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FUNDING THE TRANSITION TO ALL ZERO-EMISSION VEHICLES

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EXECUTIVE SUMMARY

Governments around the world, motivated by the necessities of clean air and a stable climate, actively steer their markets toward all zero-emission vehicles (ZEVs). Among the key questions for governments are what types of support for incentives, infrastructure, and other programs are needed; for how long this need continues; and how the costs compare to the benefits. These questions are about managing the costs across governments, industry, and drivers through the transition to ZEVs.

This paper analyzes the costs, benefits, and associated government funding, with the transition to all passenger ZEVs. The research quantifies funding based on incentives that are aligned with declining ZEV costs and the expenditures of exemplary programs in several high-ZEV uptake markets. The relative costs, benefits, and government outlays are analyzed for the transition to all ZEVs in the light-duty vehicle markets of the United States and Germany. We summarize the findings and implications in the following four conclusions.

Sustained funding is critical to growing the early ZEV market. The near-term costs to address ZEV barriers are substantial. Incentives to defray upfront vehicle costs, infrastructure to ensure convenient charging, and outreach campaigns to educate consumers on ZEV options and their benefits are all needed. As ZEVs reach cost parity and become mainstream, incentives and consumer awareness programs can evolve with a changing market, while infrastructure costs continue through the transition. Polluter-pay policies that tax higher-polluting vehicles and incentivize ZEVs could maintain steady revenue, incorporate vehicle externalities, minimize government expenses, fund ZEV campaigns, and avoid annual budget debates.

The societal benefits of ZEVs far outweigh the costs. Although the costs in the ZEV transition are substantial, the benefits greatly outweigh the costs. Benefits outweigh costs before 2030, and 2020–2050 cumulative benefits outweigh the costs by a factor of about 5 to 11, based on our analysis of Germany and the United States. Figure ES-1, shows the annual ZEV transition costs and benefits over 2020–2050 for Germany. Costs include incentives for higher-cost vehicles (before parity), consumer campaigns, and infrastructure. Benefits include fuel savings, maintenance savings, reduced vehicle prices (after parity), and greenhouse gas emission reductions. Excluding the benefits from reduced greenhouse gas externalities, the 2020–2050 cumulative benefits outweigh the costs by a factor of about 7 in the United States, and by a factor of about 4 in Germany.

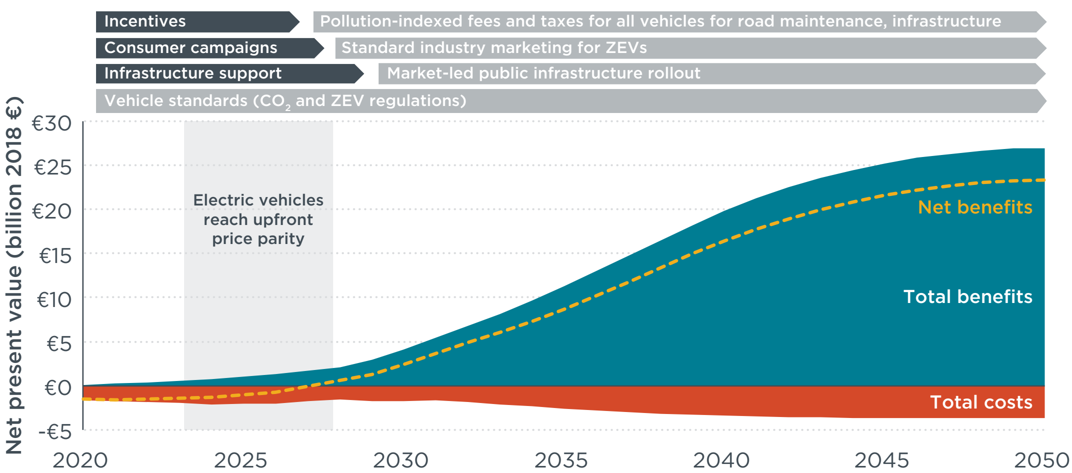

Figure ES-1. Costs, benefits, and policy over the transition to ZEVs in Germany.

Costs in the ZEV transition are transitioning to the private sector. Costs can shift from governments to private industry and consumers through the 2020–2030 period, and policies can evolve accordingly. As government incentives phase down, such programs would optimally transition to durable systems of pollution-indexed taxation for all vehicles. ZEV consumer campaigns can transition to typical automaker marketing. Infrastructure growth can shift to market-led investments and utility ratepayer-funded deployment. Collaboration between the public and private industry actors will remain crucial to identify funding gaps that governments, automakers, energy and infrastructure providers, and others can fill.

Governments are developing smart policies to support the ZEV transition. Dozens of government programs around the world demonstrate the types of policies needed to support ZEV growth while managing government expenditure over time. Persistent development of stringent vehicle emission or ZEV regulations in Canada, China, Europe, and many U.S. states ensures sufficient ZEV investment, volume, and widespread model availability. Norway and France have developed durable vehicle taxation systems. Carbon markets in British Columbia, California, and Québec create durable revenue streams and help fund several ZEV programs in these markets. British Columbia, California, Québec, and the United Kingdom each have action-oriented budgets that overcome the prevailing industry, infrastructure, and consumer awareness barriers, and link those programs to their regulatory ZEV requirements.

This research, although focused on ZEV policy and market developments in North America and Europe, has much broader implications. The ZEV barriers, costs, and benefits are broadly similar elsewhere, although different markets tend to have somewhat differing vehicles, fuel prices, and infrastructure availability. The policies, funding mechanisms, and infrastructure investment approaches assessed here can be adapted and implemented in markets of various sizes. As zero-emission truck technology continues to emerge, similar analysis to assess long-term zero-emission commercial freight costs, benefits, and public funding implications is warranted.

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INTRODUCTION

Many governments around the world, motivated by the necessities of clean air and a stable climate, are actively working to steer their markets toward all zero-emission vehicles (ZEVs). In addition to protecting public health and the environment, governments seek to gain economically from the transition to new electric and fuel cell vehicle technologies and their cleaner power sources. Further, the transition to zero-emission mobility offers the potential of enormous consumer fuel savings to individual drivers and the economy at large.

Although the potential benefits of ZEVs are enormous, there are substantial upfront costs in the early stages of the transition. These costs are related to higher upfront vehicle prices, insufficient charging infrastructure, and limited consumer awareness of the technology. To support this transition, governments have developed funding mechanisms including direct annual government budget allocations for ZEV purchasing incentives for consumers, public funding to charging providers for ZEV infrastructure, and fiscal support for public-private partnerships for campaigns to expand consumer understanding about the new technology and its benefits.

For a successful transition to all ZEVs, the relevant ZEV industries, including the automobile industry and the energy and infrastructure providers, will have to become profitable. Toward that end, parallel to the government expenditures to support ZEVs, various industry players have also invested billions of dollars to develop the vehicle and infrastructure technologies for ZEVs. As a result of the progress and increasing scale, "cost parity" approaches, whereby electric vehicles offer upfront vehicle prices equivalent to conventional vehicles (UBS, 2017; Goldie-Scot, 2019), in addition to their lower fueling costs and other benefits.

Among the key questions for governments regarding the shift to ZEVs are what types of government support are needed, for how long this need continues, and how public expenditures compare to the societal benefits. These questions are fundamentally about managing the ZEV transition costs across governments, private industries, and drivers through this period where cost parity is reached across vehicle market segments. From 2010–2018, when electric vehicles increased from virtually no sales to more than 2 million per year, nearly all those sales were in markets with government-funded incentives (International Energy Agency [IEA], 2019). As parity is reached and price is no longer a primary barrier, other barriers such as model availability, conveniently located infrastructure, and broad consumer understanding will increasingly be the focus for policy support.

This paper analyzes the costs, benefits, and associated government funding for the transition to ZEVs. The research quantifies funding needs through the development of a mainstream ZEV market. Due to the broad scale of the assessment, several markets are evaluated throughout the paper. The government expenditures of particular programs in several jurisdictions, including British Columbia, California, Québec, and the United Kingdom, are examined to assess the public costs for incentives, infrastructure, consumer awareness, and others. The markets of the United States and Germany are evaluated to quantify the relative costs, benefits, and government outlays. The research concludes with a discussion about policy, funding support, and roles of different players through the transition to ZEVs.

BACKGROUND

This section provides background in several areas as context for this paper's assessment of government ZEV funding and the associated costs and benefits in the transition. A brief review of government announcements regarding their goals for reaching all ZEVs is provided to demonstrate how widespread the vision has become. The major areas for costs and benefits of greater ZEV deployment are summarized, as is background on the evolution of consumer ZEV incentives. Finally, the prevailing ZEV market barriers are described to provide the broader context for the following sections of this assessment of long-term ZEV funding.

ANNOUNCEMENTS ON FULL ZEV TRANSITION

Several governments have announced their vision for ZEVs to make up 100% of all new passenger vehicle sales in their jurisdictions. The timelines associated with the established all-ZEV sales goals are summarized in Figure 1. Announcements by national governments are shown in green near the top of the figure whereas announcements by subnational governments are shown in blue near the bottom. Norway's goal for transitioning to all ZEVs by 2025 is the fastest, followed by six countries, including Denmark, the Netherlands, and Sweden, and China's Hainan province in 2030. Canada, France, and the United Kingdom have set a target of all-ZEV sales by 2040. Additional jurisdictions targeting all-ZEV sales no later than 2050 include Germany and 10 U.S. states. These government goals show how a complete transition to ZEVs is increasingly becoming a consensus position.

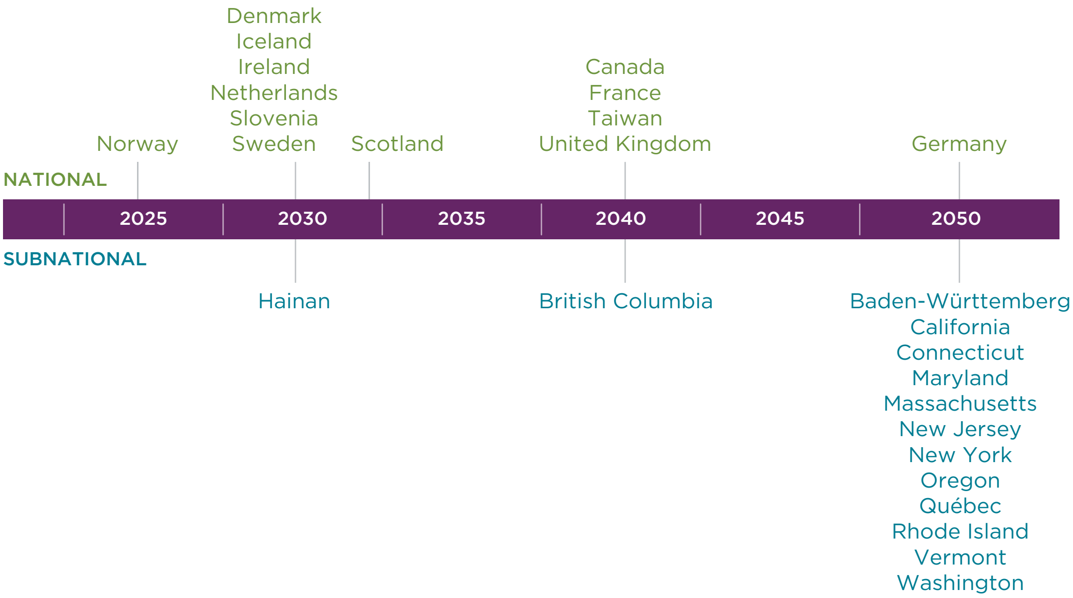

Figure 1. Timeline of selected government goals for 100% light-duty zero-emission vehicle sales.

In addition to those shown in Figure 1, high-level officials from jurisdictions including China, Costa Rica, India, and others have made less specific statements that suggest a combination of mid- and long-term ZEV goals that are on a similar trajectory. Frequently cited objectives for all of these government announcements are the needs for air quality improvements, climate change mitigation, and competitiveness of the jurisdictions' auto industry over the long term. Together, these markets show a growing consensus on moving to all ZEVs. With this increasingly global goal, it is an important time for governments to consider support policies, investments, revenue streams, and how to optimally fund the transition to zero-emission vehicles.

BACKGROUND ON BENEFITS AND COSTS

Although there are considerable upfront costs required to break down consumer ZEV adoption barriers, the benefits are also substantial, well studied, and have been found to significantly outweigh the costs (National Research Council [NRC], 2013). Table 1 summarizes the major ZEV benefits and costs. As shown, areas for benefits include fuel, maintenance, and time savings, as well as emission reductions. Costs include technological development and greater upfront costs in the early market until higher production volume delivers cost parity. Additional costs include the capital to build out the new supporting refueling infrastructure, as well as programs to raise public awareness, understanding, and exposure to the new technology.

Table 1. Zero-emission vehicle benefits and costs

	Impact	Description
Benefits	Fuel savings	• Several times more efficient than combustion vehicles. • Driving on electricity is generally cheaper than gasoline per unit distance.
	Maintenance savings	• Simplified drivetrain with fewer moving parts, meaning less expensive oil changes and other maintenance.
	Time savings	• Primarily charging at home (and/or workplace) when the vehicle is not being driven can result in fewer stops to refuel.
	Emissions reduction	• Significantly reduce (with the potential to eliminate) vehicle greenhouse gas emissions and local air pollution.
Costs	Vehicle technology	• Capital needed for R&D of new technology. • Greater upfront purchase costs initially.
	Refueling infrastructure	• Infrastructure deployment at residences, workplaces, public locations.
	Time lost (public charging)	• Charging at public locations takes longer than gasoline refueling.
	Public awareness	• Major efforts are needed to improve public awareness and understanding.

ZEVs have several additional and substantial associated benefits beyond those summarized in Table 1. For example, transitioning to ZEVs results in avoided fossil fuel exploration, extraction, refining, and transportation and the associated upstream costs and environmental effects. Also related to conventional vehicles' petroleum fuel use, ZEVs diversify the energy sources used to power vehicles, potentially reducing imports of petroleum fuels and conserving domestic petroleum resources. Many governments also are motivated to stake out a leadership position in the emerging ZEV technology to economically benefit from the manufacturing of ZEVs and the associated clean energy jobs.

EVOLUTION OF FISCAL INCENTIVES

Consumer purchase incentives are a key driver of ZEV adoption and spur the early market while technology costs fall and consumer familiarity improves. In many markets, purchase incentives represent a major share of government outlays among the various government ZEV support programs. Naturally, questions about the evolution and long-term necessity of consumer purchase incentives arise in discussions about how to durably fund the complete transition to ZEVs.

Technological advancements and battery pack cost reductions allow for reducing fiscal support for electric vehicles over time. Technological progress is advancing rapidly—much more quickly than projections from a few years previous. Based on battery cost reductions to approximately $150–$100 per kilowatt-hour, down from $176 in 2018, electric car costs are expected to decrease by $7,000–$9,000 from 2020 to 2025 (Lutsey & Nicholas, 2019). As cost parity between electric and conventional vehicles approaches, governments can phase down their incentive programs to match reductions in electric vehicle costs.

Many governments increasingly are recognizing this dynamic and announcing their intentions to phase down incentives in the 2019–2025 time frame. The phasedown of these incentives coincides with automaker announcements about increasing production of ZEVs and the corresponding decline in electric vehicle costs. Governments including China and the United Kingdom have multi-year programs in place to gradually phase down incentives in 2019 and 2020. The U.S. federal tax credit phases down after each individual automaker reaches 200,000 ZEVs sold, which occurred in 2019 for Tesla and General Motors, and could occur in subsequent years for other automakers. Colorado adopted a gradual phasedown of its tax credit from $5,000 in 2019 to half that amount by 2021–2023, and to $2,000 from 2023–2026 (Colorado General Assembly, 2019).

Although it is important to adapt incentives as the market develops, there also is evidence that stability and reliability in incentive policy promote greater consumer confidence and higher electric vehicle uptake (Slowik & Lutsey, 2016). As governments design and adapt incentive programs to acknowledge the transition to more advanced electric vehicle technology, greater sales, and mainstream consumer expectations, it is important to clearly communicate these changes to the public and make the programs simple to navigate. To date, few governments have adopted multi-year long-term incentive programs that acknowledge the full ZEV market transformation they seek. Doing so would help optimize their incentive programs to sustain market growth, provide a clear signal for automakers, and minimize government investments. Of course, with rapid advancement of ZEV technologies and market development, governments have found that some level of flexibility is advantageous; as new electric vehicle models with lower cost and longer range continue to become competitive in the market, government programs can evolve as fiscal incentives become less important relative to policies aiming to overcome other barriers.

OVERVIEW OF ZEV BARRIERS

Prevailing barriers exist that hinder the widespread adoption of ZEVs globally. These include insufficient model availability and diversity, greater upfront cost, refueling convenience and infrastructure, and limited consumer awareness and understanding. Leading governments in China, Europe, and North America are implementing comprehensive packages of policies to overcome these key barriers and grow the market. ZEV regulations and emission standards help to overcome the barrier of model availability by bringing advanced technology vehicles to market and increasing ZEV supply (Slowik & Lutsey, 2018; Rokadiya & Yang, 2019). The barrier of higher upfront costs is overcome by consumer fiscal incentives such as purchase subsidies, income tax credits, or vehicle tax reductions. The barrier of convenience and lack of infrastructure is overcome by various local, subnational, and national programs such as funding allocation, direct deployment, and incentives to build out the charging infrastructure network at residences, workplaces, and public locations. The barrier of consumer awareness is overcome by outreach and education campaigns, ride-and-drive events, media engagement, demonstration and pilot programs, consumer-friendly informational materials, and corporate leadership.

The markets that have experienced the most ZEV success are those that have the strongest policy support addressing each of the four major consumer barriers (Hall, Cui, & Lutsey, 2018). No single program or action is sufficient to grow the market.

Government initiatives to overcome the cost, infrastructure, and awareness barriers necessitate substantial funding. Government budgets often are limited, which can bring about competition for funding among different ZEV-support programs and questions about the relative effectiveness of each. Consumer purchase incentives are a core component of government support measures in the early market, but potentially become less important as ZEVs become cost competitive with their combustion counterparts. As fiscal incentives taper off, complementary policies and infrastructure deployment become increasingly important to continue addressing consumer barriers.

Government efforts to improve consumer awareness, understanding, and first-hand experiences with the new technology are needed until ZEVs become a core component of automobile company marketing strategies once cost parity is reached around the 2024–2028 time frame (Lutsey & Nicholas, 2019). There is a notable parallel to this ZEV situation with the increase in renewable energy use in the power sector. The large-scale use of incentives and policy in the power sector in markets around the world over the past decade has greatly increased the scale of solar and wind power production, reduced their costs, and made them increasingly competitive (International Renewable Energy Agency, 2019; Lazard, 2018; Mahajan, 2018).

In this paper, we analyze the costs and benefits of transitioning to ZEVs in the context of governments adopting durable funding mechanisms for incentives, infrastructure, and consumer awareness. The following section identifies and summarizes the key ZEV investments and expenditures in the private- and public-sectors. The fourth section analyzes the fleetwide and per-vehicle costs and benefits of transitioning to ZEVs. The fifth section discusses complementary government ZEV policies and programs, and the conclusion section summarizes the key findings and implications from this work.

EXISTING FUNDING SOURCES

This section compiles and tallies information on existing funding sources for ZEV programs. It includes industry investments in ZEVs and related infrastructure, as well as government expenditures and the associated funding sources.

PRIVATE INDUSTRY INVESTMENTS

Numerous private-sector stakeholders including automakers, electric utilities, and infrastructure providers are investing heavily in the global transition to ZEVs. In 2017, automakers announced investments totaling more than $150 billion through 2025 to achieve electric vehicle production targets of more than 13 million units annually (Lutsey, Grant, Wappelhorst, & Zhou, 2018). Through mid-2018, announced automaker investments totaled more than $300 billion (Lienert & Chan, 2019). Furthermore, global energy companies continue to invest in, and acquire, electric vehicle infrastructure companies. In addition to electric vehicles, automakers are investing more than $16 billion through 2030 to develop hydrogen fuel cell technology and infrastructure (Saarinen, 2018; Kim, 2018).

As part of the Volkswagen diesel scandal settlement, the company is investing $2 billion in infrastructure, consumer awareness, and other programs across the United States over a 10-year period through its subsidiary, Electrify America. About 40% of the investments are in California. The first 30-month investment cycle from January 2017 will result in several thousand charge points at more than 900 sites across the country, including local community charging and intercity fast charging corridors, with some stations capable of providing 350 kW DC charging. The second phase from 2019 to 2021 includes a $500 million investment with about 80% dedicated to infrastructure with the remaining 20% committed to education, and consumer awareness and outreach (Electrify America, 2019). Volkswagen also is investing directly in a parallel fast charging network in Canada, called Electrify Canada, with an initial 32 sites costing approximately $500,000 each (Bennett, 2019).

Ionity, a charging infrastructure joint venture among BMW, Daimler, Ford, and Volkswagen, is investing in high-power charging across Europe. The joint venture aims to deploy more than 400 rapid charging stations by 2020 and future plans are under development. In April 2019, Ionity invested €156 million with EU cofunding support of €39 million to build 340 ultra-charging stations across 13 member states (European Union, 2019). For context, the overall European electric vehicle market is approximately the same size as that of the United States, which is to say 1.1 to 1.2 million vehicles each at the end of 2018, but the Ionity investment to date is at least an order of magnitude lower than Volkswagen's Electrify America charging investment.

Electric power utilities play an especially important role in overcoming barriers to electric vehicles. Guided by their government regulatory bodies, electric utilities are increasingly investing in transportation electrification in major markets worldwide. In the United States, state utility commissions in 14 states had approved more than $1.2 billion of utility transportation electrification investments with even larger investments awaiting approval at the end of 2018 (Garcia, 2018).

In addition to automakers and utilities, multiple companies that focus only on charging infrastructure hardware or software are making significant capital investments. ChargePoint operates more than 60,000 chargers throughout North America (Center for Sustainable Energy, n.d.). In Europe, where the charging provider market is more fragmented, Allego stands out as a leader with more than 10,000 charging stations in its network (Allego, n.d.). Data on company-specific capital investments are not available.

A 2018 report evaluated the global charging infrastructure market by station type, installation type, and geographic region for more than 15 companies and assessed the global market for electric vehicle charging stations to be $5.3 billion in 2018 (Research and Markets, 2018). General Motors and Bechtel are working to bring in additional private funding to construct tens of thousands of charging stations across the United States, using GM's expertise on charging behavior. Researchers at McKinsey estimate that cumulative charging infrastructure capital investments in China, Europe, and the United States will amount to $50 billion through 2030 (Engel, Hensley, Knupfer, and Sahdev, 2018).

OVERVIEW OF GOVERNMENT ACTIONS AND EXPENDITURES

Proactive governments are implementing numerous ZEV policies and support actions to grow the market. Table 2 summarizes different actions that are underway in major markets around the world. The table also includes an indication of the relative budget impact of each action. Those shown in red typically require major fiscal expenditures, such as direct funding or lost revenues. The actions shown in yellow generally have lower relative impacts on government budgets, but typically require some level of funding for items such as staffing, administrative, or management needs. These typically include vehicle and efficiency regulations and various non-fiscal incentives such as preferential lane or parking access. The actions in blue are those that promote ZEV market growth and are either revenue-neutral or revenue-generating for government budgets, including fee-rebate schemes, low-emission vehicle zones, petroleum fuel taxes, carbon markets, electric ratepayer funded infrastructure, and electric vehicle-ready building codes.

Table 2. Summary of example ZEV support programs and funding details

Area	Action	Example	Impact on budget	Funding details	Other examples
Manufacturing	Research and development support	Germany	Direct funding	€1.5 billion for electromobility, €1 billion for fuel cell	Canada, China, Norway, Netherlands, UK, U.S.
	Manufacturing incentives	United States	Direct funding	$2.4 billion in loans for electric vehicle manufacturing	China, Germany, UK
	Long-term efficiency or emission standards	European Union	Staff and admin	Administration of government program to induce industry investment to meet 59 gCO_2/km vehicle standards by 2030	Canada, China, Japan, U.S.
	Incentive provisions within efficiency regulations	United States	Staff and admin	0 gCO2/mile accounting and ZEV multipliers	China, Europe
	ZEV regulations	British Columbia	Staff and admin	$3 million over 3 years for development and implementation	California, China, Québec, nine U.S. states
	ZEV action plan	Québec	Staff and admin	5-year plan with 37 actions, many with fiscal support	California, China, nine U.S. states, Germany, UK
Consumer purchase	Vehicle purchase subsidy, rebate	United Kingdom	Direct funding	£96 to £124 million annual budget through 2020	British Columbia, Germany, Québec, many U.S. states
	Vehicle purchase tax exemption	Norway	Foregone taxes	$350 million per year in lost taxes	Netherlands, Spain
	Vehicle fee-rebate (bonus-malus) scheme	France	Revenue neutral	Malus revenues finance bonus payments	Sweden
	Local registration, lottery, auction preference for ZEVs	Shanghai	Foregone fees	Estimated lost license auction revenue of 1.1 billion CNY ($160 million) in 2017	Beijing, Tianjin, Shenzhen, Guangzhou, Hangzhou
Consumer use	Low-emission vehicle zones	London	Revenue generating	ULEZ expected to generate £127 million in the first year	Beijing, Brussels
	Taxes on petroleum fuels, greater fuel savings for ZEVs	United Kingdom	Revenue generating	Tax on petroleum fuels generates about £28 billion in annual revenue	France, Netherlands, Norway
	Annual vehicle tax exemption	Germany	Foregone taxes	Vehicle tax reductions typically ranging from $50 to $700 per vehicle per year	Japan, Netherlands, Norway
	Preferential or discounted electricity rate structures	France	Low, lost revenues	EDF's Green Electric Car tariff offers 50% off charging energy at night	California, Connecticut, Maryland, New York, UK
	Preferential lane (e.g., bus, HOV lane) access	Maryland	Staff and admin	No direct fiscal cost or avoided revenue from priority access	California, Netherlands, Maryland, New Jersey, New York, Norway, Québec
	Reduced roadway tax or tolls	Ireland	Foregone taxes	25%–75% refunds on tolls through 2022, up to €500 per vehicle per year	Netherlands, New York, Norway, United Kingdom
	Preferential parking access	Hawaii	Foregone revenue	$10,000 per day in lost fees at Honolulu airport parking	Inner Mongolia, Nevada, Shanxi Province, Tokyo
Infrastructure	Carbon pricing scheme	British Columbia	Revenue generating	Carbon tax to generate $1.7 billion in 2019, funding clean energy programs	California, Québec, Sweden
	Low carbon fuel incentive for electricity providers	California	Revenue generating	LCFS expected to generate more than $250 million annually by 2025	British Columbia, Oregon
	Electricity ratepayer funded infrastructure	California	Revenue neutral	$200 million for 12,500 public and workplace charging stations	British Columbia, France, Maryland, Massachusetts, Minnesota, Oregon, Québec
	Public charging network deployment or funding	Norway	Direct funding	Enova support of $700,000 for rural fast charging in 2018	Baden-Württemberg, China, Germany, Netherlands, Québec
	Private charger infrastructure incentive, support	United Kingdom	Direct funding	Home charging grant scheme covers 75% or £500 for home charge point	Japan, Tokyo
	Charger requirements in building or parking codes	Washington	Revenue neutral	EV-ready building codes can avoid about $7,000 per station in retrofit costs	California, London, Ontario, Shanghai, European Union
Public exposure	Public awareness, outreach, education activities	United Kingdom	Direct funding	£4 million annually for national campaign, £40 million for eight Go Ultra Low Cities	California, British Columbia, Northeast U.S. states, Québec
	Consumer materials, resources, tools	Vermont	Staff and admin	Approximately $100,000 annual cost for website, outreach, events	California, Germany, Oregon, Norway
	E-mobility projects (e.g., carshare, ride-hail)	California	Direct funding	$1.7 million for electric carsharing in Los Angeles, $3 million for phase 2	Beijing, Germany, Oslo, Québec, Shanghai

The funding magnitude of government programs varies widely. Table 2 is intended to provide a sense of scale and summarize the publicly available information; it does not provide relative comparisons across the markets.

Governments use funding from various sources to finance ZEV programs, including from carbon markets, general budgets, polluter-pay vehicle emission fees, fee-rebate systems, utility ratepayer revenue, fuel duties, enforcement actions, industry partnerships, and road tolls. Table 3 summarizes the suite of ZEV actions and the fiscal details and revenue sources in Québec. Several hundred million dollars (CAD) have been allocated across a wide range of actions, including industrial development; incentives; home, public, and workplace charging infrastructure; public awareness; and electromobility projects. For context, in 2018 Québec had a population of about 8.4 million residents with more than 450,000 new light-duty vehicle registrations, and an electric vehicle sales share of almost 4%. Québec represents more than 40% of national electric vehicle sales in Canada.

Table 3. Selected light-duty ZEV actions, program details, and revenue sources in Québec

Area	ZEV action	Program details	Revenue sources
Manufacturing	R&D support	• $16.5 million for industrial innovation • $20 million for collaborative R&D projects to develop new EVs and their components	Green Fund (Government of Quebec, n.d.)
	ZEV regulation	• Requires manufacturers to meet minimum ZEV sales requirements	Fees for noncompliance will be credited to the Green Fund and used to finance various climate change mitigation measures
Consumer purchase	ZEV rebates	• Roulez vert – total program budget of $760.4 million from 2013 to 2021 ($433.8 million from 2019 to 2021) • Up to $8,000 for new vehicle with battery greater than 15 kWh • $4,000 for used BEV ($21.7 million available)	Green Fund
Consumer use	Free toll bridge and ferry access	• Saves paying per-trip ferry fares of approximately $8.65 per vehicle • Saves paying per-trip toll charge of approximately $2 per vehicle	Tolls and ferry charges are covered by the Ministry of Transportation
Infrastructure	Home and multi-unit residential building charger subsidies	• Roulez vert – total program budget of $760.4 million from 2013 to 2021 • $600 per home charger • 50% of purchase and installation costs up to $5,000 per station and up to $10,000, $20,000, or $25,000 based on the number of units	Green Fund
	Workplace charger subsidy	• Roulez vert – total program budget of $760.4 million from 2013 to 2021 • Program has $3.2 million budget from 2019 to 2021 • Up to 50% with $5,000 limit per station and $25,000 limit per place of business	Green Fund
	Charging infrastructure in fleet pilot project	• Total budget $1 million	Green Fund
	Utility Hydro Québec direct infrastructure deployment	• Near-term: 1,800 charging stations (10% fast) • 2029: Aiming for 1,600 fast charging stations • $5 million federal grant for 100 fast chargers • $2,5 million for fast chargers along main roads	Funded by a mix of revenues from electricity sales, the Green Fund, and federal grants
Public exposure and pilots	Business outreach and awareness	• $520,666 for the plug-in fleet project, EV trials with 30 businesses • Climate Change Action Plan, total budget of $8.6 million	Green Fund
	Public outreach	• $4 million from 2018 to 2021 for public awareness EV campaign on electrification of transportation	Quebec Budget Plan 2018
	Workplace outreach	• $634,345 to organize EV trials at workplaces	Climate Action Program
	EVs in driver's education schools	• $4.5 million for 2019–2020 fiscal year	Transportation electrification support program

Note: Dollars are Canadian.

Québec has additional incentive programs for heavy-duty trucks, infrastructure for marine and non-road equipment, $11.9 million for electric public transit, and $30 million for electric public school buses. The Québec government also provided an $8.6 million grant to launch a collaborative industry effort to design two bus and two freight truck prototypes for manufacturing.

One of the key initiatives supporting several ZEV programs in the province is the Transportation Electrification Action Plan (TEAP). TEAP had a $420 million budget beginning in 2015, with $187 million added in 2017 and 2018. Eighty percent of TEAP revenues are provided by the Green Fund, which is funded by several sources including the sale of greenhouse gas allowances under Quebec's cap-and-trade system. Ministry and agency credits represent about 20% of TEAP funding.

Québec's support programs for transportation electrification is continuous and targeted and has kept its coherence through multiple election cycles and governments, beginning with the Action Plan for Electric Vehicles in 2011. The government has reinforced various incentives and programs since 2019: in the recent 2019 budget, Québec extended the Roulez vert program until 2021 with $433.8 million, which includes the expansion of the Roulez vert program to used battery electric vehicles (BEVs) with $21.7 million, and the expansion of the Branché au travail program with $3.2 million for charging stations in the workplace. In the latest budget, the government also has allocated funding to various pilot projects, including charging infrastructure for fleets ($1 million) and electric vehicles in driving schools ($4.5 million until 2021). One financially durable program for infrastructure deployment in Québec stemmed from 2018 legislation authorizing utility Hydro-Québec to use electricity sales revenue to fund fast charging station deployment (Hydro Québec, 2019).

British Columbia, another leading ZEV province in Canada, released a 3-year fiscal plan that includes a $98 million (CAD) investment to help make ZEVs more affordable and convenient (British Columbia Ministry of Finance, 2019). The program includes $42 million in point-of-sale incentives available through March 31, 2020, or until funding is depleted. Nearly $50 million is allocated in fiscal year 2019–2020 for public fast-charging and hydrogen fueling stations, incentives for medium- and heavy-duty vehicles, training for automotive technicians and electricians, fleet procurement, home and workplace charging stations, and public outreach. Additional funding has been made available through 2022, including $3 million for development and implementation of the ZEV regulation and $5 million for charging infrastructure along highways and at government buildings. Figure 2 illustrates the relative breakdown of the various ZEV programs and their funding allocation as outlined in the 2019 budget.

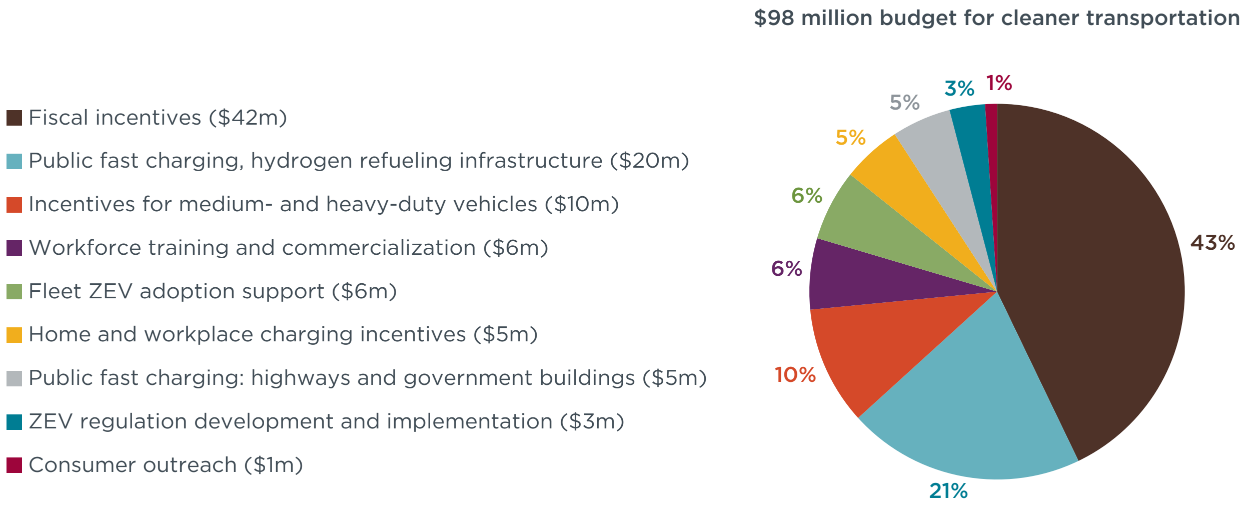

Figure 2. British Columbia 2019 budget cleaner transportation investments.

The figure shows how continuing the existing point-of-sale incentives for light-duty BEVs and hydrogen and fuel cell vehicles (HFCVs) constitute more than 40% of the budget, with an additional 10% dedicated to fiscal incentives for medium- and heavy-duty ZEVs. About 20% of the funding is allocated to deploying public infrastructure, including fast charging and hydrogen refueling, with additional funding allocated to home and workplace charging incentives (5%) and public fast charging along highways and at government buildings (5%). About 3% of the funding will support the development and implementation of the ZEV regulation. Consumer outreach and awareness is about 1% of the budget. To provide context to these values, in 2018 British Columbia had a population of about 5 million residents, about 3 million total light-duty vehicle registrations, more than 220,000 total new vehicle sales, and an electric share of new vehicles of approximately 4%.

In addition to Québec and British Columbia, the United Kingdom has committed substantial financial resources and enacted a broad suite of policies to promote ZEVs. Most programs around electric vehicles are managed by the Office for Low Emission Vehicles (OLEV), a part of the Department for Transport and the Department for Energy and Industrial Strategy. Programs include upfront rebates of up to £3,500 for BEVs; grants for home, workplace, and curbside charging stations; the Go Ultra Low consumer awareness and education program, cofunded by industry; and pilot projects in four cities as part of the Go Ultra Low Cities project. In the 2017 budget, the plug-in car and infrastructure grants were funded at £100 million and £200 million, respectively; these amounts are to be matched by private investors. The UK government is phasing out incentives as electric vehicles begin to reach the mainstream market (Hinson & Dempsey, 2019), including implementing eligibility criteria based on CO_2 emissions and zero-emission range.

By promoting ZEVs, UK leaders hope to not only reduce greenhouse gas emissions and air pollution, but also to encourage the growth and modernization of the UK automotive industry. The "Future of Mobility," with electric vehicles as a major component, is one of the four key areas in the UK's Industrial Strategy. The government has provided hundreds of millions of pounds in funding for dozens of research and demonstration projects ranging from wireless charging to zero-emission agricultural equipment and battery recycling. A central priority is the development of battery manufacturing, led by the Faraday Challenge, which provides £246 million to fund a Battery Industrialisation Centre and research by universities and industry (Engineering and Physical Sciences Research Council, 2018).

PUBLIC-PRIVATE COLLABORATIONS

In addition to the major public expenditures summarized above, public-private collaborations of various types are effective in leveraging government funding and resources to promote ZEVs. Below are a number of prominent examples of such public-private collaborations in Europe and the United States.

Three major European public-private initiatives use a combination of private and public funding to break down prevailing ZEV cost, infrastructure, and awareness barriers. Germany's ZEV purchase incentives from a total pool of €600 million in public funding are matched with €600 million from the automobile manufacturing industry (Bundesministerium für Wirtschaft und Energie, 2019). In the United Kingdom, £400 million have been committed to ZEV infrastructure—£200 million in government investment with a £200 million match by the private sector (United Kingdom, 2018). Also in the United Kingdom, Go Ultra Low is a multi-year joint government and industry electric vehicle campaign. Go Ultra Low is financially supported by the Society of Motor Manufacturers & Traders and the United Kingdom Office for Low Emission Vehicles (Go Ultra Low, n.d.). Additional funding from energy providers and charge point manufacturers is expected from 2019. Go Ultra Low has an annual budget of approximately £4 million.

Following the Go Ultra Low model, seven Northeast states partnered with 16 automakers to advance consumer awareness, understanding, and consideration of electric cars among drivers in the region. In 2018, this public-private partnership launched *Drive Change. Drive Electric.*, to highlight financial, environmental, and performance attributes of electric vehicles. In 2019, the campaign introduced a new program, *Destination Electric*, to illustrate the ability to travel with an electric vehicle by partnering with more than 100 local small businesses such as cafes, art galleries and bookstores near charging stations. *Drive Change. Drive Electric.* has an annual budget of approximately $1.4 million and is facilitated by the Northeast States for Coordinated Air Use Management, the Association of Global Automakers, and the Alliance of Automobile Manufacturers.

California also provides an exemplary approach for public-private ZEV consumer outreach. Nonprofit California-based organization Veloz aims to greatly broaden consumer awareness, understanding, and consideration of electric vehicles. Veloz is funded primarily through membership and sponsors, which include government, industry, and other nongovernment organizations. Figure 3 shows Veloz's revenues and expenditures for fiscal year 2017–2018. About three-quarters of the organization's $1.7 million expenditures supported the "Electric for All" public awareness campaign, which generated more than 53 million video views, 1,650 daily web visits, and 21,000 click-outs to automaker websites (Veloz, 2019).

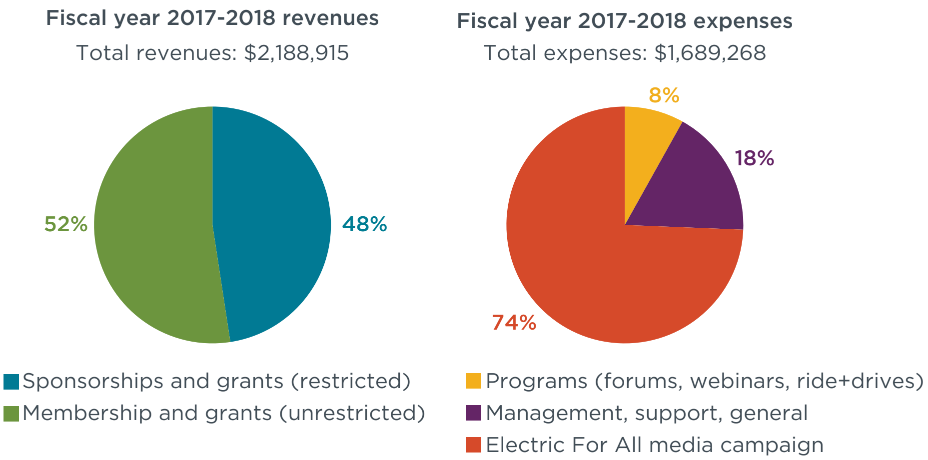

Figure 3. Example of consumer awareness campaign: Veloz fiscal year 2017–2018 revenues and expenses.

California also has leveraged public-private collaboration to build its network of hydrogen stations. In California the state has provided partial funding for 64 hydrogen refueling stations, which are then operated by private companies. The California Air Resources Board estimated that $92 million would be required to construct 40 new stations by 2020 (CARB, 2018). As the market grows, the state expects to provide less funding per station; recently, major upgrades to a station in Newport Beach were accomplished exclusively through private funding.

The Dutch government also has implemented several public private partnerships. The Coast to Coast e-Mobility program aims to promote transatlantic public-private partnership collaborations on Smart e-Mobility between California and the Netherlands. The partnership is designed to accelerate the exchange of knowledge and innovation among governments, universities, and industry in the United States and Holland (S4C Smart e-Mobility Program, 2019). Public-private collaborations at the local level are also promoting ZEVs. In Utrecht, Netherlands, "We drive solar" is a carsharing scheme of 70 Renault Zoe electric vehicles and 30 bidirectional solar powered charging stations spurred by a collaboration between industry, research institutes, and the government (We drive solar, n.d.). The vehicle batteries are charged using solar energy, and the bidirectional charging technology allows for solar energy stored in the batteries to later be returned to the grid as needed.

ANALYSIS OF ZEV TRANSITION

This section analyzes the funding expenditures, including the relative costs and benefits, of a transition to ZEVs over the 2020–2050 period. This analysis period includes the major costs to overcome the prevailing cost, infrastructure, and awareness barriers and to promote lower cost, longer range electric vehicles in the near term and the sustained investments over the longer-term transition. The funding is evaluated on a societal fleetwide basis, as well as based on the per-vehicle costs and benefits. The framework, as explained below, is based on the methodology of the National Research Council (2013), which uses net present value accounting to account for the economic effects over the long-term transition to alternative fuel vehicles.

The elements of this analysis draw from many studies. Table 4 summarizes the primary data sources and analyses applied to this analysis. The analysis builds upon research studies, including assessments of future ZEV market shares; technology improvements and battery pack cost reductions; home, workplace, and public charging infrastructure needs and costs; and fiscal incentives, greenhouse gas (GHG) reduction benefits, and various technical vehicle specifications.

The assumptions outlined in Table 4 are the core components of our analysis of transitioning to ZEVs. The following subsections illustrate several key steps of our analysis leading up to our evaluation of the fleetwide and per-vehicle estimated net present value (NPV) of the costs and benefits of transitioning to electric vehicles. We investigate two large representative automobile markets, those in the United States and Germany. We adopt a $1.13 USD to euro conversion rate based on real-world currency rates as of June 1, 2019.

Table 4. Key data sources supporting underlying assumptions for this analysis

Category	Market	Key assumptions applied to analysis	Study
ZEV share of new vehicles sales	United States	• 17% by 2030, 48% by 2035, 82% by 2040 • Applied for new vehicle penetration	Witkamp, Gijlswijk, Bolech, Coosemans, & Hooftman (2017); Lutsey (2015)
	Germany	• 30% by 2030, 63% by 2035, 91% by 2040 • Applied for new vehicle penetration	
Electric vehicle costs	United States	• Battery pack costs of $147/kWh in 2020, declining to $72/kWh in 2030 • Applied to analyze cost and the timing to phase down incentives	Lutsey & Nicholas, (2019); Witkamp et al. (2017)
	Germany		
Infrastructure costs	United States	• Chargers needed by category (home, work, public) • Applied to fleet growth to analyze total infrastructure costs	Nicholas, Hall, & Lutsey, (2019)
		• Costs of infrastructure by category (home, work, public) • Per-charger costs for infrastructure (home, work, public)	Nicholas (2019)
		• Intercity fast-charging corridors outside major metropolitan areas	Funke & Plötz (2017)
	Germany	• Vehicle stock and fleet turnover • Applied to identify number of public chargers needed	Bento, Roth, & Zuo (2016)
		• Average, per-charger infrastructure costs for home and public charging	German National Platform for Electric Mobility (2015)
		• Distribution of homes electing to upgrade to higher power chargers • Applied to assess share of homes requiring home upgrades	International Energy Agency (2018)
		• Intercity fast-charging corridors outside major metropolitan areas	Funke & Plötz (2017)
		• Consumer charging behavior • Applied to assess share of home, workplace, and public charger usage	Vogt & Fels (2017)
Fiscal incentives	United States	• The evolution of electric vehicle incentives • Applied to phaseout of state and federal incentives through 2030 based on automaker sales volume • Applied to analyze total government expenditures	Stephens, Zhou, Burnham, & Wang (2018); Witkamp et al. (2017); Zhou, Wang, Hao, Johnson, & Wang (2015)
	Germany	• The evolution of electric vehicle incentives • Applied to inform phaseout of incentives, including federal rebate through 2027, and annual ownership tax exemption through 2030	
Greenhouse gas emissions and social cost of carbon	United States	• Social value of CO_2 reductions €180/ton in 2020 to €231/ton in 2050 (2016 €) • Applied to assess greenhouse gas emission reduction benefits	Intergovernmental Panel on Climate Change (2014); German Federal Environment Agency (UBA) (2012)
	Germany		
	United States	• Grid emissions of 456 gCO_2/kWh in 2016, decreased by 80% by 2050 • Applied to upstream emissions of ZEVs	U.S. EPA (2018)
	Germany	• Grid emissions of 470 gCO_2/kWh in 2018; decrease by 80% by 2050 • Applied to upstream emissions of ZEVs	Graichen, Sakhel, & Podewils (2019)
Vehicle specifications	United States	• Electric and combustion vehicle efficiency 2020–2050 • Applied to energy costs and emission reductions	Lutsey & Nicholas (2019)
	United States	• Vehicle miles traveled (VMT) and survival rates • Applied to assess total fleet and per-vehicle VMT, fuel, maintenance	Davis & Boundy (2019); Lutsey (2017)
	Germany		
	Germany	• Combustion vehicle efficiency, CO_2 emissions, cylinder capacity • Applied to evaluate national annual tax, fuel savings, emission benefits	Mock (2018)
	Germany	• 40% diesel share of combustion vehicles • Applied to fleetwide vehicle efficiency, emissions, taxes, and incentives	Mock (2018)
	United States	• Electric and combustion vehicle per-mile maintenance • Applied to VMT for total maintenance costs	UBS (2017); Kerman (2019)
	Germany		
Fuel prices	United States	• Electric and gasoline prices 2020–2050 • Applied to per-vehicle and fleet fuel costs	U.S. EIA (2019)
	Germany		Oeko Institut and Fraunhofer ISI (2015)
Net present value discount rate	United States	• 2% discount rate • Applied to all future costs and benefits beyond year 2020	German Federal Environment Agency (UBA) (2012)
	Germany		

The pace and scale of ZEV penetration are critical inputs to transitional costs associated with various fiscal policies including incentives, infrastructure deployment, and public awareness campaigns, as well as the transitional benefits including long-term upfront reduced vehicle price, fuel savings, and greenhouse gas emission reductions. We develop hypothetical ZEV penetration scenarios based on achieving a 100% ZEV share of new vehicle sales by 2050 in the United States and Germany. Starting in 2020, we assume that ZEVs make up fewer than 5% of annual new light-duty vehicle sales in 2020 in both markets. Market growth in Germany occurs at a slightly faster pace than the United States. Specifically, we assume that ZEVs reach a 30% sales share in 2030 and increase to 90% of new sales in 2040 in Germany. In the United States, we assume that ZEVs are about 17% of new light-duty vehicle sales in 2030 and grow to more than 80% of new sales by 2040.

EVALUATING VEHICLE COSTS

A key question impacting how to durably fund the transition to ZEVs is the point at which electric vehicle technology improvements and cost reductions allow fiscal incentives to phase down. Figure 4 shows vehicle technology prices for the car segment based on a technical assessment of vehicle technology cost, including automaker profit and dealer markup, in the United States (Lutsey & Nicholas, 2019). As shown, electric vehicles are projected to see substantial cost reductions from 2020 to 2030. The highest electric vehicle cost component is the battery pack, which declines from about $147/kWh in 2020 to approximately $103/kWh in 2025 and $72/kWh in 2030.

The figure shows that electric vehicles reach purchase cost parity with conventional alternatives in the 2024–2028 time frame, depending on electric vehicle range. Shorter-range 150-mile (242-kilometer) electric vehicles (BEV-150) reach cost parity in 2024, while longer-range 300-mile (483-kilometer) electric vehicles reach cost parity in 2028. Longer-range electric vehicles reach cost parity a few years later because of their larger battery packs, which add approximately $1,600 to the cost of a vehicle with a 200-mile range (BEV-200) and approximately $4,800 to the cost of a BEV-300 over and above the cost of the 150-mile BEV by 2025. Although not shown, the parity points for the crossover and SUV vehicle segments tend to be about one to two years later because these larger vehicles also require larger batteries.

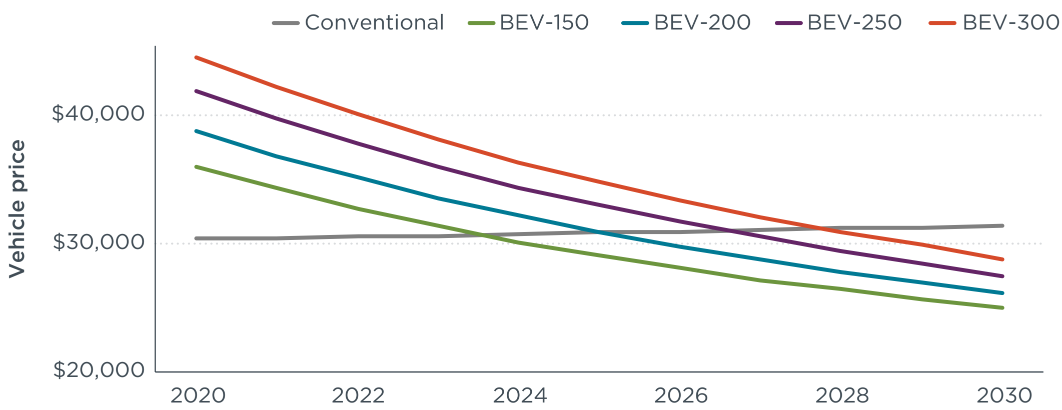

Figure 4. Initial purchase price of conventional gasoline and 150–300 mile battery electric vehicles for 2020–2030.

EVALUATING CHARGING INFRASTRUCTURE COSTS

This section analyzes the charging infrastructure costs required to support the full transition to electric vehicles by 2050. Our analysis quantifies the costs of home and public charging infrastructure in the United States and Germany, both on a per-vehicle and cumulative basis.

United States. This analysis builds on a previous study evaluating the charging infrastructure needed to power more than 3 million electric vehicles expected by 2025 across major metropolitan areas (Nicholas, Hall, & Lutsey, 2019). Infrastructure costs include installation, hardware, and planning costs, and these are separately assessed for BEVs and plug-in hybrid electric vehicles (PHEVs). Charging needs include home, workplace, public Level 2 charging, regional direct current (DC) fast, and intercity DC fast-charging corridor networks.

Based on the existing charging infrastructure and charging behavior trends, on a per-vehicle basis, we apply average home charging costs of $750 for BEVs and $320 for PHEVs starting in 2020. Regional public and workplace charging ecosystem costs are estimated at $840 for BEVs and $285 for PHEVs in 2020. Public BEV costs are higher because of the BEVs' greater needs for public, regional DC fast, and workplace charging. Per-vehicle home infrastructure costs are lower than the cost of a particular electric vehicle owner installing home charging because many owners do not upgrade their home charging (Nicholas, 2019). The per-vehicle PHEV home infrastructure costs are lower because existing household plugs without upgrades are more common. The costs for an intercity DC fast-charging network are based on one fast charger per 1,000 BEVs (Funke & Plötz, 2017).

From 2020 to 2030, infrastructure hardware costs per charger are estimated to decline by 3% per year while installation costs remain the same. In addition to hardware and installation costs, additional project-level planning costs are included, adding 15% for public Level 2 and workplace and 5% for DC fast, although planning costs for DC fast can typically be about three times those for Level 2 in absolute terms. Public charging costs decline at a faster rate than home charging costs on a per-vehicle basis for several reasons. The trend toward larger sites reduces the per-charger installation costs, dual-headed chargers provide two chargers for one pedestal and reduce total costs, and higher charger use means each outlet can supply more energy and accommodate more vehicles charging. Beyond 2030, we apply a small increase in annual overall infrastructure costs over the 2030–2050 time frame. This is expected due to increased energy capacity needed at public sites requiring more expensive upgrades, the trend toward an increasing share of more expensive home charging at apartment and multi-unit dwellings, and electric vehicle market expansion to a greater share of drivers without available home outlets.

Based on the electric vehicle growth rates outlined above for ZEVs to reach all light-duty vehicle sales by 2050, this will require significant home, public, and workplace infrastructure deployment to power these vehicles. We find that annual charging infrastructure costs over the 2020–2030 period average $1.2 billion based on our net present value accounting. Over the long term, the total cumulative infrastructure investments are $230 billion over the 2020–2050 time frame. About 55% of these costs are for home charging infrastructure, about 35% for public and workplace charging within metropolitan areas, and the remainder for intercity fast corridor charging. These costs, including relative costs and benefits of the ZEV transition, are analyzed from a broader societal perspective below.

Germany. Our assessment of charging infrastructure costs in Germany follows the same analytical framework as used for that of the United States. As above, infrastructure costs include installation, hardware, and program-level costs for BEVs and PHEVs for home, workplace, public Level 2, regional DC fast charging, and intercity DC fast charging corridor networks.

The German infrastructure analysis relies on several data sources, as listed in Table 4. Data from Vogt and Fels (2017) are applied to determine market composition for typical consumer charging and commuting behavior, which informs the relative needs and usage of home, workplace, and public charging. Compared to the United States, residences have higher electrical voltage in Europe, and many current electric vehicle owners simply used an existing 230 volt residential plug without undertaking home upgrades for an additional circuit.

Based on the existing charging trends, on a per-vehicle basis, we estimate average home charging costs of $950 (€840) for BEVs and $220 (€200) for PHEVs starting in 2020. Regional public and workplace charging ecosystem costs are estimated at $1,250 (€1,100) for BEVs and $600 (€525) for PHEVs in 2020. As above for the U.S. analysis, public charging costs are higher for BEVs than PHEVs due to greater needs for public charging, and per-vehicle home infrastructure costs are lower than the cost of a particular electric vehicle owner installing home charging because many owners do not upgrade their home charging. On a per-charger installation basis, costs are somewhat higher in Germany than in the United States (German National Platform for Electric Mobility, 2015). Higher-powered charging units, up to 22 kW compared to 7 kW in the United States, are more common in homes in Germany, so the costs to add additional circuits during home upgrades will be greater. The costs for an intercity DC fast-charging network again are based on one fast charger per 1,000 BEVs (Funke & Plötz, 2017).

The same future-year infrastructure cost assumptions are applied in Germany beyond 2020 as above for the United States. Based on the electric vehicle growth rates outlined previously for ZEVs to reach all light-duty vehicle sales by 2050 in Germany, we find that annual net present value charging infrastructure costs over the 2020–2030 period average about €545 million ($615 million). Over the long term, the cumulative net present value of infrastructure investments is approximately €66 billion ($75 billion) over the 2020–2050 time frame. About 45% of these costs are for home charging infrastructure, about 45% for public and workplace charging within metropolitan areas, with the remainder for intercity fast corridor charging. For comparison, another study estimates that total charging infrastructure costs in Germany could range from €80 billion to €107 billion (Auer, Heinz, Jochem, & Doppelbauer, 2019), which are comparable to the findings here before net present value discounting is incorporated. These costs are analyzed and placed in a broader societal perspective with relative costs and benefits of the ZEV transition below.

FLEETWIDE BENEFITS AND COSTS

Building on the above analyses of electric vehicle fleet transition, vehicle technology costs, and infrastructure costs, we assess the net present value of the costs and benefits associated with transitioning the light-duty vehicle fleet to 100% electric vehicles by 2050. Because of the greater uncertainty about when hydrogen fuel cell vehicles may reach high production volume and cost parity, we assess fuel cell vehicles in the per-vehicle analysis in the following section, but not in this fleetwide analysis. Beyond the elements outlined above, we integrate additional cost components including fiscal incentives from government purchase rebates and taxation exemptions, as well as costs associated with expanded consumer awareness efforts and outreach campaigns.

Our analysis of the benefits of transitioning to electric vehicles includes fuel savings, greenhouse gas emission reductions, and a reduced upfront vehicle price at time of purchase, which is expected around the 2024–2030 time frame (Lutsey & Nicholas, 2019). The reduction in technology component costs could lead automakers to offer cheaper vehicles or more amenities, invest in research and development, or take some fraction of this as profit. In the net present value accounting, we apply a 2% discount rate that compounds from 2021 on for all costs and benefits (German Federal Environment Agency, 2012). This accounting parallels the method of the National Research Council

(2013) analysis, which includes a societal NPV economic frame for the transitioning to alternative fuel vehicles.

United States. Figure 5 illustrates the estimated NPV of the costs and benefits of transitioning to electric vehicles in the United States in the near term, from 2020 to 2035. Annual costs are greatest in 2021 at about $6.5 billion, when the electric vehicles' upfront incremental cost is greatest, and there are also significant outlays from federal and state purchase incentives. As electric vehicles reach cost parity over the 2024–2030 time frame, which depends on vehicle segment and electric range, the upfront incremental cost of electric vehicles becomes an upfront reduced price benefit, as shown by the light gray (through 2028) and dark gray wedges (after 2028). The figure shows how the costs of federal and state purchase incentives phase down significantly beyond 2022, aligning with the pace of electric vehicle technology cost reductions.

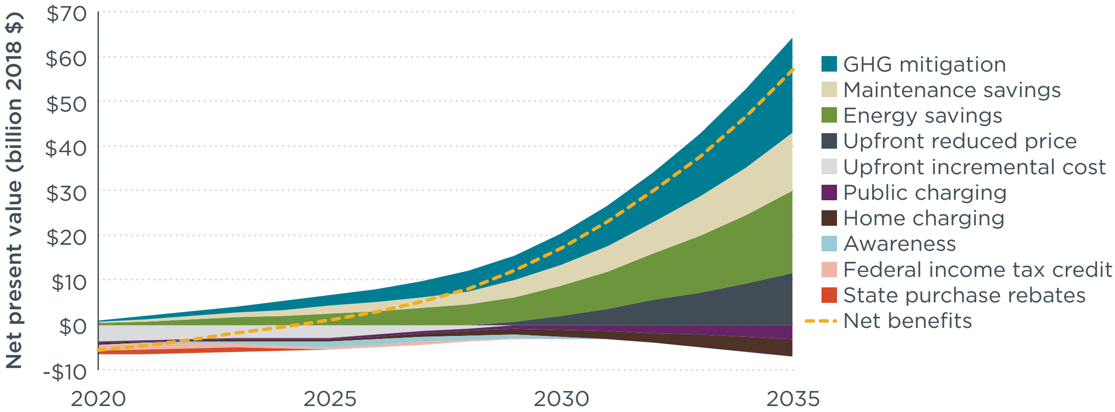

Figure 5. Net present value of the costs and benefits of transitioning to electric vehicles in the United States: 2020 through 2035.

As cost parity is reached, complementary efforts remain necessary to overcome awareness and infrastructure barriers. Figure 5 shows the estimated cost of consumer outreach and awareness in light blue, which is greatest around the 2024–2028 time frame. Home and public (workplace, public, and intercity fast charging) infrastructure costs, shown in brown and purple, increase over time with the pace and scale of electric vehicle market adoption. When electric vehicles reach around 50% of new vehicle sales around 2035, annual infrastructure costs will grow to about $6.5 billion per year, with home charging being the largest charging infrastructure need.

The benefits shown in Figure 5 include upfront reduced purchase price, energy savings, maintenance savings, and greenhouse gas mitigation. The annual net present value benefits grow to more than $17 billion per year by 2030 and scale with the electric vehicle market penetration. Although there are significant upfront costs required to overcome barriers to widespread electric vehicle adoption, the net benefits outweigh the costs beginning in 2025.

Figure 6 extends the analysis shown in Figure 5 beyond 2035 to 2050. Starting around 2038, annual costs grow to more than $10 billion as home, workplace, and public charging infrastructure deployment scales with a growing electric vehicle market. Yet from 2035 to 2050, the net benefits continue to increase as the fleet transitions toward all electric vehicle sales. The annual net present value benefits grow to more than $50 billion per year in 2035, and $100 billion in 2039. As shown, net benefits surpass $200 billion per year in 2046. The analysis indicates that cumulative long-term benefits through 2050 are about 11 times the cumulative costs.

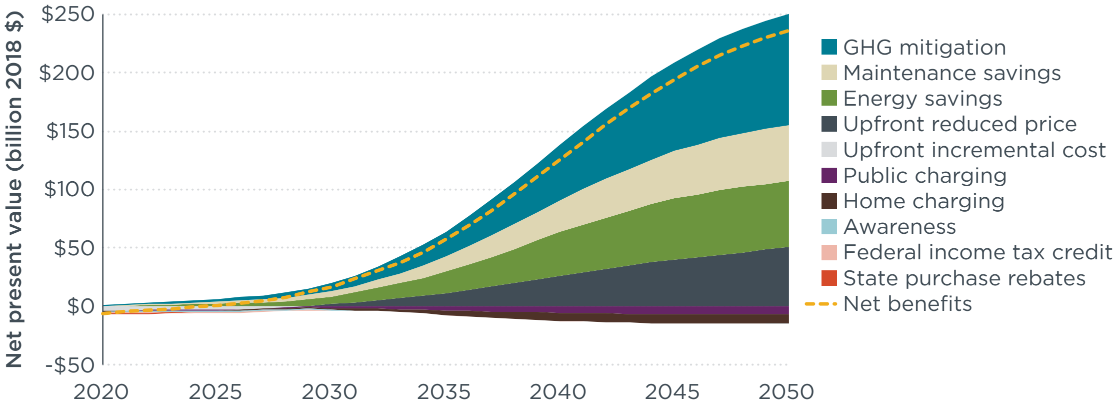

Figure 6. Net present value of the costs and benefits of transitioning to electric vehicles in the United States: 2020–2050.

Germany. We also analyze the fleetwide costs and benefits of transitioning to electric vehicles in Germany. Figure 7 illustrates the estimated cumulative present value of the transition from 2020–2050. The figure includes the same cost and benefit components as the example from the U.S. market with the addition of Germany's annual ownership tax exemption for electric vehicles. As in the analysis above, although significant upfront expenditures are needed to overcome barriers to widespread adoption, the net benefits outweigh the costs beginning in 2028.

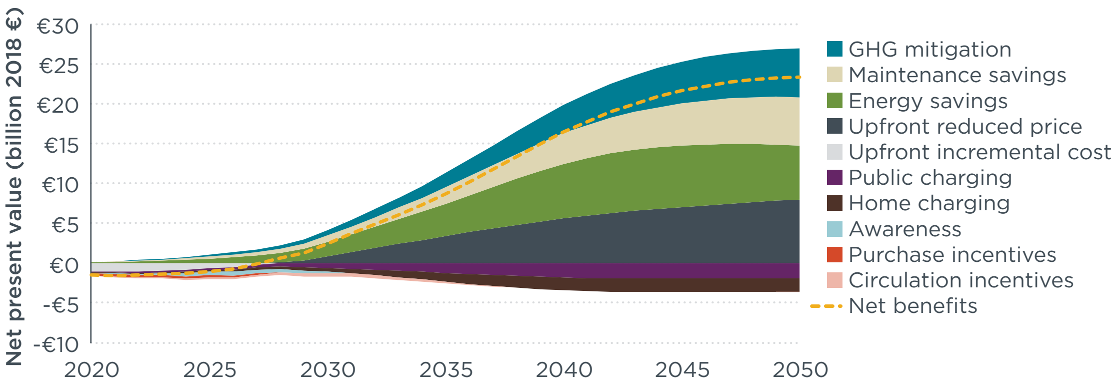

Figure 7. Net present value of the costs and benefits of transitioning to electric vehicles in Germany: 2020–2050.

As shown, the annual net benefits in Germany surpass €5 billion in 2033, €10 billion in 2036, and €15 billion in 2040. The analysis indicates that cumulative long-term benefits are about five times the cumulative costs, including all the net present value 2020–2050 costs and benefits. The contributors to the relatively smaller net benefits in Germany compared to the United States include fewer annual vehicle kilometers traveled per vehicle, smaller average size of vehicles, and lower average combustion vehicle CO_2 per kilometer. The near-term energy savings are greater in Germany than the United States because of the greater cost gap between petroleum and electricity prices in Germany. However, the long-term energy savings in Germany somewhat taper around 2040 because of projected increases in electricity price and the efficiency of the displaced combustion vehicles.

Several additional points help put the absolute costs and benefits of Figure 6 and Figure 7 in context. The magnitude of the net benefit in the United States through 2050 is about eight times greater than in Germany, in large part due to the much greater vehicle market size in the United States. The greenhouse gas emission reduction benefits are proportionally lower in Germany compared to the United States, primarily due to the lower average CO_2 per kilometer of the displaced combustion engine vehicles in Germany.

Several other potential effects are excluded in this analysis. Transitioning to electric vehicles would bring substantial benefits from reduced local air pollution in almost all conditions, given that conventional vehicles are major emitters of ozone, NO_x, and particulate matter; these benefits will grow as more electricity is produced from renewable sources (Bernard, 2018; Goodkind, Tessum, Coggins, Hill, & Marshall, 2019; European Environment Agency, 2018). In addition, benefits from petroleum use reduction, fuel diversification, and fuel imports are not quantified here, and studies indicate that these benefits may be on the order of several thousand dollars per vehicle (Leiby, Shelby, & Coe, 2014). On the other hand, the widespread adoption of electric vehicles may have environmental and social drawbacks, such as the intensive mining of lithium, cobalt, and other resources. Changes in the liquid fuel mix to biofuels or other alternative fuels are also excluded from this analysis. In addition, the study excludes the broader economic impacts from the fuel savings (e.g., see Cambridge Econometrics and Element Energy, 2018), nor does it consider the complex impacts that electric vehicles and other developments in the auto sector may have on vehicle manufacturing and associated jobs (Le Petit, 2017; FTI Consulting, 2018).

PER-VEHICLE BENEFITS AND COSTS

We also investigate the net present value of the costs and benefits of transitioning to electric vehicles on a per-vehicle basis. We analyze the costs and benefits associated with the existing incentive, infrastructure, and awareness programs in 2020, as well as proposed technological improvement-based policy modifications, such as the phaseout of purchase incentives in 2030. We analyze representative BEV models with a 250-mile range in the United States and Germany. In the U.S. case, California is shown, which thereby includes the applicable state level purchasing incentive and applicable fuel cost assumptions.

Figure 8 illustrates the societal per-vehicle lifetime costs and benefits for 250-mile electric vehicles in California in 2020 (left) and 2030 (right). Shown in red, 2020 costs include home and public charging infrastructure, consumer awareness, state and federal incentives, and the remaining vehicle upfront incremental purchase cost. Shown in blue, 2020 benefits include fuel savings, maintenance savings, and greenhouse gas emission mitigation. By 2030, as electric vehicles reach cost parity and incentives have phased out, the remaining costs include charging infrastructure and awareness programs. From 2020 to 2030, electric vehicles' upfront incremental cost shifts to an upfront reduced-price benefit for consumers. Benefits in 2030 include reduced upfront vehicle price, fuel savings, maintenance savings, and greenhouse gas emission mitigation as shown in blue on the right side of the Figure 8.

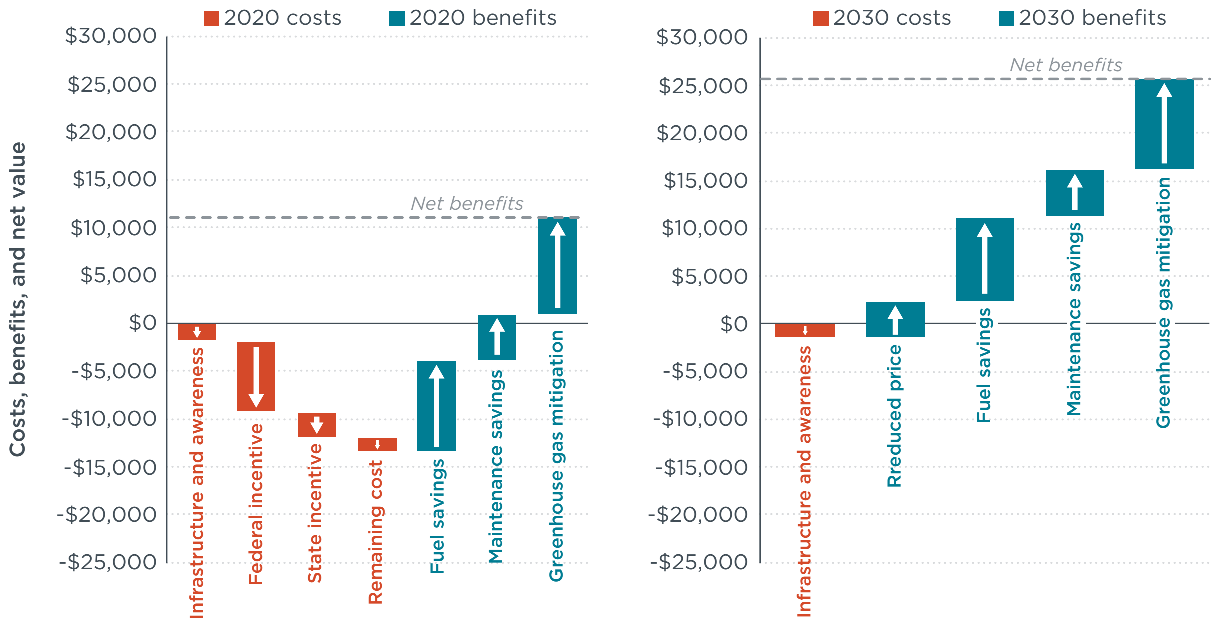

Figure 8. Per-vehicle lifetime costs and benefits in California for new 250-mile electric vehicles in 2020 and 2030.

The net per-vehicle benefits for greater deployment of electric vehicles is shown in the right side of Figure 8. The net benefits from a new electric vehicle increase more than twofold from 2020 to 2030, from about $11,000 to about $26,000. This is primarily attributable to electric vehicle technology advancements, especially the declining costs of batteries.

Although plug-in electric vehicles make up the vast majority of zero-emission vehicles through 2019, many governments and automakers also are investing in hydrogen fuel cell vehicles. Upfront costs for these vehicles are also falling, but the shift to competitive high-volume production is less certain than for plug-in electric vehicles. Research estimates that fuel cell vehicles would face an upfront price increment of about $15,000 in 2020 and $5,000 in 2030 versus conventional vehicles, and could reach price parity by 2040 (NRC, 2013). Hydrogen fuel station and per energy-unit costs, including from renewable hydrogen, also are expected to decline with increasing scale and improving technology. To assess fuel cell vehicle deployment as above for electric vehicles, we apply a hydrogen cost of $4 per gallon of gasoline-equivalent and hydrogen fuel station costs declining to $1 million (Isenstadt & Lutsey, 2017).

In Figure 9, we examine the costs and benefits of fuel cell vehicle deployment in California in 2020 and 2030 (as above in Figure 8 for BEVs). The figure shows the societal costs, benefits, and net benefits for a representative fuel cell vehicle in 2020 and 2030. We assume the same maintenance savings and awareness costs as for BEVs. In 2020, we assume that hydrogen is a mix of 30% renewable hydrogen and 70% hydrogen from steam methane reformation; by 2030, we assume that all hydrogen will come from renewable sources (Hydrogen Council, 2018).

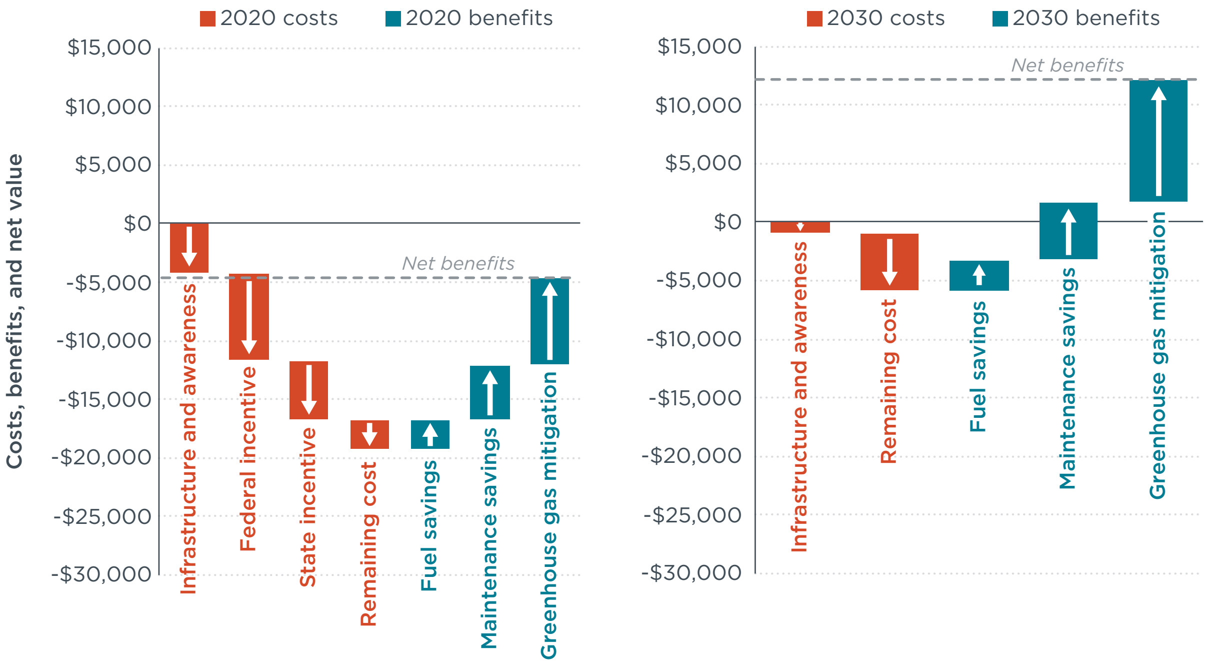

Figure 9. Per-vehicle lifetime costs and benefits in California for new hydrogen fuel cell vehicles in 2020 and 2030.

As indicated in Figure 9, a fuel cell vehicle purchased in 2020 poses a net cost of about $4,700 over its lifetime, whereas the situation reverses to a net benefit of more than $12,000 for a vehicle purchased in 2030. This is primarily due to the decreasing cost of the vehicle, as well as to increased fuel savings from less expensive hydrogen and lower per-vehicle infrastructure costs. The per-vehicle infrastructure costs are higher than for a BEV in 2020, but they are lower in 2030. Although not depicted, a comparable Germany-specific fuel cell vehicle analysis would result in a similar result with net costs turning to benefits by 2030.

Figure 10 shows the societal per-vehicle lifetime costs and benefits for 250-mile electric vehicles in Germany in 2020 and 2030. The same cost and benefit elements as above are included. As above, the figure shows that there are substantial net benefits to transitioning to electric vehicles. The right side of the figure shows that the net benefits in 2030 are about €17,000 per vehicle, up from approximately €2,700 per vehicle in 2020. This large increase in benefits from 2020 to 2030 is largely a result of reductions in electric vehicle technology costs. The greenhouse gas mitigation benefits in Germany also increase over time with the decarbonization of the power grid.

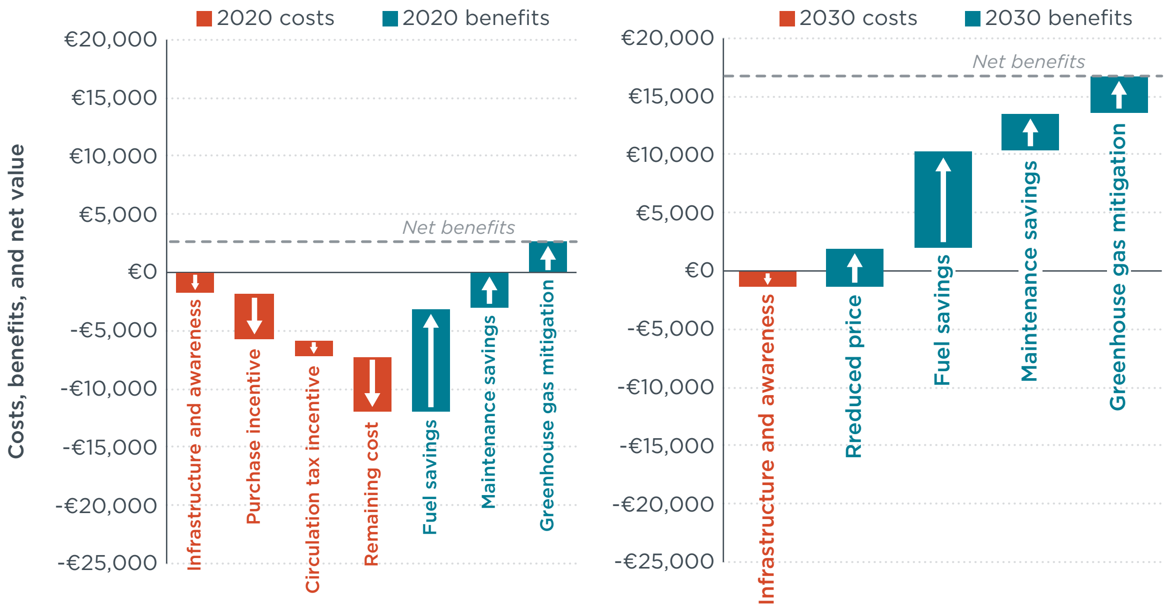

Figure 10. Per-vehicle costs and benefits in Germany for new 250-mile electric vehicles in 2020 and 2030.

AUTOMAKER PERSPECTIVE

This section complements the above societal analysis with an illustrative discussion of per-vehicle automaker costs during the transition to electric vehicles. Applying the underlying technology costs from the above analysis, we examine the interplay between conventional vehicle prices, electric vehicle prices, and incentives through the cost-parity period. We take the example of a representative BEV with a 250-mile electric range through the 2018–2032 period, approximating the U.S. situation in which incentives are expected to be phased out.

Figure 11 shows the price of a representative 250-mile range electric vehicle, before and after incentives, compared to a similar average conventional vehicle in the United States. The incentives initially are assumed to be $7,500 for the federal tax credit plus $1,500 for a state incentive. For this example, the state incentive is assumed to expire at the end of 2022, followed by the federal incentive phasing down to half the full amount in 2025 before expiring at the end of that year. The analysis includes a nominal 5% profit margin for automakers, which is customary for passenger cars (UBS, 2017; Lutsey & Nicholas, 2019); however, the actual point at which each automaker starts producing a profit from electric vehicles is unknown and dependent on their production volume. Nonetheless, the figure indicates that under our assumptions regarding technology cost and pace of market transition, electric vehicles move from unprofitable in 2018 to very profitable by 2030.

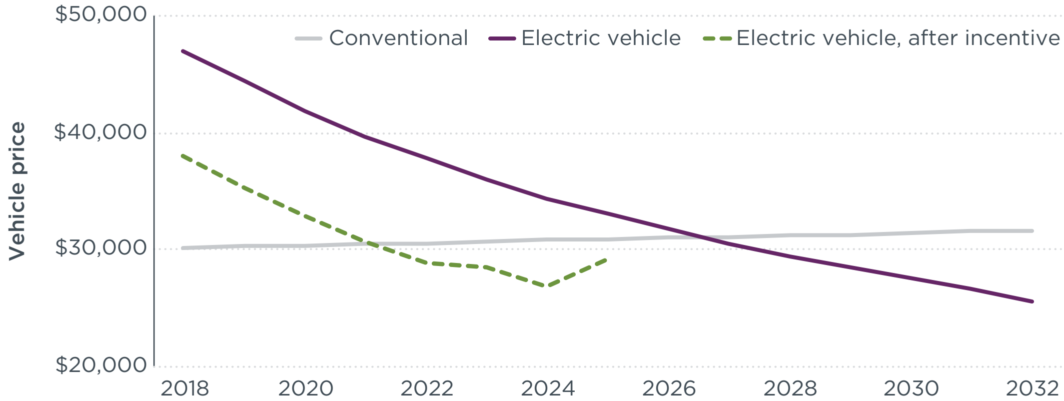

Figure 11. Price of a conventional and 250-mile electric vehicle, including incentives.

Figure 11 provides an illustrative view of the transition to profitability of electric vehicles. Electric vehicle price after incentives remains higher than the conventional vehicle through 2021, when the incentives reduce the electric vehicle price below that of the conventional vehicle from 2022–2025. After 2026, when electric and conventional vehicles reach cost parity, shown in Figure 11 by the crossing of the purple and gray lines, the electric vehicle could offer a substantial cost savings for the consumer. This figure suggests that automakers and consumers will share the higher costs from 2018 to 2021. Then between 2022 and 2025 automakers with higher production volumes begin to make a profit, whereas consumers purchase electric vehicles that are less expensive than conventional vehicles where incentives remain. The illustrative analysis underscores the importance of phasing down incentives as parity approaches to avoid the situation where automakers, after they reach parity, make additional profits from vehicles sold within incentives.

Trends toward shorter or longer electric ranges would shift the Figure 11 results, which are for a representative 250-mile range electric vehicle. For a 300-mile range, BEV prices would be several thousand dollars higher, and 200-mile range BEV prices would be several thousand dollars lower, than the 250-mile electric vehicle shown. This suggests that automakers' ability to grow the market for 200-mile and shorter-range vehicles will allow better pricing dynamics for consumers and higher profitability for automakers. As a result, it is in automakers' interests to support charging infrastructure buildout and consumer education to inform prospective drivers on how shorter-range electric vehicles can fit within most household driving needs.

Figure 11 provides another indication of the profound implications of electric vehicle parity. Based on the figure's example, after 2026 automakers will have the ability to either make a much larger profit—perhaps keeping electric vehicles near the price of conventional vehicles, despite their lower cost—or share the vehicle cost saving with vehicle buyers by offering a lower cost vehicle. After cost parity, vehicle price reduction for electric vehicles will create a substantial benefit of several thousand dollars per vehicle. This dynamic is shown in Figures 6, 7, 8, and 10 as reduced vehicle price. Due to a competitive automotive market, it is likely that some of the cost reduction is passed to prospective vehicle buyers in the form of lower purchasing price. However, that incremental cost difference also could be directed to automaker research and development, increased consumer amenities, and profit.

PHASING DOWN GOVERNMENT EXPENDITURES

As electric vehicle sales increase, many governments are exploring how to reduce and eventually phase out direct subsidies for ZEVs as they approach cost parity with combustion vehicles. In this section, we discuss approaches to phasing down incentives and lower-government-outlay actions that complement government spending to break down ZEV barriers.

PRINCIPLES FOR PHASING DOWN INCENTIVES

Financial incentives have been a major driver for early ZEV market development. With continued growth in electric vehicle sales volumes, these programs will become more expensive in absolute terms. As the market grows, declining battery and electric vehicle prices allow for more strategic use of purchasing incentives to target the market segments with the greatest barriers to adoption, such as low-income drivers, drivers without home charging, and drivers in rural areas. Examples for evolving government electric vehicle incentives include lowering incentive values in absolute terms to approximately match battery cost reductions, targeting the incentive availability to specific customers (e.g., below income thresholds), and targeting vehicles in more difficult market segments (e.g., vehicle segments without mainstream models available or vehicles below given price thresholds). Other, more durable, approaches involve indexing taxation to emissions levels to sustain relative ZEV incentives over longer time periods.

Governments around the world have begun to implement many such approaches to reduce and target their incentives. Table 5 lists several criteria upon which eligibility for ZEV incentive programs have been restricted, along with examples of their implementation. These restrictions serve not only to pace the flow of government outlay, but also to encourage automakers to bring longer-range, lower-cost, or more advanced ZEVs to market. Although many of these criteria have been applied by governments in isolation, the criteria are not mutually exclusive.

Table 5. Examples of electric vehicle incentive eligibility restrictions

Eligibility restriction	Example	Details	Other examples with similar eligibility criteria
Number of vehicles	United States	Tax credits reduced after 200,000 ZEVs per manufacturer.	None identified
Vehicle purchase price	Canada	Incentive available for ZEVs with base price below $45,000 CAD.	Germany, Massachusetts, Québec, New York, United Kingdom, Washington
Vehicle range	New York	Incentives range from $500 for electric range under 20 miles to $2,000 for electric range over 120 miles.	China, United Kingdom
Vehicle technology	Massachusetts	Only battery electric and fuel cell vehicles are eligible for rebates. PHEVs are ineligible.	British Columbia, California, Germany, Québec
Vehicle battery specifications	China	Incentives restricted to vehicles with battery density over 125 watt-hours/kg.	None identified
Customer income	California	Greater incentive available to those with household incomes less than 300% of federal poverty level; high-income households are ineligible.	Oregon

Implementing polluter-pay principles in vehicle taxation systems is a sustainable approach to incentivizing ZEVs. In such approaches, fees or taxes are proportional to the emission level of vehicles, thus more heavily taxing emissions-intensive vehicles. Linking the lower taxation of ZEVs and higher taxation of higher-polluting vehicles in taxation systems, as in Norway, ensures revenues can be regularly tracked and tax structure modified as needed to maintain steady revenue. Such a system also avoids the need for a political annual budget allocation process to determine ZEV rebates, thus avoiding uncertainty for consumers, automakers, and dealers.

Beyond simply indexing taxation to emission levels, some policies go further by collecting additional fees from higher polluting vehicles and disbursing the revenues as an incentive for ZEV buyers. Several ZEV-related incentive programs, including the bonus-malus schemes of France and Sweden, have revenue-neutral designs. Sweden's system is projected to generate enough net revenue in its first three years to provide relatively long-term funding for incentives and other transportation projects (Wappelhorst & Tietge, 2018). New Zealand is also developing a similar "feebate" program to provide incentives of up to $8,000 for BEVs (Walls, 2019).

California's Low Carbon Fuel Standard (LCFS) works similarly to lower transportation fuels' carbon intensity and create revenue to fund greater deployment of the lower-carbon fuels. In the LCFS system, companies selling electricity or hydrogen as a vehicle fuel can earn LCFS credits. Higher-polluting fuel providers can then purchase credits from electricity and hydrogen providers. This system, without requiring annual government budget outlays, creates a transfer of money that is then passed on to consumers. The cap-and-invest program, under development by the Transportation and Climate Initiative, a coalition of Northeast and Mid-Atlantic states and Washington, D.C., could work similarly based on transportation fuels (Transportation and Climate Initiative, 2019). The cap-and-invest system would establish a declining regional carbon pollution limit and require major fuel suppliers to pay for the associated pollution. This, in turn, could fund ZEV and other clean transportation projects.

Additionally, because consumers are persuaded by different ZEV perks, governments can allow consumers to select one of several financial and nonfinancial incentives based on what is most useful to them. One example is California, where high-income buyers of fuel cell vehicles have restricted eligibility and can either opt for the vehicle purchase rebate or a sticker that gives access to the high-occupancy vehicle lane (California Clean Vehicle Rebate Project, n.d.). Similarly, the Sacramento Municipal Utility District in California allows drivers to choose either a home charging equipment rebate or a cash rebate based on revenue from the LCFS program.

SUMMARY OF FUNDING SOURCES FOR ZEV PROGRAMS

As summarized above, governments have funded their ZEV incentive programs, charging infrastructure, and related activities through a variety of revenue streams, policies, and strategies. Table 6 describes funding mechanisms that have been used to fund ZEV promotion actions in different jurisdictions. For each mechanism, a prominent example where such an action is in place is provided. The viability and relative benefits of each measure depend on the specific context of each jurisdiction. We provide general pros and cons of each mechanism. Each mechanism can be designed, and continually adapted, to better capture the pros and minimize the cons. For example, vehicle feebate systems typically are modified to ensure revenue neutrality, and clean fuel regulations are periodically reviewed and the crediting mechanisms are modified to clarify and improve credit transfers revenues over time.

Table 6. Funding mechanisms used for ZEV promotion actions

Funding mechanism	Examples	Pros	Cons
Carbon taxes	• British Columbia • Sweden	• Encourages emissions reductions • Potentially very large funding revenue	• Exact emissions effect and revenue are uncertain • Limited effect on transport sector
Cap and trade	• EU Emission Trading Scheme • California Climate Investments • Québec Green Fund	• Ensures emission reductions if allocations are set strongly enough • Potentially very large funding revenue	• Uncertain revenue based on emission cap and credit market • Limited effect on transport sector • Competition among programs for revenue use
Bonus-malus fees	• France • Italy • Sweden	• Encourages ZEVs, discourages polluting vehicles • Can design to be revenue-neutral	• Revenue fluctuates based on sales • Requires adjustment over time • Backlash if fees too high
Emission-indexed vehicle taxation	• Norway	• Encourages ZEVs, discourages polluting vehicles • Potentially large funding revenue	• Revenue fluctuates based on sales • Requires adjustment over time • Backlash if fees too high
Fuel taxes or revenues	• Norway Enova charging infrastructure	• Linked to fuel consumption, meaning higher-polluting vehicles pay more • Potentially large funding revenue	• Use for ZEV support reduces funds available for other transport projects • May be regressive
Low-carbon fuel regulation	• British Columbia • California • Oregon	• Encourages low-carbon fuels, discourages polluting fuels • Generates revenue that scales with greater adoption of clean fuels; can be used for ZEV support activities • Long-term price signal to stakeholders	• Potentially complex to create • Less government control over revenue spending
Utility ratepayer revenue	• Hydro Québec Electric Circuit • Southern California Edison Charge Ready 2	• Vests utilities in success and planning of the electric vehicle market • Provides broader ratepayer benefits from shift to electric vehicles	• Potentially less government control over revenue spending
Awareness campaign support from industry	• United Kingdom Go Ultra Low • U.S. Drive Change. Drive Electric.	• Shifts public campaign cost to industry • Steers industry to collaborate and educate customers, market ZEVs • Brand neutral	• Some automakers may pursue their own marketing strategies
Enforcement action or settlements	• Electrify America (from Volkswagen settlement)	• Likely would have public support • No government spending or revenue loss	• Dependent on rare formal determination of corporate wrongdoing
Industry matching funds for incentives	• Germany ZEV Environmental Bonus	• Shifts cost of transition to industry	• May encourage automakers to inflate base vehicle price
General budget	• Norway tax exemptions	• Funds are flexible and less constrained	• Subject to political pressures • Typically debated annually
Fee on ZEV registration	• Proposed Minnesota EV fee	• Generates revenue for ZEV-related investments, e.g., infrastructure	• Raises cost of ZEVs, hindering consumer value proposition

During early stages of market growth, multiple funding streams typically support various ZEV financial incentives, infrastructure, and consumer awareness programs. As the ZEV market grows, and financial incentives evolve with lower upfront vehicle prices, governments may want to adopt emission-indexed and revenue-neutral funding programs. Many of the funding mechanisms in Table 6 can incorporate polluter-pay principles that shift the costs to vehicles and fuels with greater environmental costs to ensure durable revenue to support the ZEV activities. Mechanisms using polluter-pay principles such as carbon taxes, cap and trade markets, emissions-indexed taxation, and bonus-malus feebates can be designed for stable revenue. The specific design for such policies would need to be tailored to the ZEV policy and market context in each jurisdiction, and that market's desired ZEV penetration through the 2020–2030 period and beyond.

DISCUSSION OF COMPLEMENTARY POLICY

Although financial incentives are important for reducing the upfront cost differential in the near term, other barriers, such as model availability, charging access, and consumer awareness, can be substantially reduced with policies and programs that have relatively modest public spending. Table 7 presents several ZEV policies that can be adapted or extended to avoid government outlays while promoting mainstream ZEV adoption. These policies are broadly grouped into the categories of model availability and supply, vehicle purchase, charging infrastructure, operating costs, and vehicle access benefits. Many of these policies require some degree of administrative expenditures from government agencies. Such administrative costs could be covered using polluter-pay funding principles, such as pollution-indexed vehicle taxation, cap-and-trade, or carbon pricing revenues.

Table 7. Summary of long-term ZEV support programs with low government outlays

Category	ZEV action	Program details	Expenditure considerations
Model availability and supply	ZEV regulation	Require automakers supply increasing quantities of ZEVs and provide clarity on increased long-term ZEV growth	• Regulation induces industry investments in ZEV technology and market development • Company credit exchanges generate industry investments in emerging and over-complying companies
	Vehicle CO_2 standards	More stringent CO_2 standards promote greater deployment of ZEVs	• Low administrative costs (sometimes borne by automakers); noncompliance can generate fee revenue • Regulation induces industry investment in ZEV technology and market development
Vehicle purchase	Bonus-malus	Additional fees (malus) on highly-polluting vehicles, which are used as bonus incentives for ZEVs	• Low administrative costs • Can be revenue neutral if fees and bonuses are indexed to vehicle sales and adapted over time
Charging infrastructure	EV-ready building and parking codes	Require wiring for electric vehicle supply equipment during construction or retrofit	• Low administrative costs • Policy induces private investment at time of building retrofits that are just 25% of costs for later installation (Pike, Steuben, & Kamei, 2016)
	Utility-funded infrastructure	Direct utilities to support charging infrastructure build out from ratepayer funds	• Matches rate-based revenue to charging infrastructure investment • Must pass cost-benefit analysis for general electricity ratepayer base
Operating costs	Low carbon or clean fuel standard	Require fuel providers to lower average fuel carbon intensity and incentivize low-carbon fuels	• Some administrative costs • Regulation induces industry investments that support electricity and hydrogen deployment and rebates for ZEV owners
	Discount for smart charging	Require utilities to offer special electricity rates for EV smart charging	• Reduces operating costs for drivers and reduces grid upgrade costs; may require additional short-term investment
Access benefits	Low-emission zone (LEZ)	Restrict urban access, only allowing low-emission vehicles	• Considerable administrative costs, but typically undertaken for broader transit and planning purposes • Some schemes can generate revenue
	High-occupancy vehicle (HOV) or bus lane access	Offer preferential lane access as a non-fiscal perk	• Minimal cost outlay, but effectiveness can be limited with greater ZEV penetration
	Priority parking	Provide ZEVs priority in queue or lottery for limited parking permits, or dedicate ZEV parking spots	• No loss of revenue if ZEVs receive priority rather than price discount

Many of the regulatory actions described in the table have administrative costs that are much lower than the investments by industry to deploy the associated ZEV technology. For example, the administrative costs of having small regulatory development and enforcement teams for the regulations such as vehicle or fuel standards are associated with regulations that can ultimately involve billions of dollars in private industry investments. These technology investments result in societal benefits that are several times higher than the costs, as shown above. In essence, these public investments entail significant upfront government staff resources but result in a shift in the ZEV support funding from the government to the automotive and fuel sectors.

Additional policy opportunities and needs may arise as ZEVs develop an upfront cost advantage and enter the mainstream market. By 2030, it is likely that BEVs with up to 250 miles (400 km) range would have an upfront cost of several thousand dollars less than conventional vehicles, in addition to ongoing operational savings from fuel and maintenance. Governments could, over the long term, leverage this cost differential to break down remaining barriers for ZEVs, for example by imposing a fee on the order of a few hundred dollars at the point of sale. This funding source could be applied toward charging infrastructure, consumer awareness programs, and accelerating turnover in hard-to-reach market segments like low-income vehicle buyers.

Charging or refueling infrastructure will require continued investment for the remainder of the transition to ZEVs, creating possibly the greatest long-term funding challenge. Although a business case for the private operation of public charging stations is emerging in some markets with high electric vehicle penetration, this may be challenging in rural areas or in markets with lower petroleum fuel prices or higher electricity prices. However, governments can help bolster the business case by using their permitting and planning authorities to conditionally provide land and concessions to charging operators. In Norway and the Netherlands, this tendering approach has enabled decreasing government support and, in some cases, major charging deployments without public funds. In 2025, we estimate that the per-vehicle costs required of non-home charging for BEVs in the United States is about $570 (Nicholas, 2019). Although the long-term costs of infrastructure are less certain, these investments could be covered by a variety of government or private industry fees. In the long term, building codes requiring make-ready wiring for charging will substantially reduce the costs associated with home and workplace charging, potentially slowing the demand for new public charging as a result.

How best to ensure that ZEV users pay into transportation infrastructure funding is a complicated and controversial question. In the United States, for example, transport infrastructure, including roads and public transit, is funded largely by petroleum-based fuel taxes. As combustion vehicles, which comprise more than 97% of vehicle sales in most markets, become increasingly efficient to meet prevailing emission standards, average fuel tax revenues per vehicle are expected to decline. As a result, some changes such as higher per-gallon taxes and/or a shift to a vehicle-miles-traveled fee basis are needed to keep revenues stable, even before considering a shift to ZEVs. A key finding of this report is that securing the substantial net societal benefits of ZEVs requires a combination of regulatory and fiscal policies to overcome high upfront ZEV purchase and charging infrastructure costs. Although most markets are still in the early stages of a ZEV transition, adding special ZEV fees is unlikely to make up for the anticipated revenue shortfall from declining petroleum sales. Moreover, while many governments still provide direct purchase incentives for ZEVs, singling out ZEVs for additional fees could send conflicting and confusing messages to consumers.

In the future, as ZEVs approach and eventually surpass purchase cost parity, direct government outlays to support ZEV purchases could evolve to target hard-to-reach segments and be superseded by polluter-pay policies such as emissions-indexed vehicle taxes and carbon markets. Such policies would provide a consistent market signal regarding ZEVs and could be revenue-sustainable even at high or near-total ZEV uptake; yet polluter-pay policies are insufficient by themselves to ensure that ZEV users pay into transportation infrastructure funding. User-pay policies are important complements to polluter-pay policies to fund the provision of transport infrastructure. Vehicle miles traveled fees and other road user charges, such as tolls, are examples of user-pay policies that could be employed by governments to increase funding for transport infrastructure in a manner that is synergistic with polluter-pay policies and the ZEV transition.

CONCLUSIONS

The transition to zero-emission vehicles is underway in major markets around the world, spurred by substantial public and private investments. This research summarizes funding mechanisms in use by governments in high-uptake ZEV markets around the world that provide examples of the types and levels of funding support to plan for the transition ahead to ZEVs. The analysis above quantifies the funding needed from various stakeholders, as well as the associated costs and benefits, through the transition to all ZEVs. In this section we summarize the high-level results and their implications for policy.

Sustained funding is critical to growing the early ZEV market. The costs to address ZEV barriers are substantial, and in the near term many of those costs are at least partially borne by public funding sources. The costs are highest in the earliest years, due to high upfront vehicle purchase and infrastructure costs. Government incentives to partially defray upfront costs; home, workplace, and public charging infrastructure to ensure convenient and low-cost charging; and consumer outreach campaigns to raise public awareness are needed to grow the early market. In the two large markets we analyzed, the 2020–2030 transition costs average $5 billion per year in the United States and €2 billion per year in Germany.

After purchasing incentives phase down, consumer outreach costs are likely to remain to help overcome consumer understanding barriers until ZEVs are marketed to the same degree as conventional vehicles. Home and public ZEV infrastructure buildout costs will continue through the long-term transition. Going forward, as governments consider their ZEV incentive programs, polluter-pay principles such as bonus-malus systems or carbon markets that more heavily tax polluting vehicles and incentivize ZEVs are a sustainable approach. Such emission-indexed taxation can be used to maintain steady revenue, minimize government expenditures, fund various types of ZEV campaigns, and avoid frequent budgetary negotiations. Adopting polluter-pay principles internalizes the external costs of polluting vehicles, rather than imposing these costs on governments and society.

The societal benefits of ZEVs far outweigh costs. Although the costs in the ZEV transition are substantial, this analysis indicates that the benefits quickly, and by a very large margin, outweigh the costs. Our analysis indicates that net benefits outweigh costs by 2025 in the United States and by 2028 in Germany. The annual U.S. net benefits surpass $10 billion in 2029, $50 billion in 2035, and $100 billion in 2039. The annual net benefits in Germany surpass €1 billion in 2029, €10 billion in 2036, and €20 billion in 2044. The 2020–2050 cumulative benefits outweigh the costs by a factor of about 11 in the United States, and by a factor of about five in Germany. Excluding the benefits from reduced greenhouse gas externalities, the 2020–2050 cumulative benefits outweigh the costs by a factor of about 7 in the United States, and by a factor of about 4 in Germany.

Figure 12 illustrates the annual ZEV transition costs (in red) and benefits (in blue) over the 2020–2050 time frame for Germany. The figures offer a high-level summary of the Germany results from Figure 7. The costs include higher-cost vehicles (before parity), incentives, awareness programs, and infrastructure. The benefits include fuel savings versus increasingly efficient combustion vehicles, maintenance savings, reduced upfront vehicle prices (after parity), and greenhouse gas emission benefits. To put these benefits in context, a new representative 250-mile (400-kilometer) electric vehicle in 2030 would result in about €17,000 in lifetime benefits in Germany. In the U.S. case, the same new representative vehicle in 2030 would result in about $26,000 (about €23,000) in net benefits.

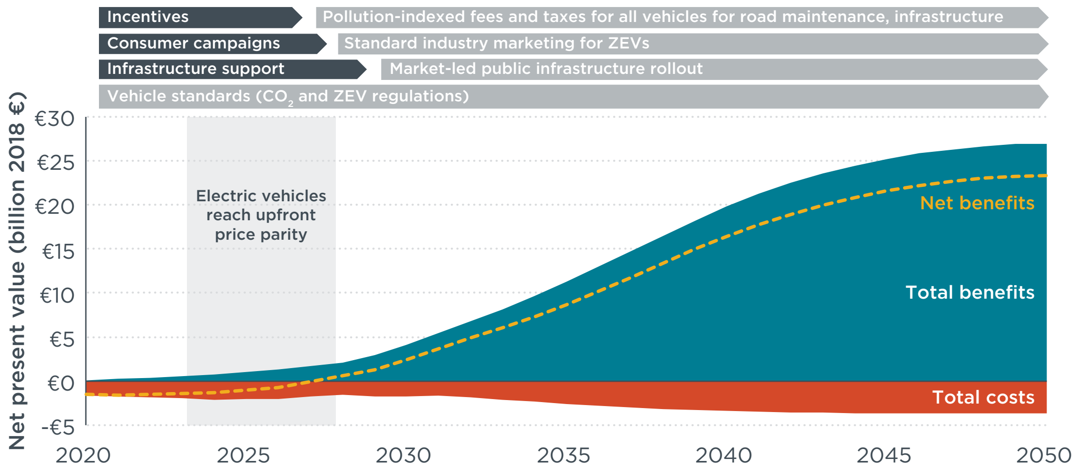

Figure 12. Costs, benefits, and policy over the transition to ZEVs in Germany.

Costs in the ZEV transition are transitioning to the private sector. This work points to the evolution of costs that correspond to the different stages of ZEV market development and has several implications for policy. As indicated on the top of Figure 12, stronger policy on incentives, consumer campaigns, and infrastructure will be necessary over the initial time period where upfront electric vehicle cost parity is reached across different vehicle segments, which is shown as 2024–2028. The phasedown of governments' incentives can occur and transition to durable systems of pollution-indexed fees and taxation for all vehicles.

Similar to incentive programs, after ZEV cost parity is reached across market segments, ZEV consumer campaigns via public-private partnerships can phase down as ZEVs become fully marketed as typically done by automakers for conventional vehicles. Infrastructure growth will be needed throughout, and public outlays will largely shift to market-led investments and utility ratepayer-funded deployment. Through the transition to a mainstream ZEV market, collaboration between the public and private industry actors will remain crucial. Public-private partnerships through the transition from largely publicly-funded incentives, infrastructure, and consumer programs to profitable industry practices will identify gaps that governments, automakers, energy and infrastructure providers, and others can fill.

Governments are developing smart policies to support the ZEV transition. Managing the levels, types, and timing of government support will be a key to sustaining the market growth over the decades-long transition to ZEVs. The report highlights dozens of ZEV-supporting programs around the world that demonstrate the types of funding and other policy mechanisms to manage growth and sustain investments. Persistent development of stringent vehicle emission or ZEV regulations in Canadian provinces, China, Europe, and many U.S. states ensure sufficient ZEV investment, volume, and widespread model availability. Norway and France have each developed vehicle taxation systems that are durable enough to spur ZEVs and manage the impact on government revenues. Similarly, Sweden is piloting a bonus-malus scheme that is designed to provide a durable funding source to support ZEVs. Carbon markets in British Columbia, California, and Québec create durable revenue streams and help fund several ZEV programs in these markets. The United Kingdom has catalyzed ZEV industry developments with ZEV manufacturing grants and its Go Ultra Low public-private consortium to tackle consumer barriers. British Columbia, California, and Québec demonstrate comprehensive action-oriented budgets to overcome market barriers and link those to their regulatory ZEV requirements. California also has exemplary programs coordinating industry and government consumer outreach with Veloz, encouraging direct electric utility investments in infrastructure, and funding ZEV investments through its Low Carbon Fuel Standard and greenhouse gas cap-and-trade program.

This study's scope, research, and analysis were broad; ideally follow-on studies could be conducted that target specific markets, specific existing policy context, and the design of policies to accelerate ZEV markets through the transition. As a logical next step to this study, follow-on analyses would examine specifically how emission-indexed or bonus-malus type vehicle taxation and other policies such as fuel policy and economy-wide carbon policy could be designed to maintain revenue and spur ZEV adoption. Such analysis could be done for particular European markets that have set strong goals for the full transition to ZEVs but have not yet implemented supporting elements discussed above. Follow-on studies would also more deeply analyze differing mixes of ZEV types and corresponding needs for residential and public charging infrastructure and how this infrastructure could be funded.

This research, although focused on ZEV policy and market developments in North America and Europe, has much broader implications. The ZEV barriers, costs, and benefits are broadly similar elsewhere, although different markets tend to have somewhat differing vehicles, fuel prices, and infrastructure availability. The policies, funding mechanisms, and infrastructure investment approaches assessed here can be adapted and implemented in markets of various sizes. More rigorous assessment is needed to better evaluate the amount and placement of home and public ZEV infrastructure. Broader inclusion of full costs and benefits, including local air quality, could increase the motivation to develop equity-focused ZEV policies and vehicle scrappage programs to further accelerate the transition. As zero-emission truck technology continues to emerge, similar analysis to assess long-term zero-emission commercial freight costs, benefits, and public funding implications is warranted.

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APPENDIX

Table A1. Summary of selected government announcements, legislation, and goals for all zero-emission vehicle sales

Government	Timeline	Source
Norway	2025	Norwegian Electric Car Association (2019)
Denmark	2030	Bloomberg (Levring, 2018)
Iceland	2030	Government of Iceland (2018)
Ireland	2030	Government of Ireland (2019)
Netherlands	2030	Netherlands Enterprise Agency (2018)
Slovenia	2030	Reuters (Novak, 2017)
Sweden	2030	Electrive (Hampel, 2019)
Hainan (China)	2030	Government of Hainan Province (2019)
Scotland	2032	Scottish Government (2018)
Canada	2040	Government of Canada (2019)
France	2040	Government of France (n.d.)
Taiwan	2040	Xinhua ("Taiwan to phase out", 2018)
United Kingdom	2040	Government of the United Kingdom (2019)
British Columbia	2040	Legislative Assembly of British Columbia (2019)
Germany	2050	International Zero-Emission Vehicle Alliance (2015)
Baden-Württemberg	2050	International Zero-Emission Vehicle Alliance (2015)
California	2050	International Zero-Emission Vehicle Alliance (2015)
Connecticut	2050	International Zero-Emission Vehicle Alliance (2015)
Maryland	2050	International Zero-Emission Vehicle Alliance (2015)
Massachusetts	2050	International Zero-Emission Vehicle Alliance (2015)
New Jersey	2050	International Zero-Emission Vehicle Alliance (2015)
New York	2050	International Zero-Emission Vehicle Alliance (2015)
Oregon	2050	International Zero-Emission Vehicle Alliance (2015)
Québec	2050	International Zero-Emission Vehicle Alliance (2015)
Rhode Island	2050	International Zero-Emission Vehicle Alliance (2015)
Vermont	2050	International Zero-Emission Vehicle Alliance (2015)
Washington	2050	International Zero-Emission Vehicle Alliance (2015)