has begun to phase-out rebates for PHEVs and reduce overall incentives for ZEVs. France phased out PHEV incentives completely in 2024. California is also revamping its PHEV incentive program with a focus on low- and middle-income buyers. In all regions, there is an effort to identify complementary policies to maximize electric-mode use of PHEVs, or else phase out PHEV subsidies entirely.

4.2 Decarbonizing Medium and Heavy-Duty Trucks

The global transition of medium and heavy-duty vehicles (MHDVs) to zero emission is still in its early stages. Significant progress has been made on the adoption of electric buses, but progress on freight vehicles has been slower. In 2022, about 60,000 MHDV zero-emission trucks (ZETs), which were nearly all battery-electric trucks (BETs), were sold globally, reaching about 1.2% of new truck sales. About 80% of these sales were in China, followed by the EU and the US (IEA 2023).

In terms of technology, battery electric, hydrogen fuel cell and hydrogen-ICE are the primary powertrains being explored by manufacturers. In the case of battery electric trucks (BETs), there is a trade-off between battery size/vehicle range, payload capacity, and vehicle cost (with higher battery capacities). As the weight of battery increases, generally to accommodate a longer range, the payload decreases, which is especially a concern with long-haul trucks. For hydrogen trucks, the cost of hydrogen as a fuel and the absence of adequate hydrogen infrastructure are still major barriers for a transition. On the other hand, advancements in hydrogen fuel cell technology offers proven durability and large national programs are being introduced to lower the cost of green hydrogen production, such as the Hydrogen Hubs Program of the US Department of Energy.

Transitions to zero-emission trucks will require addressing key barriers around technology, infrastructure, and cost/finance. As technology develops, and operating practices evolve to account for new powertrains, policy clarity and certainty will be critical in enabling this transition. Requiring ZET sales as a percentage of total sales through a mandate as in the case of California, or through fleet average CO_2 emission requirements as in the EU, sends a clear market signal. The combination of regulatory and policy actions that governments can implement include identifying sales targets, adopting GHG emissions standards for ICE trucks, offering purchase incentives, and preferential financing.

In this section, we provide an overview of key ZET policies in California and Europe, including a comprehensive review of the total cost of ownership (TCO), current incentives, and emission regulations.

4.2.1 California MHDV Policy Overview

California has taken global leadership in driving the sales of ZETs, through a comprehensive set of policy measures. The two key regulations are the Advanced Clean Trucks (ACT) Rule and the Advanced Clean Fleets (ACF) Rule. The ACT acts as a supply-side measure focusing on OEM sales requirements while the ACF serves as demand-side regulation requiring trucks fleets to purchase a progressive share of ZETs each year. These regulations are supported with incentive programs for purchase of ZETs (Heavy Vehicle Incentive Program) and other policy measures regulating criteria pollutants, as well as the Low Carbon Fuel Standard. These collective measures provide a strong environment encouraging the adoption of ZETs.

Advanced Clean Truck Rule

The Advanced Clean Truck Rule (ACT) was approved by the California Air Resources Board in June 2020 and established a timeline by which medium and heavy-duty truck manufacturers must increase their sales of zero emission vehicles (CARB ACT 2022). This is intended to help increase the supply and expand the model availability of ZETs. The ACT regulation took effect on 1 January 2024, with annual new sales percentages increasing through 2035, when 55% of Class 2b-3 sales, 75% of class 4-8 sales, and 40% of Class 7-8 truck sales must be zero emission (**Figure 8**). Percentages are based on the number of vehicles produced and delivered for sale in California for each manufacturer by model year. As of early 2026, ACT is not in force, but the percentage targets for ZET sales each year to 2035 are still used by CARB to guide policy (CARB ACT 2022 [includes updates]). ACT was suspended in 2025 after EPA did not grant a waiver under the Clean Air Act, though it could be returned to active status pending the outcome of various lawsuits, or a change in administration (Berkeley Law, 2026).

ACT additionally includes flexibility for near-zero emission vehicles, including plug-in hybrid electric trucks, which can generate credits until 2035. These vehicles receive only a percentage of the multiplier value of full zero emission vehicles. This percentage is calculated by multiplying the vehicle's all electric range by 0.01, with a maximum of 0.75. These vehicles can be used to satisfy up to 50% of the credits required each model year. Source:(CARB ACT 2022).

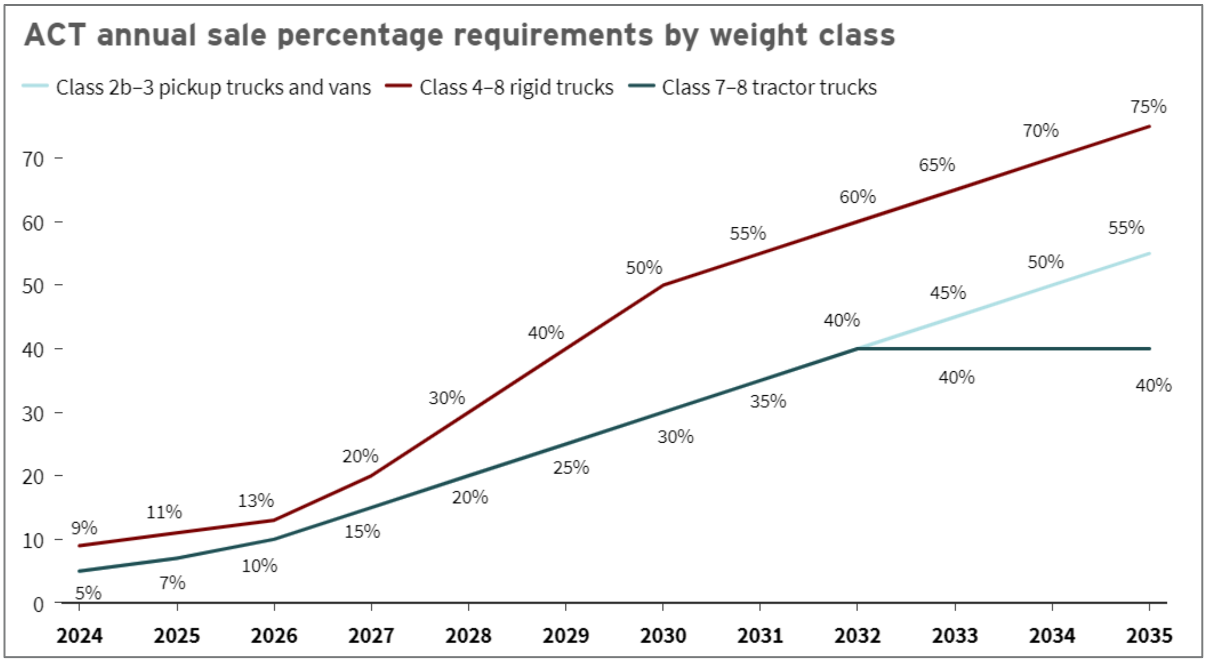

Figure 8. ACT Annual Sales Percentage Requirements for Different Truck Weight Classes.
Source: https://rmi.org/understanding-californias-advanced-clean-truck-regulation/.

4.2.2 European MHDV Decarbonization Policy

In the EU, there exists an established CO_2 emission reduction target for truck sales requiring a 15% reduction in average fleet CO_2 emissions by 2025 compared to 2019 levels (European Commission 2019). In November 2023, the EU Parliament passed a landmark legislation that sets more stringent CO_2 emission reduction targets for MHDVs. Compared to the 2019 level of fleet GHG emissions, this rule requires a 45% reduction by 2030, 65% by 2035 and 90% by 2040. While the current EU regulation only applies to N2 (3.5-12 tonnes) and N3 (>12 tonnes) vehicles, the new rule expands the scope to include N1 (small commercial) vehicles as well, with exceptions for special purpose, off-road, off-road special purpose, and vocational vehicles.

According to the European Automotive Manufacturers Association (ACEA), the new rules will require over 400,000 ZETs on the roads, which translate to about 100,000 new ZET sales annually or about one-third of new sales. Further, this will also require 50,000 publicly accessible chargers and 700 hydrogen refilling stations with a daily capacity of about 2 tonnes.

The EU has also passed the Alternative Fuels Infrastructure Regulation (AFIR) which requires member states to develop national policy frameworks for ensuring sufficient coverage of recharging and refueling infrastructure. The legislation was updated in 2021 and extends beyond road vehicles to include shipping and aviation (European Union, 2023).

The proposed regulation (European Commission, 2021) requires European member states to ensure the construction of a minimum network of charging and refueling stations along the TEN-T, including several urban nodes. This is in addition to the development of a wide range of technical standards. The choice of a regulation, rather than a directive, follows calls from both OEMs and non-governmental organizations (NGOs) for greater political commitment (ACEA, BEUC and T&E, 2021).

- For light and heavy vehicles, the proposed regulation also includes geographical availability requirements. These are expressed both in terms of maximum distance from each other (60 km) and power output per recharging pool (i.e., one or more recharging stations at a specific location), at different points in time.
- For heavy vehicles, power requirements range from 1400 kW (for the for the comprehensive TEN-T network) or 2800 kW (for the core TEN-T network) to 1500 or 3600 kW per pool (with at least one 350 kW charger), in 2027 (2025 for 15% of the network) and 2030, supplemented by additional 100 kW chargers in safe and secure parking areas (European Union, 2023).
- Requirements for road vehicles using hydrogen focus on heavy vehicles to the year 2030. These include minimum station capacity (1 t/day) and geographical availability, expressed in terms of maximum distances between refueling points, focusing on gaseous hydrogen at 70 MPa (200 km) and the core TEN-T network (European Union, 2023).

Publicly accessible charging pools of 900 kW or more shall be deployed in each urban node by 2025 (double the power in 2030) for light and heavy vehicles, and hydrogen refueling stations by 2030 (European Union, 2023). For heavy-duty vehicles, the Commission shall report by end 2024 on the technology and market-readiness of different options, also regarding technical specifications for charging and refueling (European Union, 2023).

While CO_2 emission reduction targets are the key policy lever for decarbonization of MHDTs at the EU-level, some of the member states have set their own goals either by way of an ambition level or a specific target. These are shown in **Table 4**, along with California.

Table 4. Comparison of ZE-MHDV Targets Across Europe and California.

Region/Country	Goal	Policy Type	Year
EU-27	45% CO_2 emission reduction from 2019 reporting levels for MHDVs (translates to approx. 20-30% of new sales in 2030)	Legislation	2030
Austria	100% of ZETs (<18T) and 60% ZET (N3)	Ambition	2030
Finland	Cumulative 5,400 ZETs	Ambition	2030
France	65,000 low-emission HDVs	Target	2028

Region/Country	Goal	Policy Type	Year
Germany	33% of heavy road haulage kms. to be zero emission	Target	2030
California	40% ZETs (Class 2b-3, 708 tractor trucks); 60% ZETs (Class 4-8 rigid trucks)	Legislation	2030

With the new EU CO_2 regulations, it is expected that the roll-out of ZETs will increase across member states and may spur these states to adjust their existing ZET incentive targets and programs or introduce new ones to support the transition.

4.3 Incentives

In California, the Heavy Vehicle Incentive Program (HVIP) is the primary initiative that provides purchase subsidies for zero emission trucks. The incentives range from as low as $7,500 for Class 2B trucks to $240,000 for Class 8 fuel cell trucks. **Table 5** shows the incentive levels by vehicle type (BEV for FCEV), and truck class using the UC Davis Transportation Transition Model classification system. Other incentive programs, such as the US IRA Clean Vehicle Credit Program had purchase incentives that could be combined with the California HVIP incentives. The Carl Moyer Air Quality Standards Attainment Program in California provides grant funding for heavy duty vehicles in certain air districts where standards are not met. The incentives from this program cannot be combined with any other incentive.

Table 5. California HVIP Vehicle Incentive Schedule (in USD).

	BEV	FCV
LH	120,000	240,000
SH	120,000	240,000
MD urban	85,000	85,000
TB	120,000	240,000
SB	160,000	240,000
HD **vocational**	120,000	240,000
MD **vocational**	85,000	85,000
HD pickup	7,500	7,500

In Europe, Spain, France, and the Netherlands have the highest levels of subsidy, and Sweden and Poland have the lowest. For the N3 vehicles (trucks with gross vehicle weight over 12 tonnes), the subsidy could potentially cover up to 50% of ZET costs in countries such as Spain and France. A comparison of ZET incentives in Europe and California is provided in Table 6.

Table 6. Comparison of ZET Incentives Across Europe and California.

Country	Power Types (H2, BEV, RNG, Hybrid)	Class	Max Subsidy for Stated Class
Germany	BEV, Hybrid, H2	N3	80% of additional cost
Spain	H2, BEV, Hybrid, CNG/LNG	N3	130,000-190,000 Euros depending on company size
France	H2, BEV, Hybrid, CNG/LNG	N3	150,000 Euros
Netherlands	H2, BEV- any zero emission	N3	up to 37% or € 131,900 for small biz, less for large
Poland	N/A	N/A	No incentives
Sweden	Bio, H2, BEV	Over 3.5 Tons	20% of total cost of the truck
California	BEV, H2-fuel cell	Over 4 Tons	$7,500 for Class 2B; $45,000 for Class 3; $60,000 for Class 4-5; $85,000 for Class 6-7; $120,000 for Class 8

4.4 Market Trends

As California and Europe look to accelerate ZET adoption, the Zero Emission Truck Inventory (ZETI) dataset can be used to analyze different market trends between the two regions.

In terms of model availability, the US (and by extension, California) has 134 ZET models available in the market as of December 2023, a 50% jump from 89 models in 2021. Most of the models are in the medium duty truck segment, with increasing model availability in both the cargo van and heavy-duty truck segment over the past two years (**Figure 9**). In contrast, Europe has far fewer models (58) available as of 2023, up from 40 models in 2021. The European ZET market largely consists of models in the heavy-duty truck segment and the cargo van segment, both of which have continued to grow since 2021 (**Figure 10**).

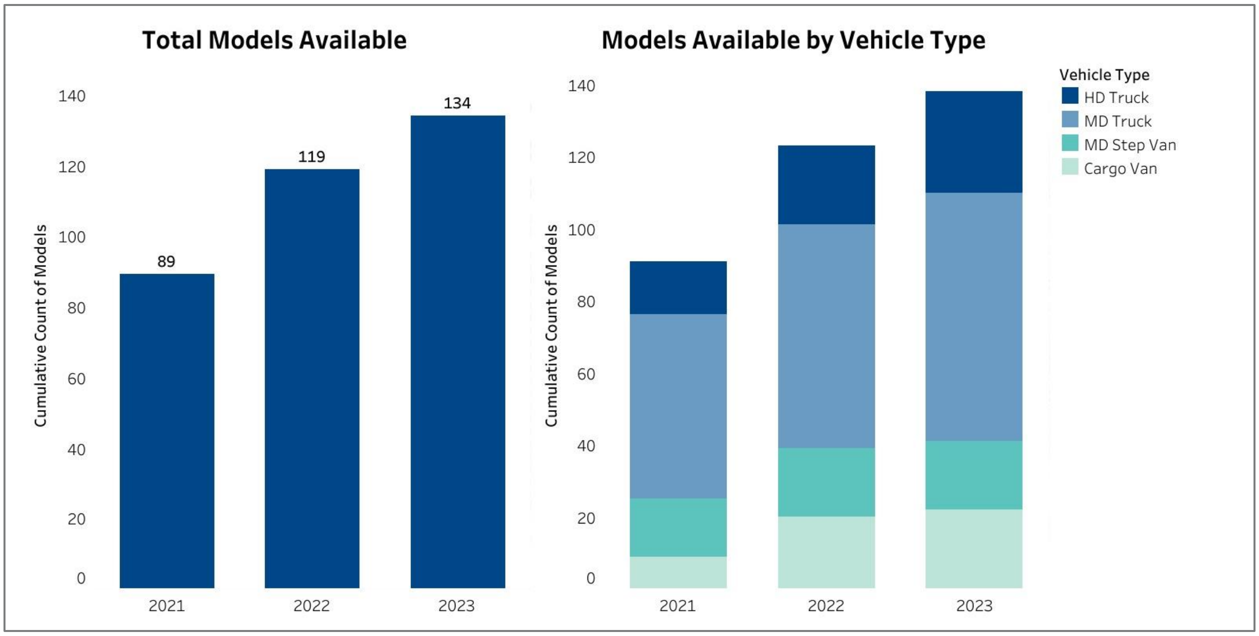

Figure 9. ZET Model Availability by Segment in the US.
Source: ZETI Data Explorer, Calstart, Global Drive to Zero

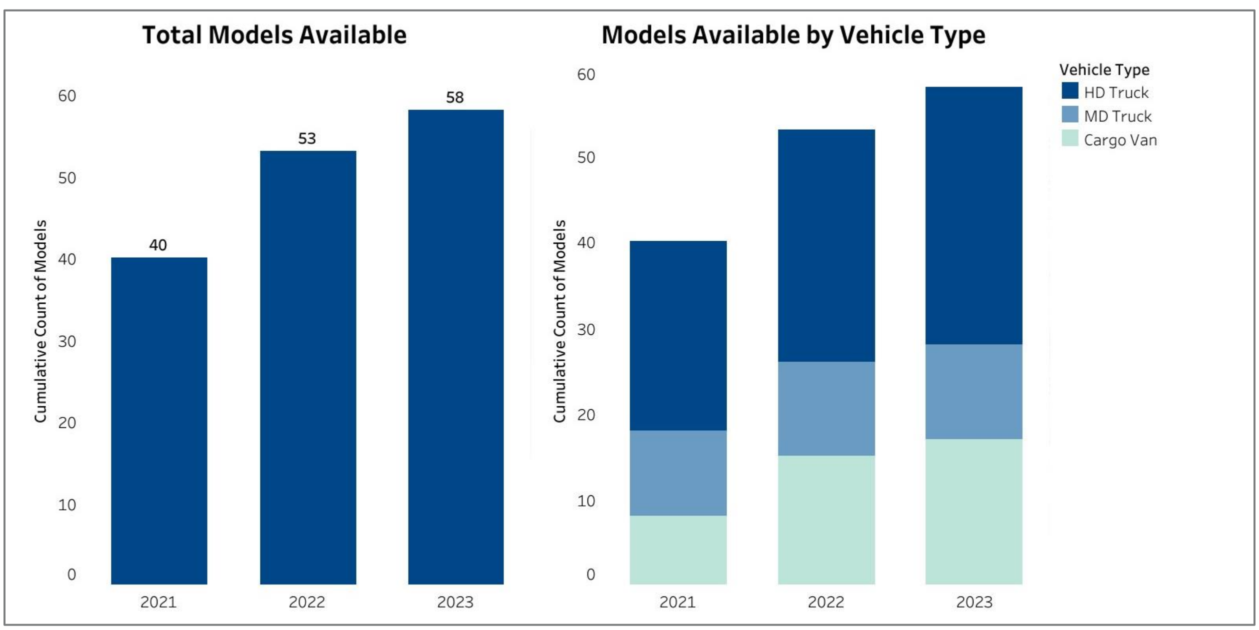

Figure 10. ZET Model Availability by Segment in Europe.
Source: ZETI Data Explorer, Calstart, Global Drive to Zero

In terms of range of ZETs, heavy-duty trucks in the US have a median range of 193 miles, with most models clustering around 150 miles. For medium duty trucks, the median range is 170 miles, with most models clustering around either the 150-mile or the 200-mile range threshold. Step-vans in the medium duty segment have a median range of 150 miles (**Figure 11**). While the range of available models in the cargo van segment is distributed, the median range is around 170 miles. In contrast, heavy duty ZETs in Europe have a median range of about 175 miles, medium duty trucks have a median range of 124 miles, and cargo vans have a median range of 144 miles (**Figure 12**).

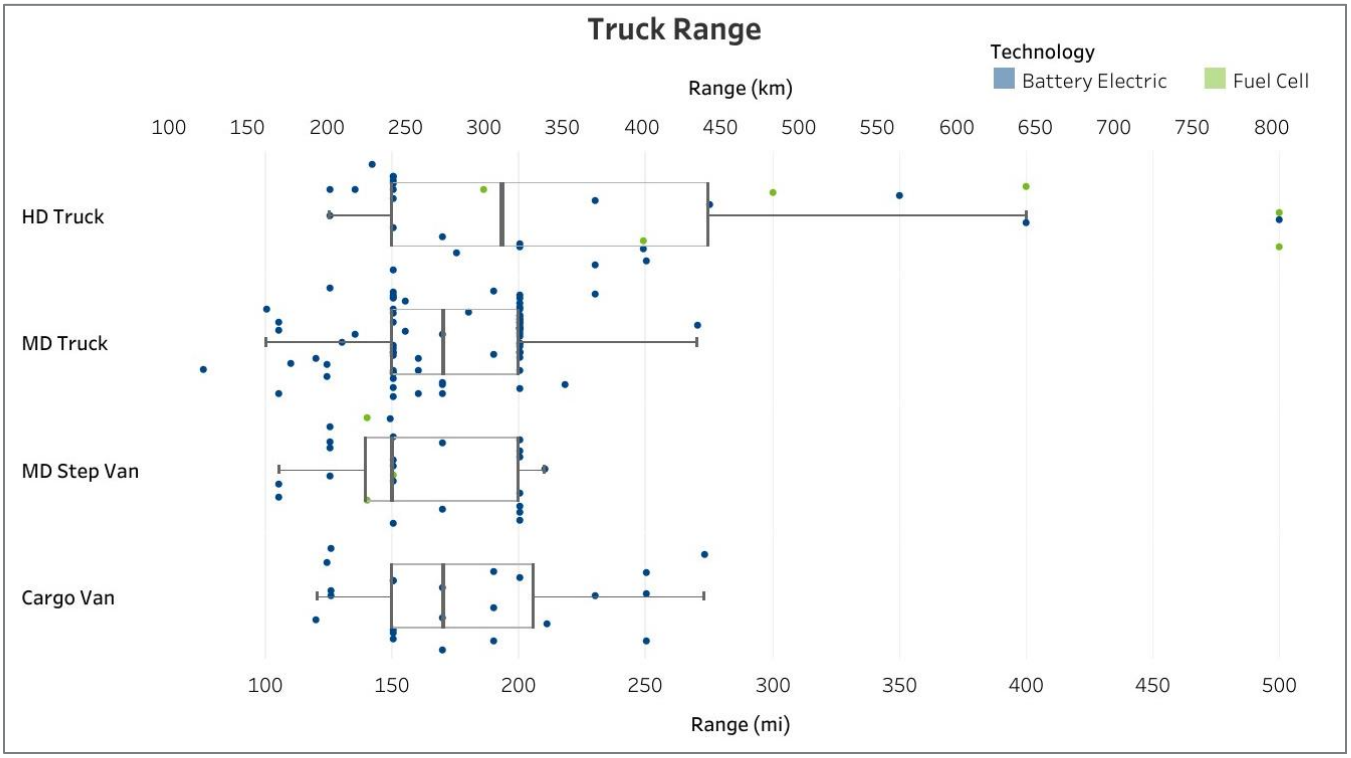

Figure 11. ZET Model Range by Segment in the US.
Source: ZETI Data Explorer, Calstart, Global Drive to Zero

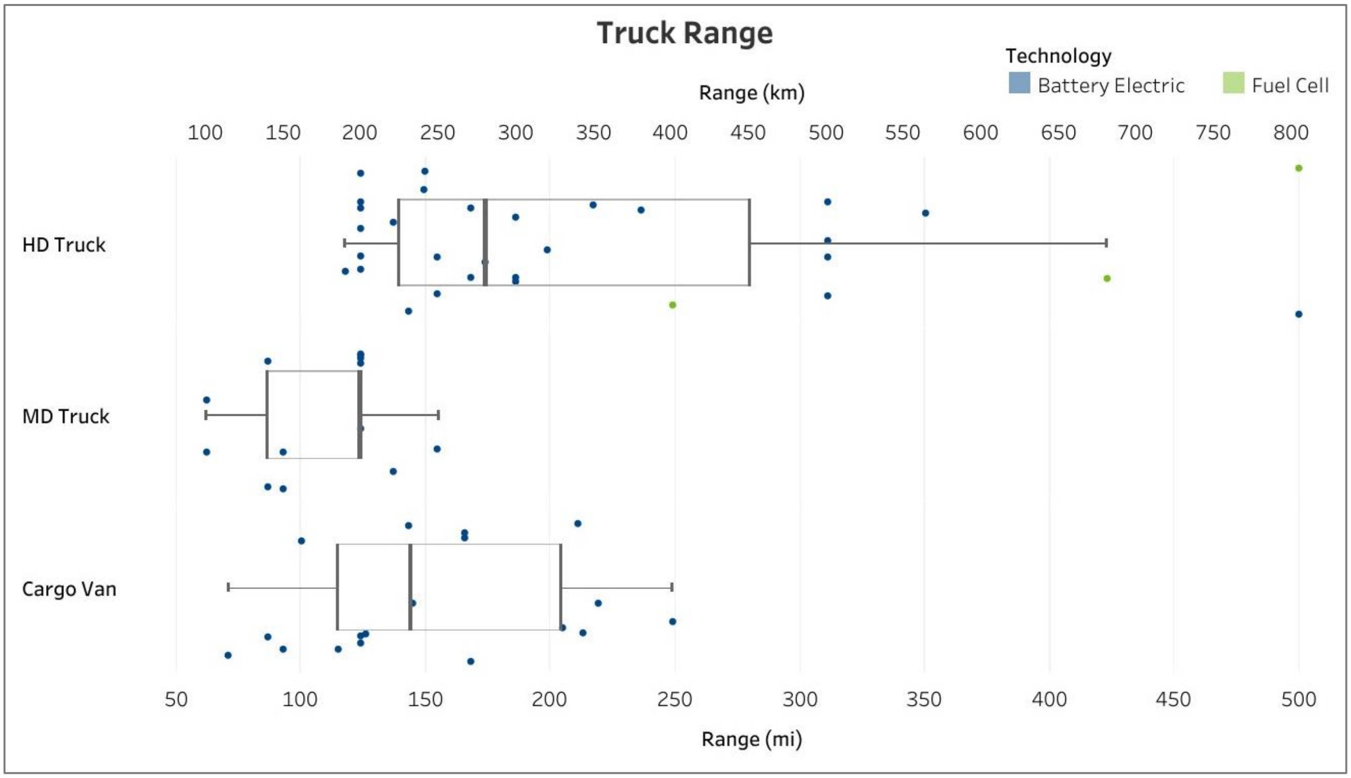

Figure 12. ZET Model Range by Segment in Europe.
Source: CALSTART (2022): Drive to Zero's Zero-Emission Technology Inventory Data Explorer. Version 1.0. Available online at: https://globaldrivetozero.org/zeti-data-explorer/

4.5 TCO Comparison

The total cost of ownership (TCO) can be a useful measure to compare the economic viability of ZETs and diesel trucks. TCO takes into account purchase price, operating and fuel cost, resale value, and expected duration of ownership. The TCO for ZETs must become competitive (and hopefully lower) than for diesel trucks in most of the major trucking categories to accelerate adoption. Higher upfront purchase prices for ZETs are still a barrier to adoption but are expected to come down as sales and production volumes increase, and with technology development.

During this transition phase, policies must ensure that ZETs are affordable and can achieve TCO parity for the customer and eventually achieve purchase price parity (in many cases, considering lower per-kilometer operating costs). But even if lower operating costs offset higher purchase costs, this represents a change in balance and can create a finance and cost recovery challenge for fleets. Policies (such as incentives) to lower purchase price can play a critical role in this regard.

Several studies have estimated the TCOs for ZETs and diesel trucks, across Europe and California. These provide interesting insights as shown in **Figure 13**. The studies indicate that TCO parity for heavy duty trucks could be achieved as early as 2028 (or as late as 2035), depending on certain specific use cases and vehicle specifications for battery electric trucks. In the case of heavy duty fuel cell and hydrogen ICE trucks, TCO parity is not expected even up to 2040, with some use cases showing parity beyond 2035.

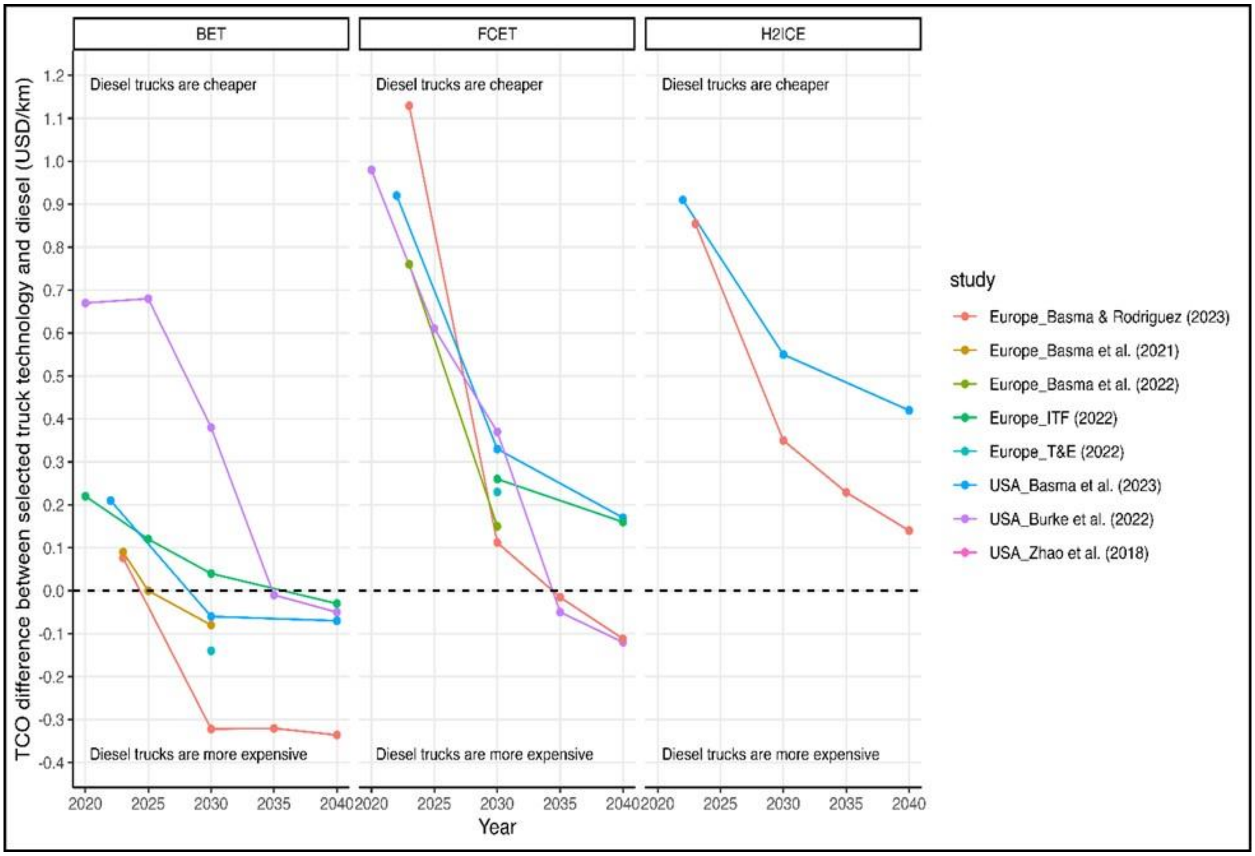

Figure 13. TCO Comparison for Zero Emission Heavy Duty Trucks Across Europe and the US (California).

4.6 Summary of California and European MHDV ZEV transitions

Key takeaways from the comparison of California and European policies for decarbonizing medium- and heavy-duty trucks are:

- Both regions have already adopted a range of policies to promote this transition, including regulatory and market-based policy approaches.
- While California is relying primarily on "ZET mandates" (sales and purchase requirements of ZETs, increasing over time), Europe is relying primarily on vehicle CO_2 regulations to help promote ZET

adoption. Both strategies can work, but the CO_2 strategy is indirect and has a wider range of possible outcomes.

- Both regions acknowledge the need for price incentives to help adoption rates, though in Europe this happens at the member-state level and these policies can vary considerably across jurisdiction. This is true in California too, with some incentives differentiated by air quality districts (such as only in those districts where air quality standards are not met). California also has different incentive systems than other states within the US, and could be considered as equivalent to a single EU member state in that regard.
- The two markets are linked by the need to bring ZET prices down, which will occur over time and with increasing sales volume. In cases where the same vehicles—or even the same manufacturers—operate in both regions, the manufacturers leverage scale across the US and EU markets.

5. Aviation and Maritime Sectors

This section provides an overview of the EU policy on aviation and maritime sectors. While California has limited regulatory oversight on aviation and maritime sectors compared to the US federal government, it has a long coastline and among the busiest ports and airports globally. California has 12 maritime ports including the Port of Los Angeles and Long Beach (the busiest port in North America) and about 9 large and medium major airports along with many smaller regional airports. For context, the Los Angeles International Airport (LAX) handled about 66 million passengers while the San Francisco International Airport (SFO) handled over 42 million passengers and about 0.5 million metric tons of air freight in 2022. The Port of Los Angeles handled 9.9 million containers (TEUs[2]) and about a million passengers in 2022.

5.1 Aviation and the EU Emission Trading System (ETS)

Since 2012, the EU European Trading System (ETS) has covered CO_2 emissions from flights within Europe (i.e. intra-European Economic Area[3] flights) by all airlines, European and non-European alike (European Commission, 2022).

Under the EU ETS, regulators allocate a share of free permits to limit carbon leakage[4] in industries with strong international competition. In the EU 'Fit for 55' policy package, an alternative approach has been proposed to progressively phase out free allocations of allowances to airlines (European Commission, n.d.). This approach is combined with the option to address the risk of carbon leakage and fuel-tankering[5] from airports outside the EU by ensuring that imported products are subject to equivalent carbon pricing as domestic products. In June 2022, it was proposed to include flights flying out of the EEA within the scope of the ETS(European Parliament, 2022). The final ETS revision covers only intra-EEA flights at least until 2026, including departing flights to the United Kingdom and Switzerland (European Commission, 2022, European Parliament, 2022, European Council, 2022 and European Union, 2023). Flights not covered by the EU ETS will be subject to the Carbon Offset and Reduction Scheme for International Aviation (CORSIA) under the International Civil Aviation Organisation (ICAO). While the ICAO has a long-term global goal of meeting the Paris Agreement outcomes, it currently remains a voluntary mechanism. In the case that CORSIA is not gaining strength by 2026, it is recommended that the EU ETS should be extended to cover departing flights from the EEA (European Union, 2023). This will be like the Carbon Border Adjustment Mechanism (CBAM), which applies a carbon price on commodities entering from outside of Europe if they do not meet carbon emission intensity targets. The inclusion of aviation

[2] TEU = twenty-foot equivalent unit, a measure of volume in units of twenty-foot long containers.
[3] The EEA includes EU countries and also Iceland, Liechtenstein, and Norway.
[4] Carbon leakage is a situation that can arise when companies transfer production to other countries that have more relaxed emissions requirements in order to save costs. This can lead to an increase in overall emissions, despite emissions in the regulated jurisdiction nominally declining (European Commission, n.d.).
[5] Tankering is a practice whereby an aircraft takes on more fuel than is needed for a safe flight to reduce or avoid refueling at the destination airport, where fuel is more expensive, for subsequent flights (ICAO).

in the EU ETS should provide a stronger price signal than through CORSIA (European Council, 2022, European Union, 2023). As a regional initiative, the EU ETS can limit fuel-tankering and carbon leakage risks and serve to drive ambition for a global carbon pricing scheme for international aviation.

In its deliberations on the revision of the ETS, the EU Commission also touched on the allocation of ETS revenues to a support scheme for increasing the use of sustainable aviation fuels (SAF), leading to an agreement in the provision deal of December 2022 (European Commission, 2022).

The final regulation also established a new system for airlines to monitor, report and verify non-CO_2 emissions and climate effects of aviation, which make up two thirds of the sector's total climate impact (European Commission, 2022), with the possibility of a future legislative proposal containing mitigation measures for non-CO_2 aviation effects (European Union, 2023).

5.2 Aviation Fuels in the EU

The ReFuelEU Aviation Regulation was adopted in October 2023 with the objective of decarbonizing air transport in line with the EU's climate targets for 2030 and 2050. The regulation requires fuel suppliers to deliver an increasing share of SAFs in the fuel mix supplied at EU airports (European Parliament, 2023). SAFs include advanced biofuels produced from agricultural or forestry residues, algae, bio-waste, used cooking oil, animal fat wastes, and synthetic aviation fuels (aviation RFNBOs[6]). These fuels count as SAFs if they meet the sustainability and GHG emissions criteria that ensure significant life-cycle emission reductions and limit scope for land-use change.

Fuel suppliers are obligated to gradually increase the share of SAF supplied to operators in EU airports from 2% by 2025 to 6% by 2030, reaching 70% in 2050. Additionally, from 2030 onwards, 1.2% of the fuel mix must be synthetic aviation fuel, reaching 35% in 2050 (EU Parliament, 2023).

The regulation also aims to tackle fuel tankering practices, which then generate additional emissions to carry the extra fuel (European Parliament, 2023). The law establishes an obligation for aircraft operators to ensure that the yearly quantity of aviation fuel uplifted at any given EU airport is at least 90% of the yearly aviation fuel required (EU Parliament, 2023).

Since the aviation fuel regulation is within the Renewable Energy Directive of the EU Commission, this new regulation will differentiate between types of SAF by considering their capacity to deliver net CO_2 emission savings on a life-cycle basis, ensuring credits from GHG capture are not double-counted (European Union, 2018). For instance, RFNBOs can only be counted towards compliance targets if they have GHG emissions savings of at least 70%.

[6] RFNBOs are renewable liquid or gaseous transport fuels for which none of the energy content of the fuel comes from biological sources. These fuels are considered renewable where the energy content of the fuel comes from renewable energy sources but excluding bioenergy.

Non-compliance fines that are at least double the price difference between SAF and conventional aviation fuels will be introduced ((European Parliament, 2023). This strengthens the incentive to invest which depends on the certainty around non-compliance penalties and their value.

In addition to setting SAF mandates, the ReFuelEU initiative also creates a new labeling program for the environmental performance of operators using SAF, to reflect the expected carbon footprint and CO_2 intensity per passenger kilometer (European Parliament, 2023). Despite a disproportionate climate impact per passenger-kilometre and a growing market after COVID-19, private jets are not included within the scope of the ReFuelEU Regulation (T&E, 2021).

5.3 Integration of Maritime Transport in the EU ETS

The 'Fit for 55' proposal also includes the enlargement of the scope of the EU ETS[7] to maritime transport for emissions from ships when at berth in EU ports, and emissions from intra-EU voyages (European Commission, 2021). Discussions led to the proposal to include 50% of emissions from extra-EU voyages, confirmed in a December 2022 agreement and the final legal text, which sets a start date of 2027 (European Council, 2022 and Hagberg, 2022; European Union, 2023). Ships over 5000 gross tonnes are covered. General cargo vessels and offshore vessels above 400 gross tonnes (and below 5000) will be included from 2025 in the regulation regarding the reporting of emissions, already applicable to larger vessels. Their inclusion in the EU ETS will be reviewed in 2026 (Hagberg, 2022, European Union, 2023).

The creation of a new 'Ocean Fund,' specific to the maritime sector and bound to use 75% of ETS revenues from shipping to support the transition to an energy-efficient and climate-resilient maritime sector, was also under discussion before the December agreement (EPRS, 2022, European Parliament, 2022). The final agreement and legal text exclude this, allocating ETS revenues to the Innovation and Modernisation funds. These are meant to support breakthrough innovative technologies and infrastructure, including production of low- and zero-carbon fuels, to decarbonize the maritime, aviation, rail and road transport sectors (European Union, 2023). Investments to decarbonize maritime transport, including investments in energy efficiency of ships, ports and short-sea shipping, in electrification of the sector, in sustainable alternative fuels, such as hydrogen and ammonia that are produced from renewables, in zero-emission propulsion technologies such as wind technologies, and in innovations with regard to ice-class ships are all explicitly included within the scope of the Innovation Fund (European Union, 2023).

The inclusion of the maritime sector in the EU ETS is a key development to ensure that fuel used in ships is subject to carbon pricing, addressing the fact that this was one of the key sectors still exempt from it (OECD,

[7] Article 5.1 of the FuelEU Maritime regulation proposal: "From 1 January 2030, a ship at berth in a port of call under the jurisdiction of a Member State shall connect to on-shore power supply and use it for all energy needs while at berth" (EC, 2021). The proposed sustainable Fuels Infrastructure Regulation also includes provisions for member states to ensure installation of a minimum shore-side electricity supply for certain seagoing ships in maritime ports and for inland waterway vessels (EC, 2021).

2019). This initiative, as well as the introduction of a cap on shipping emissions, has crucial importance beyond the EU, even after the progress made by the intergovernmental negotiations on the revision of the GHG emission reduction strategy at the International Maritime Organisation (IMO), because the increased ambition of the strategy introduced in July 2023 (IMO, 2023), marking a major progress, is still not matched by binding implementing measures.

Other challenges are: (i) the risk of a diversion of investments from efficiency improvements towards GHG emission allowances (including those arising outside the sector[8]) and (ii) limited capacity to stimulate the uptake of low-carbon fuels and other innovative emission-saving technologies, due to the likely low end-user price signals.

The risk of split incentives (shipowners paying for energy efficiency measures but not reaping the benefits) between ship operators and owners, and in particular the risk that shipowners do not act on energy efficiency, is tackled by increased transparency requirements on actual ship performance, thanks to the EU Monitoring, Reporting, and Verification (EU-MRV) system for ships. This is already in place and allows the price signals to be passed through to asset owners, who would then be stimulated to invest in energy efficiency and fuel switching technologies. This is also addressed by the proposed obligation to pass carbon prices to charters, stimulating them to minimize their carbon emissions (https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2022)698890). The integration of maritime transport in the EU ETS includes nitrous oxides (N_2O) and methane emissions within the scope of what will be monitored (Hagberg, 2022, European Union, 2023).

5.4 FuelEU regulation for Maritime

The FuelEU Maritime Regulation (European Union, 2023) focuses on driving the shift towards low carbon fuels in shipping by mandating limits on the GHG intensity of energy used on board of ships with a gross tonnage above 5000, currently responsible for 90% of the GHG emissions from maritime transport, and by mandating use of onshore power supply in EU ports. It requires a full life-cycle assessment of the fuel supply chain to determine emissions of CO_2 equivalents (including methane and nitrous oxide) from the energy used. Progressive reductions of the GHG intensity of energy used on board are required, which would start with a 2% reduction in 2025 compared to the 2020 baseline, followed by a 6% reduction by 2030 and a progression towards an 80% reduction by 2050. Additionally, a dedicated incentive for renewable fuels of non-biological origin (RFNBO), consisting of a multiplying factor equal to 2 to be applied to a 2% share in 2031 (or 2034 in case of constraints),[9] is meant to encourage their early market development and deployment, in light of a sizable growth potential.

[8] The application of EU-ETS to international aviation (for intra-EU flights) has not resulted in any reduction to absolute emissions from this sector (Hughes, 2020).
[9] This does not apply in cases of insufficient production capacity and availability of RFNBO to the maritime sector, uneven geographical distribution, or a too high price (European Union, 2023).

Requirements contained in the Commission proposal apply to all energy used on board a ship in or in-between EU ports but only to 50% of the energy usage on ships sailing to or from ports in third countries, while also making sure that the risk of evasive port calls and the de-localization or rerouting of activities outside the Union are avoided (by excluding port calls at neighboring container trans-shipment ports where the share of trans-shipment of containers exceeds 65% of the total container traffic of that port and the port is less than 300 nautical miles from an EU port) (European Union, 2023). This approach will address the potential for carbon leakage and maintain the competitiveness of the EU maritime transport sector (Lagouvardou and Psaraftis, 2022).

Responsibility for compliance lies with the company responsible for the ship operation (shipowner or charter). Technological neutrality is ensured by the life-cycle GHG-based approach defining the obligations.[10] This enables technologies such as LNG and those with high GHG emission abatement capacity to contribute, even if the scope for meaningful emission abatement for LNG of fossil fuel origin is limited. Non-compliance fines are comparable to those introduced for aviation and significantly higher than technical estimates of low-carbon fuel production costs (European Parliament, 2023).

Similar to the case of private jets in the ReFuelEU Aviation, FuelEU Maritime does not include large leisure/luxury ships. Recreational crafts are also excluded, despite being best suited for a significant shift to direct electrification (Panteia et al., 2021).

5.5 Aviation and Maritime Sectors in California

While California has a net zero goal for 2045, there is no holistic strategy on decarbonizing aviation and maritime sectors. It must be acknowledged that as a state government, California does not have the regulatory powers to address emissions from the aviation and maritime sectors, which are both a federal and international policy challenge as well. With regards to aviation, while technology maturity and commercial viability is yet to be achieved in terms of electric or hydrogen aircrafts, there has been policy push for the inclusion of SAFs. As of December 2023, the only form of SAF that has achieved significant deployment is made by the hydrotreatment of lipids, like fats, oils, and greases. Vegetable oils make up an increasingly large share of SAF but raise sustainability and land use concerns that will limit their growth. Other SAF production technologies are yet to demonstrate viability at commercial scale. As a result, SAF growth potential may be limited until an advanced production technology, such as cellulosic fuels or e-fuels, reaches technological and commercial maturity.

[10] The life-cycle approach, i.e. considering a 'well to wake' approach as well as CO_2 equivalent emissions of methane and nitrous oxide, already addresses limitations also being overcome in the IMO policy framework, thanks to the recent revision of its GHG emission reduction strategy and the adoption of life cycle GHG emission assessment guidelines (IMO, 2023).

With regards to maritime operations, California has made efforts to address logistics operations through the Advanced Clean Trucks and Advanced Clean Fleets Rule which aims to decarbonize majority of truck fleets including drayage trucks. In 2022, California announced a USD 1.2 billion program for port and freight infrastructure projects aimed at a more efficient, sustainable, and resilient goods movement system. Japan and California, key trading partners, entered into a formal collaboration in March 2023 to jointly work on strategies for pollution reduction at seaports and establish green shipping corridors.

Studies have found that with the right design, California's Low Carbon Fuels Standard (LCFS) in combination with other policies for aviation can be effective in addressing aviation emissions in the state. Currently, SAFs can generate credits as an opt-in fuel under the LCFS policy since 2019. They are used to demonstrate attainment with gasoline and diesel targets but have no compliance obligation. As of December 2023, the California Air Resources Board has indicated its intent to add fuel consumed on intra-state flights into the LCFS.

With majority of SAFs for the US expected to be hydrotreated vegetable oil, there are capacity constraints that the sector will have to contend with. In North America, expected capacity in 2028-2029 for hydrotreated lipid fuels is about 6 billion gallons per year. Beyond 2029, sustainability constraints including land use implications are likely to emerge. This capacity will have to satisfy SAF and renewable diesel demand for the US, Canada and Mexico (although Mexico is likely to be a negligible consumer given the lack of any fuel policy as of 2023). California alone has a baseline demand of about 4 billion gallon per year of diesel and another 4 billion gallon per year of SAF, thus even if it were to consume the entire anticipated North American supply, it would not fully displace its own consumption.

Marine diesel is treated the same way as all other non-road diesel, so the LCFS does have some impact on marine applications. Marine diesel is used for tugs, harborcraft, and small ships. Bunker fuels, used for long-distance shipping are excluded from the LCFS. Extra-California shipping voyages will require a concurrent federal policy in the US to address maritime emissions. Also, with the current lack of feasible low carbon alternatives to marine bunker fuels, apart from LNG, efforts will be needed on exploring hydrogen, ammonia, RNG, and others.

Marine bunker fuels remain cheap relative to low-carbon alternatives, despite recently higher petroleum prices and the implicit avoided cost for additional processing and waste disposal. Bunker fuels contain harmful residuals from crude oil, including metals and sulfur (though recent IMO regulations limit the sulfur content of bunker fuels to some extent). Burning them at sea effectively disposes of them by dispersal into the ocean. Absent the ability to use bunker fuels as a waste disposal mechanism, refineries would otherwise have to bear this cost directly. Along with the fact that marine bunker fuel is a tiny fraction of petroleum consumption and GHG emissions, it has been a comparatively lower priority for policy makers.

Lastly, there is uncertainty around the transition pathway that the shipping industry would like to see, i.e., a portfolio of different technology options or convergence on a single alternative technology or fuel to maximize interoperability. Ammonia, methanol, hydrogen, biomethane, or synthetic liquid hydrocarbons have been proposed as low-carbon alternatives to replace bunker fuel.

In the short- to medium-term, scaled deployment and demonstration projects will remain critical to evaluate which alternatives could move along a technology maturity curve. In the California context, it will also require strong US federal policy on targeting emissions in aviation and maritime operations to have the intended impact.

Table 7. Comparison of EU and US Policy on Aviation and Maritime Sectors.

Nation	Law	Policy	Sector	Level of policy	Type	Issue	Base	Goals
EU	Fit for 55 packages	RED II	Renewable Energy	Directive	Mandate	2021	GHG	20% reduction by 2030 (base 1990)
		Refuel EU Aviation	Biofuels	Regulation		2022	Volume	5% SAF supply by 2030
		Fuel EU maritime	Biofuels	Regulation		2022	GHG	6% reduction by 2030 (base 2020)
		AFIR	Infrastructure	Directive		2014	Rate of supply and demand	Min. one charging hub every 60 ~ 100 km (TEN-T)
US	Clean Air Act	RFS II	Renewable Energy	Federal	Mandate and RINs	2007	Volume	varies in biofuels
	Inflation Reduction Act		Biofuels	Federal	Tax credit	2022	Life Cycle Carbon Intensity (CI)	1.25 ~ 1.75 USD / gallon

5.6 Key Common Policy Considerations for Aviation and Maritime Sectors in California

1. ***Include aviation and maritime in 'Cap and Trade' program*** and allocate revenues for SAF in case of aviation and fleet modernization for shipping.
2. Introduce an overall cap on aviation and maritime emissions within California (intra-state), in line with the state net zero goals.
3. Explore a regional initiative to address aviation and maritime emissions with other 177 states, Northeast states, or LCFS states.
4. ***Implement a monitoring, reporting and verification (MRV) framework for CO_2 and non-CO_2 emissions*** for both aviation and shipping (at least for intra-California travel and eventually California-origin trips). Such an MRV framework can potentially lead to legislative action on emission mitigation.

5.6.1 Additional Policy Considerations

1. In aviation, ***explore a new flight labelling program*** for the performance of flights, to reflect the expected carbon footprint and CO_2 intensity per passenger mile or freight mile (for air cargo).
2. Include jet fuel (intra-state jet fuel to begin with) and maritime fuels in the LCFS program and introduce obligations for fuel suppliers to gradually increase the share of SAF / low carbon maritime fuels supplied to California air- and sea-ports.
3. Consider including private jets within the scope of regulations especially on aviation fuels and similarly, and extend regulations to private cruises and yachts operating through California ports.
4. Regulate shipping emission when at berth in California ports and emission from intra-CA voyages, such as mandating use of onshore power supply while berthed at California ports.
5. Potentially cover majority of extra-California maritime voyages from 2030 onwards.
6. Integrate the California ARCHES program on Green Hydrogen with aviation and maritime sectors.

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