

TECHNICAL ASSESSMENT FOR ELECTRIC CARS

SECTOR: TRANSPORTATION

AGENCY LEVEL: INDIVIDUAL

KEYWORDS: ELECTRIFICATION, EFFICIENCY, BATTERY

VERSION 3

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*Note: For some of the technical reports, the result section is not yet updated. Kindly refer to the model for the latest results.

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ACRONYMS AND SYMBOLS USED

- **BTS** – Bureau of Transportation Statistics
- **CO2/ CO₂/CO₂e/ CO₂e** – Carbon Dioxide/ Carbon Dioxide Equivalent
- **DOT** – Department of Transportation (of US)
- **EIA** – Energy Information Administration (of US)
- **EU28** – Group of first 28 Countries of the European Union
- **EV** – Electric Vehicle
- **EVs** – Electric Vehicles
- **GHG** – Greenhouse gas
- **Gt** – Gigatons
- **ICCT** – International Council on Clean Transportation
- **ICE** – Internal Combustion Engine
- **ICEVs** – Internal Combustion Engine Vehicles
- **ICT** – Information and Communication Technology
- **IEA** – International Energy Agency
- **IPCC** – Intergovernmental Panel on Climate Change
- **kWh** – Kilo-Watt-hour
- **PDS** – Project Drawdown Scenario
- **Pkm** – Passenger-kilometer
- **REF** – Reference (Scenario, of Project Drawdown)
- **RefPol** – Reference Policy Scenario
- **TAM** – Total Addressable Market
- **TNC** – Transport Network Companies
- **UCD** – University of California at Davis
- **UK** – United Kingdom
- **U.S.** -United States
- **OPEC** – Organization of the Petroleum Exporting Countries

EXECUTIVE SUMMARY

Most light duty vehicles (LDVs) in use today rely on liquid fuel for energy storage and propulsion in an internal combustion engine (ICE). Electric vehicles (EVs) use a more energy-efficient electric motor, and use high-capacity batteries on-board that can be charged from the electric grid. EVs are, in general, much less polluting than internal combustion engine vehicles (ICEVs), and are growing cleaner annually as more renewable energy sources are added. The EV market has been growing dramatically over the past ten years. Even though EVs are still only a tiny fraction of LDVs (sales and stock), they are expected to grow dramatically over the coming decades, replacing a large share of ICEVs and causing a dent in the CO₂ emissions from road transportation.

Our model proposes the deployment of EVs as a substitute for ICE cars. Project Drawdown Scenario (PDS) adoptions are compared to a Reference (REF) scenario, which is defined by assuming that EV adoption remains fixed as a percentage of total passenger kilometers (pkms) based on start year of this study (2018). The net carbon abatement from EV adoption is a sum of the change in emissions from usage, i.e. fuel combustion and electricity generation, and the emission change from vehicle production between these two scenarios.

EV adoption in the Ambitious scenario, where there is more ambitious solutions implementation, leads to a cumulative 17111.9 billion pkm by 2050, compared to only 137.1 billion pkm by EVs in 2018. This rapid growth in EV adoption results in 22.13 gigatons (Gt) of CO₂-equivalent greenhouse gas emissions avoided in total between 2020 and 2050. This corresponds to an overall reduction of approximately 1.96 ppm in atmospheric CO₂ concentration. The emissions from vehicle production are in fact higher for EVs than for ICEVs, and there are additional usage emissions from electricity generation, but these extra emissions are both counteracted by the substantial emissions avoided from fuel combustion. The marginal benefits of EV deployment increase with time, as the electrical grid becomes less emitting. These improvements in the grid are not included in these results.

EV adoption is also beneficial for the financial impact. The financial analysis shows that it will also save money for households. Considering the entire fleet of LDVs, the net operation costs are reduced by around \$14 trillion from 2020 to 2050, or \$24 trillion over the vehicle's full lifetime in that period. The current price of EVs is higher than ICEVs. However, assuming price reductions continue, EV adoption will bring additional savings \$804 billion through reduced first costs, indicating a need to drive battery (and EV) costs down to attract consumers and provide a better economic incentive. Consumer education is a key component of EV adoption to relieve concerns about the upfront price premium and the reduced range of EVs compared to conventional cars. As battery technology matures, the price of manufacturing high capacity batteries will decrease, so both the purchase price and range of EVs will become more attractive to consumers.

Battery production may have other environmental, economic, and social impacts that must be dealt with, such as mining and battery disposal. The rapid adoption of EVs will not overcome the challenges of urban congestion. Despite these issues, EVs still play a significant role in decarbonizing the global transport system.

1 LITERATURE REVIEW

Globally, transport of people and goods produces 9.5 gigatons of carbon dioxide-equivalent greenhouse gas emissions annually, equivalent to 23 percent of *energy-related* emissions, or 14 percent of *all* emissions (IEA, 2018a)¹. In individual countries, where transport is based on high-emission modes, transport can account for much higher shares. The sources of those 9.5 Gt are chiefly from cars and light trucks, which account for over 50% of all transport emissions. Heavy freight trucks and buses contribute an additional 26% and air transport and shipping each generate 10% of global transport emissions (IEA, 2018a). Growth rates in emissions for some subsectors like air transport and shipping are very high, so the Transport Sector requires special focus to keep emissions from ballooning out of control, as some projections indicate. Transport, however, is a service derived from economic growth. Research shows that wealthier people travel more, locally and internationally, and demand more goods and services. So, as a country develops economically, movement of people and goods increases. Solutions generally can be classified using the “*avoid-shift-improve*” framework: *avoid* travel altogether, *shift* travel to low-carbon modes or *improve* modes to generate lower emissions.

1.1 STATE OF ELECTRIC VEHICLES

The transportation sector produces nearly a quarter of global CO₂ emissions (IEA, 2020). In 2019, transportation in the US alone was responsible for 1.9 billion metric tons CO₂-equivalent of greenhouse gas emissions, including CO₂, N₂O and HFCs, which account for around 29% of greenhouse gas emissions in the US (US Environmental Protection Agency, 2020). Currently, most light duty vehicles (LDVs) on the road today are propelled by burning gasoline, and to a lesser extent, diesel fuel in an internal combustion engine (ICE). Furthermore, emissions from transportation are increasing every year, largely due to the growing stock of passenger vehicles with internal combustion engines (ICE).

Electric vehicles (EVs) substitute ICEVs with an onboard battery to store energy and an electric motor for propulsion (IEA, 2019b). EVs have several advantages over ICEVs:

- (1) EVs’ energy efficiency is two to four times than ICEVs (IEA, 2021b). EVs convert between 59%-62% of electrical energy from the grid to power all the wheels, while ICEs convert around 17%-21% of fuel energy.

¹ Non energy-related emissions include land use change emissions (including deforestation), and methane and F-gas release from agriculture, refrigeration, and industrial activity.

- (2) EVs emit no tailpipe pollutants, including carbon emissions as well as other harmful emissions, which help improve public health and reduce ecological damage.
- (3) Electric motors are quiet, allow the car to be smoother, have a stronger acceleration, and require less maintenance than ICEs (US Department of Energy, n.d.). Tesla's Model S P85D is the quickest sedan globally, capable of accelerating from 0 to 60 mph in 2.8 seconds (Tesla, 2015).
- (4) EVs could help reduce the high dependence on fossil fuels.

Meanwhile, EVs also have some disadvantages related to batteries, such as the driving range, the recharge time, the battery cost, and the bulk and weight of the vehicle (IoT Marketing, 2021). Currently, it takes around 30 minutes to recharge the Tesla Model S with 274 kilometers (170 miles) of range (Tesla, 2015). Besides, consumers have limited EV models to select (IoT Marketing, 2021).

1.1.1 Types of electric cars

This report uses the term EVs to refer to passenger cars with high-capacity batteries that power electric motors and receive energy from the electrical grid. Our definition includes battery EVs (also known as BEV), and plug-in hybrid EVs (also known as PHEV). Some cars have ICEs on board as a means of energy generation only, rather than propulsion. These special types of ICEVs are called range-extended EVs (REEVs) and they are considered a type of PHEV. These categories are shown in Table 1. The definition of EVs in the report notably *excludes* Hybrid electric vehicles (HEVs) (as shown in Table 1.1), which have a battery and an electric motor onboard. HEVs are different from EVs in the report due to two reasons:

- (1) HEVs rely solely on liquid fuel as an external energy source;
- (2) HEVs' batteries are different.

Table 1.1 Definitions of vehicle types

	Propulsion		Energy source	
	ICE	Electric motor	Gasoline	Electricity
Internal Combustion Engine (ICE)	X		X	
Hybrid Electric Vehicle (HEV)	X	X	X	
Plug-In Hybrid Electric Vehicle (PHEV)	(X)	X	X	X
Battery Electric Vehicle (BEV)		X		X

Note: Gray shading indicates EVs in the context of this report. Parentheses indicate that a technology is not always present in that category. Table adapted from Amsterdam Roundtables Foundation, 2014. (Amsterdam Roundtables Foundation & McKinsey & Company, 2014)

1.1.2 Battery types and cost

PHEVs have longer total ranges because of an extra internal combustion engine. But PHEVs have smaller battery capacity and shorter all-electric ranges compared with BEVs. The HEV has a NiMH battery with a 1-2 kWh capacity, whereas EVs use Li-ion batteries that typically carry tens of kWh, ranging from 12-85 kWh in BEVs and 4-22 kWh for PHEVs. The largest capacity EV battery currently sold is available in the Tesla Model S and Model X, with an 85 kWh capacity and a 426 kilometer (265 miles) all-electric range (Stacy C. Davis, Susan W. Diegel, Robert G. Boundy, & Sheila Moore, 2015).

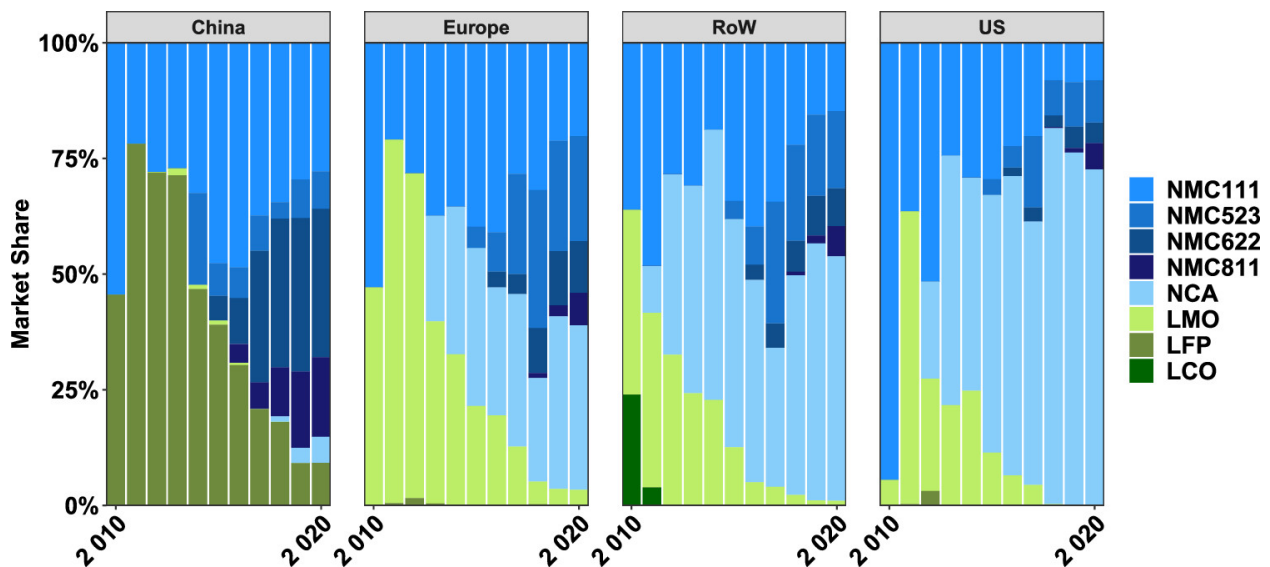


Figure 1.1 Battery cathode chemistry in selected regions (Dunn, Slattery, Kendall, Ambrose, & Shen, 2021)

Except for the battery capacity, the battery cathode chemistries are various in different regions (Dunn et al., 2021). The battery cathode chemistries will also lead to various climate and financial impacts because of the battery lifetime and material composition. The market share of battery cathode chemistries is various in various regions (Dunn et al., 2021). China mainly depends on LFP batteries previously because they are cheaper than NMC batteries. China is gradually shifting to NMC batteries to pursue higher energy densities and extended range. This transition will lead to more demand for cobalt under state-of-art battery technology (Hsieh, Pan, & Green, 2020), and may also result in a higher cost of batteries because the price of cobalt is currently very high.

Battery costs have been decreasing rapidly (Nykvist & Nilsson, 2015a). The observed average EV battery pack cost has decreased from approximately 850 euro/kWh in 2010 to 200 euro/kWh (Noah Kittner et al., 2020). However, the current EV purchase price is still higher at US\$268/kWh in 2015 (IEA, 2016). If costs reach as low as US\$150 per kWh, it is possible that EVs can move beyond niche market to a mass market penetration, “leading to a potential paradigm shift in vehicle technology” (Nykvist & Nilsson, 2015, p. 330). Bloomberg Global EV Outlook shows that lithium-ion battery prices decrease by 87% from 2010 to 2019 (Bloomberg NEF, 2020). The continued declining battery pack costs will further reduce the EV price in the future.

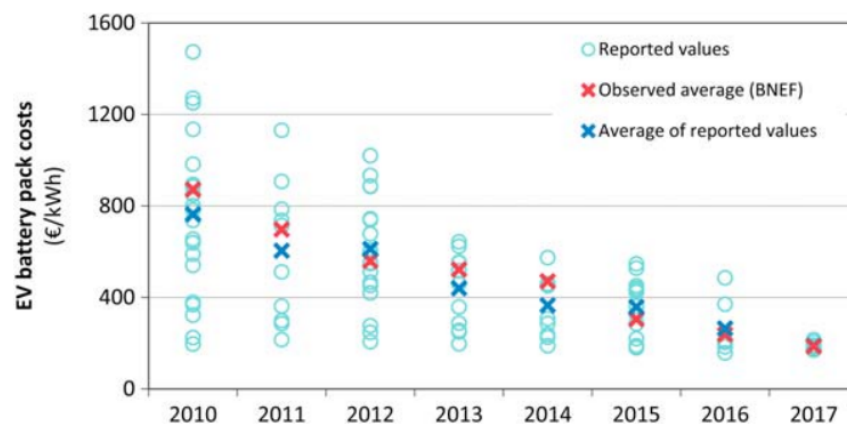


Figure 9.5

Reported lithium-ion battery pack costs for electric vehicles. *Note:* Observed average prices are based on BNEF's industry survey in 2018. Reported average is the simple average of the data included in the graph. Source: *Based on Tsiropoulos et al. (2018)*

Figure 1.2 EV battery pack costs (Noah Kittner et al., 2020)

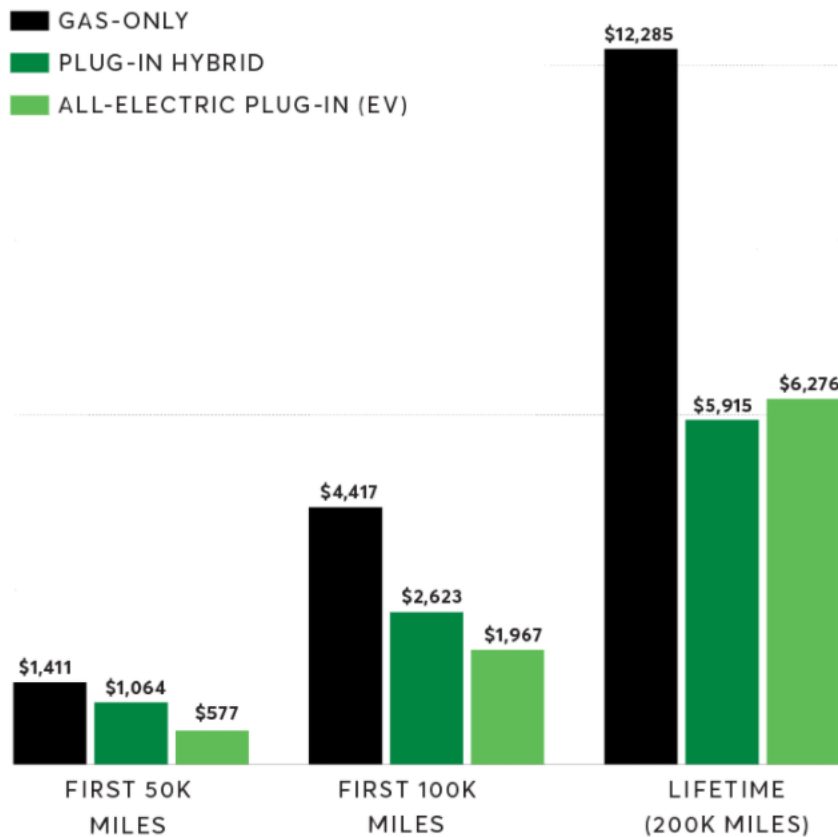
1.1.3 Electric vehicles and financial savings

The recent news shows that the average sticker price for an EV and ICEV is 33,300 Euro and 186,000 Euro currently, which means that EV price is approximately 14,700 euro higher than ICEVs (the Guardian, 2021). This situation is similar in other countries, such as UK (Lewis, 2020). The purchase price of EVs is higher than ICEVs, but the operating cost of EVs is lower than ICEVs. A recent study has identified that EVs will bring big financial savings even with higher purchase prices because of cost savings in fueling costs and maintenance expenses (Preston, 2020).

Fuel savings alone could bring about \$4700 or even more for the first seven years. The total ownership savings of one EV lifetime have been estimated at \$6,000 to \$10,000 (Preston, 2020). The reason for the financial savings of EVs is mainly fuel savings, maintenance and repair, and depreciation. Regarding fuel savings, EV owners can save around \$800 to \$1,000 compared with ICEVs, if they charge EVs at home (Preston, 2020) because of the potential to take advantage of the off-peak electricity prices. Normally, EV owners would charge their EVs at night when the overall electricity demand is lower. This can help solve the challenges of imbalance between electricity supply and demand. Therefore, some electricity companies provide lower prices for off-peak times, which will further reduce the operating cost of EVs (Union of Concerned Scientists, 2017).

In terms of maintenance costs, ICEV cost more than EVs because the systems of more complex ICEVs than BEVs. As Figure 1.3 shows, the maintenance cost of ICEV is slightly higher than that of EVs. In contrast, the maintenance cost of ICEVs over lifetime is almost double of EVs. For depreciation, the long-range EVs still have more residual values than traditional ICEVs.

POWER STRUGGLE: ELECTRIC VS. GAS MAINTENANCE COSTS



Source: Consumer Reports' 2019 and 2020 reliability surveys.

Figure 1.3 Maintaining cost comparison in ICEVs, PHEVs and BEVs (Preston, 2020)

1.1.4 Electric vehicles and climate impact

The significant reduction in emissions is an important reason for considering EVs as a Drawdown solution, depending on the fuel source composition of local grid generation. Road transport systems, especially cars are the main contributor of CO₂ emissions in the transport sector. It is now widely recognized that EVs are a promising way to reduce CO₂ emissions (IEA, 2019b). The total climate impact in the Project Drawdown model are determined by the EV adoption data (or PKM by EVs), a net reduction of CO₂ emissions between EVs and ICEVs, and the carbon intensity of the power generation mix.

EVs could reduce the direct CO₂ emissions directly compared with ICEVs because they use electricity to provide propulsion. However, EVs have higher indirect CO₂ emissions than ICEVs as a result of the:

- (1) extra power battery pack embodied in EVs will lead to higher carbon emissions in the manufacturing stage; and
- (2) increased electricity consumed by EVs also leads to extra carbon emissions in the energy sector.

Therefore, the net CO₂ benefit depends on the trade-off of indirect carbon emissions of the energy supply (Zhang & Fujimori, 2020).

In the future, the carbon intensity of local electricity generation will decrease vastly compared with gasoline and diesel as more renewable energy systems are employed in the future. Meanwhile, the decarbonization of electricity generation will further help reduce the indirect carbon emissions of EVs life cycle, especially battery production (IEA, 2021b). A recent study shows that the lifecycle CO₂ emissions, including vehicle manufacturing use, operation, and end-of-life management per km for BEV, are approximately 20-30% lower than ICEVs. For the EU, the lower carbon intensity of electricity generation will result in 45-55% lower carbon emissions per BEV Pkm than ICEVs (IEA, 2019b). Therefore, the final impact of EV deployment is also determined by the grid mix.

1.2 ADOPTION PATH

1.2.1 Current Adoption

As mentioned earlier in the report, EV adoption has taken off since the beginning of this decade. Sales volume increased 250-fold from 2010 to 2018, and growth is predicted to continue throughout the century (IEA, 2021b). By 2018, over 5 million units of EVs were employed worldwide (as shown in Figure 1.4). China accounts for the biggest global EV stock by 2018. (IEA, 2019b). The current EV adoption accounts for an estimated 0.22% of global pkm based on the average of various sources (IEA, 2016b, 2021b), as seen in Table 1.2.

Table 1.3 shows EV adoption share by region in 2018 based on IEA (IEA, 2021b). Regionally, Asia (Sans Japan) accounts for the biggest share. For the country level, China accounts for the biggest share, followed by the US.

It is expected that the EVs stocks will continue to grow. Adoption projections are gathered from as many credible sources as possible. Sources include highly renowned and respected institutions and a commercial market research firm (Bloomberg NEF, 2020; IEA, 2016b, 2021b; OECD/ITF, 2021; OPEC, 2017, 2020).

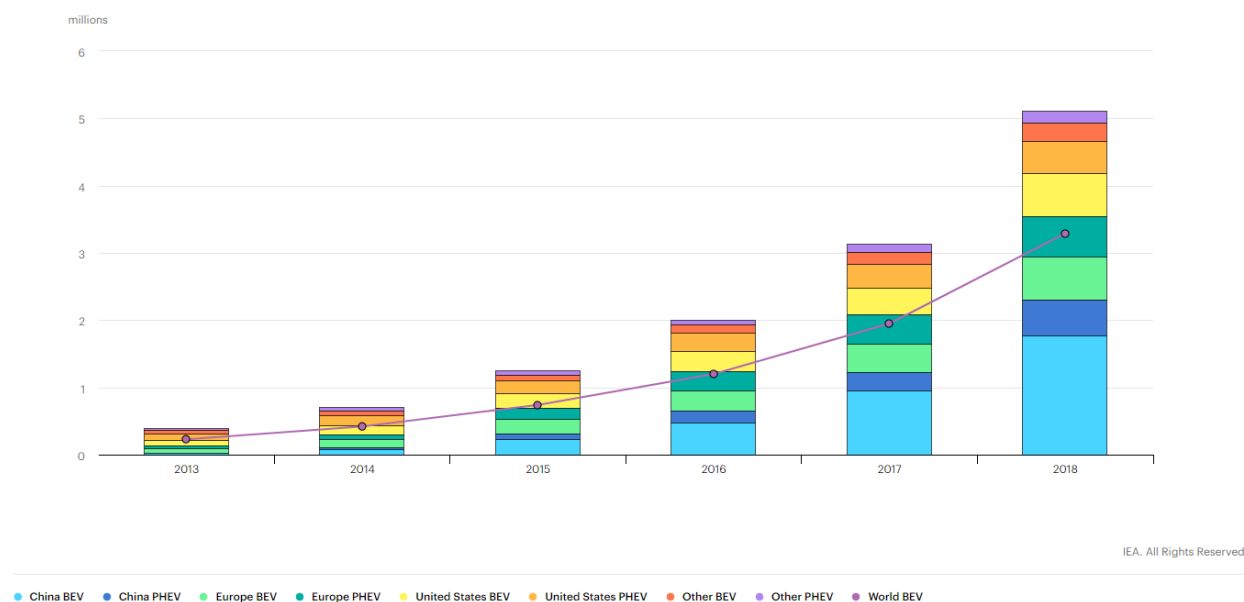


Figure 1.4 Electric car deployment in selected countries, 2013-2018(IEA, 2019b)

Table 1.2 Current Global Modal Share and Adoption of E-bike in billion pkm

	Percent (%)	Billion PKM
Current Adoption	0.22%	137.1

Table 1.3 Current Global EVs use by region and specific country

Region	Percent (%)
OECD 90	21.4%
Eastern Europe	2.7%
Asia (Sans Japan)	25.1%
Middle East and Africa	6.0%
Latin America	5.2%
China	22.2%
India	0.1%
EU	6.5%
USA	10.9%

Region	Percent (%)
Total	100%

1.2.2 Trends to Accelerate Adoption

Regional and countryside programs

Road transport dominates transport emissions for a long time. While many regions and countries promise to take many actions to speed up carbon neutrality, the market share of EVs remains very low with the share of total car stocks less than 1%. Therefore, many regions and countries have set targets for EV deployment (IEA, 2021b) in order to fulfill commitments of carbon neutrality. Some countries such as Ireland and Norway set the ambitious target of realizing 100% EV share in all car sale markets by 2030 and 2025 (IEA, 2021b). Under various targets set by the government, more and more EVs will be deployed in the future. Around 13 countries and 31 cities/regions already announced the plan to prohibit ICEV sales by (Bloomberg NEF, 2020).

Economical Costs

Historically, economics has been a primary factor of EV adoption across countries and periods (Standing et al., 2019; Chan and Shaheen, 2012; DeLoach & Tiemann, 2012). The purchase costs of EVs are still much higher than traditional ICEVs. The significant difference between the ICEVs and EVs is powertrain batteries, which is also the main reason for higher EV price. The price of powertrain batteries has dropped greatly over the past several years (Hsieh et al., 2020; Noah Kittner et al., 2020; Nykvist & Nilsson, 2015a), and it is assumed that the fast-declining battery cost will further decrease EV prices (Bhutada, 2021).

Critical Technology

As already mentioned, battery technology is a key driver for EV development. Driving range is limited only by the current state of battery technology. Further advancements in battery technology with higher battery capacity will help EVs reach higher ranges (Sanguesa, Torres-Sanz, Garrido, Martinez, & Marquez-Barja, 2021). The energy intensity is also limited because of current battery technology and financial cost. The wide deployment of EVs requires batteries with high performance and low cost (Cano et al., 2018). Various battery technologies also influence the charging mode and charging time. Currently, the waiting time for charging an EV is too long for most consumers, and limits the uptake of this solution. Advanced battery technology could possibly make the charging time much faster. Air charging technologies, for example, could make the recharging time extremely fast (30 seconds) (Pocket-lint, 2021).

Air Quality

BEVs do not produce direct emissions during the operation stage, and PHEV do not produce direct emissions when driving in electric mode. EVs have potential to directly reduce emissions in the operation stage compared with ICEVs (U.S. Department of Energy, n.d.). Except for direct emissions, EVs will not produce toxic gases such as NO_x, HC, and carbon monoxide (Barisione, 2021). Some studies have also shown that EVs will reduce particle pollution (OECD, 2021). The total CO₂ emissions and air pollution of EVs are therefore lower than ICEVs, even considering the indirect emissions and pollution in the energy supply chain and car manufacturing (European Environment Agency., 2018).

1.2.3 Barriers to Adoption

Economic barrier

A significant challenge facing the EV market at present is the higher upfront purchase price for an EV compared with a similar ICE vehicle. For example, the Electric Power Research Institute reports that two of the most popular EVs in the US (Chevrolet Volt, a PHEV, and Nissan LEAF, a BEV) had a price premium of US\$8,400 and US\$2,200 respectively, compared to ICEVs of similar size and equipment level. EV batteries are expensive to produce and are largely responsible for this additional cost to consumers. The much higher purchase price of EVs than ICEVs will influence the adoption of EVs without any financial subsidy and tax reduction (Adhikari, Ghimire, Kim, Aryal, & Khadka, 2020). Although EVs could help make financial savings over EV lifetime (Harto, 2020), the cheaper cost for electricity, maintenance, and operation will not be usually considered when consumers buy an EV.

Infrastructure barrier

In the future, it could be possible to charge cars while they are moving. Researchers at the Fraunhofer Institutes for Manufacturing Technology and Advanced Materials IFAM and for Transportation and Infrastructure Systems IVI have developed a cost-effective design for a wireless charging system that would allow EVs to charge their batteries while also feeding energy back into the grid. So far, they constructed a 25-meter-long test route and a car was successfully driven while being charged (Fraunhofer-Gesellschaft, 2015). A recent survey conducted in the UK showed that the EV charging infrastructures would be the biggest barrier for consumer adoption (Fleet News, 2020).

Variety barrier

The consumer choices for EVs are much less than ICEVs. There are only 368 EV models including 235 BEV model and 133 PHEV model (IEA, 2021b). The limited model choice for BEV and PHEV will influence consumers' choice.

Technology barriers

The technology barriers, especially battery technology, are the biggest barrier to EV adoption. The IEA Global EV Outlook shows that the average range is only 338 km and 58km for BEV and PHEV, respectively (IEA, 2021b), compared to 470km for ICEV (Wallbox, 2021). Further, the EV range could be shorter under extreme temperature conditions while ICEVs are more stable even under such extreme conditions.

Other barriers

The implementation of EVs results in extra demand for Li-ion batteries, resulting in several extra problems. Firstly, the Li-ion batteries' demand with increasing e-bikes sales will lead to extra demands for critical

materials, e.g., Lithium, Cobalt, Manganese, etc. (Dunn et al., 2021). Secondly, the energy consumption and carbon footprint during manufacturing are higher for EVs than conventional ICEV (Mellino et al., 2017). Thirdly, battery recycling problems associated with EVs will lead to severe environmental problems if they were not recycled properly (Jean, 2021).

1.2.4 Adoption Potential

The adoption potential for EVs is high for several aspects. Faced with serious environmental problems, governments would like to set targets for EV deployment. Further financial subsidies and tax reductions will be implemented to motivate more consumers to choose EVs when buying a new car. The fast development of lithium battery technology will result in batteries with better performance and lower price. Less utilization of critical materials in advanced batteries, such as cobalt-less batteries and even solid batteries without cobalt, will further also help reduce the battery pack price. The fast-declining battery price will further help drop the EV price, resulting in more consumers choosing EVs. The financial savings and climate benefits will drive more consumers to purchase EVs in the future. Meanwhile, the increasing EV market will also drive EV manufactures to produce more EV models.

1.3 ADVANTAGES AND DISADVANTAGES OF ELECTRIC VEHICLES

1.3.1 Similar Solutions

Solutions that are similar to or can replace EVs are: HEVs and fuel cell electric vehicles (FCEVs). HEVs have been explored and employed for longer history than EVs. HEVs have higher energy efficiency than traditional ICEVs. It is also a solution included in Project Drawdown. However, HEVs also need fossil fuels in the use phase, leading to direct carbon emissions. FCEVs are another promising solution to combat climate change for the transportation sector. FCEVs will depend on hydrogen in the use phase and will not lead to any carbon emissions. But FCEVs is still in the infancy stage and not employed at a large scale.

Compared with HEVs, EVs could totally eliminate fossil fuels and direct carbon emissions in the use stage. And unlike FCEVs, the technology of EVs is highly developed, especially battery technology and the fuel source (electricity) is more mature than hydrogen.

1.3.2 Arguments for Adoption

EVs are identified as a promising solution for replacing ICEVs. Although improving the EVs is the lowest priority in the transport solutions modeled, numerous other non-motorized and shared modes are adopted fully before EV's deployment. For some trips that are too long and can not be replaced by non-motorized modes, EVs could still play a significant role in replacing those motorized pkm. The solution's advantages

and disadvantages are better understood when compared to the other available passenger motorized mode choices.

EVs purchase price is more than conventional ICEVs. The financial subsidies and taxes are different for different regions and times. It is difficult to compare the purchase price of an EV after-tax to an ICEV because of the differences. Even considering the after-tax, the price of EVs is still higher than ICEVs for most regions. The purchase cost will prohibit some consumers from choosing EVs when they buy a new car. However, it should be noticed that EVs' operation costs and maintenance costs are much lower than ICEVs.

Compared with ICEVs, the solution does not emit direct carbon emissions and could significantly reduce the direct emissions of the use phase. It is difficult to compare the total carbon emissions of EVs to ICEVs because the embodied emissions in car production and energy are different for different regions. EVs will lead to more embodied emissions in car manufacturing, especially battery production. Therefore, the real net savings of carbon emissions are determined by trade-offs of decreased direct emissions and increased embodied emissions.

This solution helps improve air quality generally. This solution will not produce toxic emissions from engines, such as NO_x, HC, and carbon monoxide in the operation stage (Barisione, 2021). Besides, this solution will reduce particle pollution (OECD, 2021).

1.3.3 Additional Benefits and Burdens

Additional benefits of EVs include avoiding dependence on fossil fuels and air quality improvements. On the one hand, EVs will only consume electricity (excluding PHEV), which could reduce the dependence on fossil fuels. On the other hand, this solution will not produce toxic emissions from engines, such as NO_x, HC, and carbon monoxide in the operation stage (Barisione, 2021). This solution will reduce particle pollution (OECD, 2021) because of the changing power source from gasoline to electricity.

Burdens of EVs include increasing demand for critical materials and battery recycling problems. The massive deployment of EVs will lead to huge amounts of batteries and corresponding critical materials. These critical materials will overdistributed in some countries and regions. The imbalance between supply and demand will curb the development of EV development. Meanwhile, the fast development will bring potential problems of battery recycling. Unreasonable battery recycling treatment and technology will lead to worse environmental problems.

Table 1.4 Alternative Comparison

	Total User Cost	User Convenience	Comfort	User Safety/ Security	Speed	Uncertainty (Including Congestion)	Negative Environmental Impact
Electric vehicles	High	Med	High	Med	Med	High	Med
Fuell cell vehicles	High	Med	High	Med	Med	High	Med
Internal combustion vehicles	Med	High	High	High	High	High	High
E-bike	Low	Med	Med	Low	Med	Low	Med
Walking	Low	Low	Low	Med	Low	Low	Low
Biking (Including Bikeshare)	Low	Low	Low	Low	Low	Low	Low
Public Transit	Low	Med	Med	High	Med	Low	Low

2 METHODOLOGY

2.1 INTRODUCTION

Project Drawdown's models are developed in Microsoft Excel using standard templates that allow easier integration since integration is critical to the bottom-up approach used. The template used for this solution was the Reduction and Replacement Solutions (RRS) which accounts for reductions in energy consumption and emissions generation for a solution relative to a conventional technology. These technologies are assumed to compete in markets to supply the final functional demand which is exogenous to the model, but may be shared across several solution models. The adoption and markets are therefore defined in terms of functional units, and for investment costing, adoptions are also converted to implementation units. The adoptions of both conventional and solution were projected for each of several scenarios from 2015 to 2060 (from a base year of 2014) and the comparison of these scenarios (for the 2020-2050 segment²) is what constituted the results. The most updated year (current year) is 2018.

The use of cars varies widely worldwide. Annual vehicle-km travelled per car per year in the US can be very high, partly due to cultural factors, but in other parts of the world, like Asia, the figures can be much lower while also growing and are leading to changes in the car occupancy (more leisure trips could increase the car occupancy). The use of cars for commuting is lower than the US in many countries, with other modes of transport (public transit, cycling, walking) claiming a larger share of the market.

In many regions, the number of cars per capita remains high, and in others it is growing. In developing countries such as China and India, cars per capita are low. It is anticipated that the share of vehicles in these regions will increase. Electric vehicles are a promising solution to model globally because vehicle electrification could reduce the direct carbon emissions in the operation stage. Many countries have set the target of electric cars. The expanding electric cars further will continue to mitigate the well-to-wheel carbon emissions with the net savings compared with ICEVs (IEA, 2021b). The implementation of electric cars are mainly from IEA Energy Technology Perspective (IEA, 2016a), IEA Global EV Outlook (IEA, 2018b, 2021b), Bloomberg Global EV Outlook (Bloomberg NEF, 2020), OPEC World Oil Outlook (OPEC, 2020), ITF Transport Outlook (OECD/ITF, 2021).

² For most results, only the differences between scenarios, summed over 2020-2050 were presented, but for the net first cost, the position was taken that to achieve the adoptions in 2020, growth must first happen from 2015 to 2020, and that growth comes at a cost which should be accounted for, hence net first cost results represent the period 2015-2050.

The conventional technology in this model will be all modes used for passenger travel from specifically ICEVs. The functional unit of the analysis is billion passenger kilometers (pkm) and the implementation unit is the number of electric cars. The agency level is individual.

The Project Drawdown Scenario (PDS) shows a slow continue increase of the modal share of EVs in urban and nonurban environments. The increased number of EV pkm will come from trips of ICEVs. The solution is EV travel in passenger mobility. Climate and financial impacts will be calculated by billion pkms (functional unit) and the number of EVs (implementation unit).

2.2 DATA SOURCES

As Drawdown models are based on a meta-analysis of published values for each variable and input where ever possible, several data sources are used for this work, and averages are used for the majority of inputs.

Global TAM was projected mainly using data obtained from highly respected international institutions, such as the International Energy Agency’s Energy Technology Perspectives 2016, the ICCT’s 2012 publication, and the Institute for Transportation and Development Policy with the University of California at Davis in their joint publication of a global high shift scenario for transport (IEA, 2016b; The International Council on Clean Transportation, 2012; UC Davis, Fulton, & Mason, 2015)

Adoption projections are gathered from as many credible sources as possible. The key data on adoption data are from multiple institution report, such as IEA Energy Technology Perspective (IEA, 2016a) ,IEA Global EV Outlook (IEA, 2018b, 2021b), Bloomberg Global EV Outlook (Bloomberg NEF, 2020), OPEC World Oil Outlook (OPEC, 2020), ITF Transport Outlook (OECD/ITF, 2021).

Variable inputs are used in the Variable Meta-Analysis and are updated to reflect current conditions at each update. These variables regarding climate input, financial input, and technique input came from wide range of literature, such as peer-reviewed scientific papers, reports, and grey sources (see section 2.5).

2.3 TOTAL ADDRESSABLE MARKET

The addressable market for EVs is defined as the total measurement of the function provided, mobility in passenger-km units³. We include urban and non-urban mobility since EV’s have been growing in range for some time and can be expected in the future to provide intercity mobility. The addressable market therefore includes the mobility provided by ICE cars, 2-wheelers, public transport and non-motorized modes (bicycle and walking) within cities but also these and rail outside cities. One of the purposes of this report is to

³ One “passenger-km” is the mobility provided by one person that has been moved 1 km.

estimate the reduction of carbon emissions and household savings from buying and driving an EV instead of an ICEV. Vehicles bought by customers who operate fleets (corporations, car rental agencies and governments for example) are excluded and only retail vehicles are considered for the final part of this analysis.

The total EVs available market is defined as global urban and nonurban passenger mobility. Therefore, it changes annually according to total passenger urban and nonurban mobility, adoption of other urban modes, and this also varies by scenario. Global TAM was projected mainly using data obtained from the International Council on Clean Transportation (The International Council on Clean Transportation, 2012), Institute for Transportation and Development Policy (UC Davis et al., 2015) and International Energy Agency (IEA, 2016b). Since most of the collected data report values in 5-year intervals, values for the in-between years were estimated with the use of data interpolation.

2.4 ADOPTION SCENARIOS

Two different types of adoption scenarios were developed: a Reference (REF) Case, which was considered the baseline, where there were not many changes in the world, and a set of Project Drawdown Scenarios (PDS) with varying levels of ambitious adoption the solution. Published results show the comparison of one PDS to the REF, and therefore focus on the change to the world relative to a baseline.

2.4.1 Reference Case / Current Adoption

The Reference scenario for most Project Drawdown Solution models assumes that the percent current adoption of the solution (as defined in 2018) remains fixed for the future. This therefore ignores growth that may result in the Business as usual due to existing policy and committed investments worldwide, however it allows us to capture the impact of both those initiatives and additional initiatives which are needed to achieve the high growth scenarios. The Reference case however is defined as a fixed percent of the total mobility and grows with the total mobility. The current adoption, as described and calculated in the Current Adoption Section is 0.21% of all car pkm.

2.4.2 Project Drawdown Scenarios

Three Project Drawdown scenarios (PDS) were developed for each solution, to compare the impact of an increased adoption of the solution to a reference case scenario. In each case, a car occupancy target in 2050 was identified and a linear interpolation from the current value to that value in 2050 was created to estimate adoption each year. These car occupancy adoptions were converted to percent of adoption each year and the percent is converted to passenger-km by multiplying by the TAM each year.

Three Project Drawdown scenarios (PDS) were developed for each solution, to compare the impact of increased adoption of the solution to a reference case scenario. Three Project Drawdown scenarios (PDS) were developed for each solution, to compare the impact of increased adoption of the solution to a reference case scenario. Five sources were used to make the PDS projections, IEA Energy Technology Perspective (IEA, 2016a) , IEA Global EV Outlook (IEA, 2021b), Bloomberg Global EV Outlook (Bloomberg NEF, 2020), OPEC World Oil Outlook (OPEC, 2020), ITF Transport Outlook (OECD/ITF, 2021)

The implemented electric car stock in IEA Global EV Outlook (IEA, 2021b), Bloomberg Global EV Outlook (Bloomberg NEF, 2020), OPEC World Oil Outlook (OPEC, 2020) were converted into the functional unit PKM with the help of the model variable *Average Annual Use* for the solution in the model. The ITF reports urban and nonurban PKMs globally to 2050. Estimates of EV share were made based on the proportion of EV pkms of car pkms based on the IEA EV30@30 scenario in Global EV Outlook(IEA, 2018b).

Plausible Scenario

This scenario assumes Electric car adoption will reach 9% of total TAM data. This scenario assumes the baseline TAM predictions based on ETP (IEA, 2016b) 6 DS and ICCT (The International Council on Clean Transportation, 2012). In the Plausible Scenario, the adoption data is based on ITF Reshape Plus (OECD/ITF, 2021) + IEA EV30@30 (IEA, 2018b), IEA ETP 6DS scenario (IEA, 2016b), and IEA Global EV Outlook (IEA, 2021b).

Ambitious Scenario

This scenario assumes Electric car adoption will reach 15% of total TAM data. This scenario assumes the Conservative TAM predictions based on ETP (IEA, 2016b) 4DS scenario. In the Drawdown Scenario, the adoption data is based on ITF Recover (OECD/ITF, 2021) + IEA EV30@30(IEA, 2018b), OPEC World Oil Outlook ((OPEC, 2017, 2020)).

Maximum Scenario

This scenario assumes Electric car adoption will reach 34% of total TAM data. This scenario assumes the Ambitious TAM predictions based on ETP (IEA, 2016b) 2DS scenario. In the Maximum Scenario, the adoption data is based on IEA ETP 2DS scenario (IEA, 2016b), ITF Recover (OECD/ITF, 2021) + IEA EV30@30 (IEA, 2018b), and IEA Beyond 2DS Scenario (IEA, 2016b). Here we perform a vehicle survival analysis using data from 6 countries scaled to the world to estimate the maximum adoption rate possible if all new cars from a specified year were EVs. Using 2018 stock estimates and Weibull survival distribution coefficients from the ICCT (2012) for US, China, India, Brazil, Mexico and Canada (~50% of global fleet),

estimates of maximum EV car sales and replacements out to 2060 were calculated and then scaled to global fleet.

2.5 INPUTS

Many variables have been defined and calculated for this analysis. They are grouped by climate inputs, financial inputs and technical inputs. Each variable is described below.

2.5.1 Climate Inputs

The climate analysis in this model uses the values for fuel and electricity consumption for conventional (ICEV) and solution (EV), respectively. To calculate key emissions results, the model uses reported emissions factors for the electric grid as well as fuel emissions factors. Emissions factors for electricity generation are derived from the projected global energy generation mix from three AMPERE RefPol scenarios in the IPCC AR5 model Database (GEM3, IMAGE, MESSAGE) and the IEA's ETP 6DS scenario. Fuel combustion emissions factors come from the Intergovernmental Panel on Climate Change (IPCC) Guidelines for Fuel combustion (IPCC, 2006). The values used are shown in **Error! Reference source not found.**

Fuel consumed per functional unit for conventional and solution

The energy per functional unit (billion pkm) are gasoline and electricity for ICEV and EV respectively. For ICEV, average global fuel consumption is compiled by the values from the main car market (the U.S., Japan, EU, and China) and from a range of sources like IEA, ICCT, and numerous other research papers (Bieker, 2020; Hilary, 2020; Kara, Li, & Sadjiva, 2017; Schäfer & Yeh, 2020a; T. Wu et al., 2020; Z. Wu et al., 2018a). Average global fuel intensity was estimated based on data from various sources for the main car market and the world.

For EVs, average global fuel consumption is compiled by the values from the main car market and from a range of sources like IEA, ICCT, and many other research papers ("Alternative Fuels Data Center: Vehicle Cost Calculator," n.d.; IEA, 2019a; Kane, 2019; Kara et al., 2017; OECD, 2019; T. Wu et al., 2020; Yang et al., 2021)

Fuel efficiency factor -solution

The variable is to quantify how much fuel is saved for each pkm when switching from an ICEV to an EV (BEV, PHEV). The EV includes both technologies appropriately weighted with another variable. For a BEV, 100% of fuel is saved, and replaced with 100% electricity (defined in another variable). For PHEV, the fraction of fuel saved depends on the fraction of the time that the PHEV runs on fuel (hybrid, ICE) and

on the fuel consumption during that time. The fuel efficiency factor for PHEV are from various sources (IEA, 2019a; Milovanoff, Posen, & MacLean, 2020)

Direct emission per conventional/solution functional unit

The direct emission per functional unit indicates the direct emissions in the use phase. There is no direct emission per solution unit because EVs don't lead to emissions. The direct emission per conventional functional unit is from three sources (Hasan, Frame, Chapman, & Archie, 2021; ODYSSEE-MURE, 2021; Z. Wu et al., 2018a).

Indirect emission per conventional/solution implementation unit

Indirect emissions from vehicle manufacturing must also be taken into account. Values from various sources related to the CO₂e emissions generated to produce an ICEV and EV are considered to calculate the indirect emissions of implementing one ICEV and EV. The indirect emission per conventional implementation unit is mainly from various reports and journal articles (Aguirre et al., 2012; Chester & Horvath, 2009; European Environment Agency, 2018; Hasan et al., 2021; Hawkins, Gausen, & Strømman, 2012; Hawkins, Singh, Majeau-Bettez, & Strømman, 2013; Joseck & Ward, 2014; Lattanzio & Clark, n.d.; Lave & MacLean, 2002; Patricia Baptista, Carla Silva, Goncalo Goncalves, & Tiago Farias, 2009; Qiao, Zhao, Liu, He, & Hao, 2019; Samaras & Meisterling, 2008; Wilson, 2013; Z. Wu et al., 2018a, 2018b). The indirect emissions per solution implementation unit are from various sources (Chester & Horvath, 2009; European Environment Agency, 2018; Hasan et al., 2021; Hawkins et al., 2012, 2013; Lattanzio & Clark, n.d., n.d.; Qiao et al., 2019; Z. Wu et al., 2018b)

Table 2.1 Climate Inputs

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Total Energy Used per functional unit - SOLUTION	Twh per billion passenger-km	0.040-0.109	0.081	15	15
Fuel Consumed per Functional Unit - CONVENTIONAL	Fuel unit (Liter) per billion passenger-km	32756941 – 67786794	50271868	13	13
Fuel Efficiency Factor - SOLUTION	Fuel % saved	75% –104%	90%	7	7

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Fuel Emissions Factor		0.002238 – 0.002505	0.002274		Source: 2006 IPCC Guidelines for National Greenhouse Gas Inventories
Direct Emissions per CONVENTIONAL Functional Unit	t CO ₂ -eq per billion passenger-km	62548.367 – 81144.120	71846.2	17	17
Indirect CO ₂ Emissions per CONVENTIONAL Implementation	t CO ₂ -eq per vehicle	3.3 – 17.2	10.2	20	20
Indirect CO ₂ Emissions per SOLUTION Implementation Unit	t CO ₂ -eq per vehicle	6.3 – 18.8	12.6	26	26

Note: Project Drawdown data set range is defined by the low and high boundaries which are respectively 1 standard deviation below and above the mean of the collected data points⁴.

2.5.2 Financial Inputs

First Cost Factor

This analysis calculates costs and benefits for individuals who engage in EVs. For conventional technology (ICEV), the first cost is the purchase cost. The values of conventional first cost are collected for the main car market (the U.S., Japan, EU, and China) and global average. The conventional first cost are from range of sources (Carnext, 2019; Carview, 2019; Coren, n.d.; EIA, n.d.; Feijter, 2018a, 2018b; Gasnier, 2019; Hu, 2019; IEA, 2019a; IEA & ICCT, 2019; ITDP, 2019; JATO, 2019; Lutney & Nicholas, 2019; Lutsey, Cui, & Yu, 2021; Mock, 2019; Ning, 2018, 2018; Tate, 2019; Wang, 2017, 2018). The solution first cost indicates the sale-weighted purchase price or retail price of the main car market and global average. The solution first cost is from range of sources (Brasor & Tsubuku, 2018; Coren, n.d.; EIA, n.d.; IEA, 2019a;

⁴ In some cases, the low boundary is negative for a variable that can only be positive, and in these cases the lowest collected data point is used as the “low” boundary.

JATO, 2019; Lutney & Nicholas, 2019; Sheldon & Dua, 2020; the Guardian, 2021; WattEV2Buy, 2020b, 2020a). Using a selection of this research for several countries, average global value was estimated.

Operational Cost

Operating costs are most prominently fuel and maintenance. The operating cost in this report only represents maintenance cost. The fuel cost is a separate variable in the advanced control TAB. Data from 15 sources indicate average maintenance costs for EVs(Berman, 2016; Eisenstein, 2020; Electric Power Research Institute, 2014; Gert Berckmans et al., 2017; Halvorson, 2020; Harto, 2020; Harto, Winer, & Friedman, 2020; Hasan et al., 2021) and ICEVs (AAA Association, 2014, 2016; Autocosts, 2021b; De Clerck et al., 2018; Electric Power Research Institute, 2013; Hagman, Ritzén, Stier, & Susilo, 2016a; Harto, 2020; Harto et al., 2020; Hasan et al., 2021).

Fixed Operating Cost

Fixed operating costs in the report indicate the insurance cost of the conventional and solution technology. The report considered the insurance cost for main countries in the world, such as U.S., China, Germany, France, Brazil et. Data from four sources indicate average fixed operating costs (Autocosts, 2021a; Hagman, Ritzén, Stier, & Susilo, 2016b; Hagman et al., 2016a; Victoria Transport Policy Institute, 2017)

Solution Learning Rate

The solution learning rates in different regions are very different. Even in the same region, the EV learning rates are different for various EV models. For example, the learning rate of Tesla and BYD in China is 8% and 21%. In the old model, the solution learning rate is assumed 2% because of conservative assumptions and limited sources. In the new model, the solution learning rate is based on the average values from six sources and 17 data points (Hsieh, Pan, Chiang, & Green, 2019; IEA, 2016c; Nykvist & Nilsson, 2015b; Qiu, Yu, Liu, Zhao, & Song, 2021; Safari, 2018; Weiss, Zeffass, & Helmers, 2019).

Table 2.2 Financial Inputs

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
CONVENTIONAL First Cost per Implementation Unit for replaced practices/technologies	<i>per implementation unit</i>	\$18371 – \$32340	25356	14	14

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Lifetime Capacity - CONVENTIONAL	<i>use until replacement is required</i>	2.61E-04 – 4.32E-04	3.47E-04	16	16
Average Annual Use - CONVENTIONAL	<i>annual use</i>	2.09E-05 – 2.81E-05	2.45E-05	12	12
CONVENTIONAL VARIABLE Operating Cost per Functional Unit	<i>per functional unit of measure</i>	5,784,652 – 25,011,611	\$15398132	16	16
CONVENTIONAL FIXED Operating Cost per Implementation Unit	<i>per implementation unit</i>	409 – 857	\$633	11	11
SOLUTION First Cost per Implementation Unit	<i>per implementation unit</i>	\$25,678 – \$46,957	\$36440	11	11
Average Annual Use - SOLUTION	<i>annual use</i>	1.76E-05 – 3.87E-05	3.47E-04	11	11
SOLUTION VARIABLE Operating Cost per Functional Unit	<i>per functional unit of measure</i>	5,132,733 – 18,010,497	\$12831862	19	19
SOLUTION FIXED Operating Cost per Implementation Unit	<i>per implementation unit</i>	371 – 897	\$634	25	25
Discount Rates - Households	Percent	3% – 5%	4%	10	10
EV Learning Rate	%	1.41% – 17.86%	11%	17	17
Learning rate factor (solution)	%		0		

Technical Inputs

Besides only climate- and financial-oriented variables, some variables have been defined which apply to both climate and financial results. These are called Technical inputs, and are described below.

Fraction of BEV and PHEV

EVs in this report included BEV and PHEV. The fraction of BEV and PHEV for EVs is different regionally and globally. Different EV fractions will lead to different fuel consumption and climate impact because PHEV will consume electricity when driving electric. This reports collects eight sources and use the average

values of those sources (Bloomberg NEF, 2020; “Europe Became The World’s Biggest Plug-In Electric Car Market In 2020,” n.d.; Goosen, 2017, 2017; IEA, 2016c, 2021a; Nextgreencar, 2021; Wagner, 2021, pp. 2009–2020; Wong, 2020).

Fuel Consumption

Average global fuel consumption is the subject of global initiatives such as the Global Fuel Economy Initiative (GFEI) of the IEA, ICCT and many other partners, and of many research papers. Using a selection of this research for several countries, average global fuel intensity was estimated. Note that total energy consumption is there the sum of fuel and electricity consumption per pkm.

Car occupancy

Average car occupancy comes from a variety of sources, including peer-reviewed sources (H. Liu et al., 2017; McQueen, MacArthur, & Cherry, 2020; Schäfer & Yeh, 2020b), international research institutions (Center for Sustainable Systems University of Michigan, 2020; ITF/OECD, 2020) and government (Environmental and Economic Policy Research Center of the Ministry of Ecology and Environment, 2018). Although solution car occupancy is also collected, there is limited source for solution car occupancy. Therefore, the solution car occupancy is assumed the same as the conventional technology

Average Annual Use

This is defined as the total amount of functional units that a single implementation unit can provide over its lifetime. Dividing this value by the average annual use gives us a lifetime. As the functional unit is passenger-km and the functional unit pkm for a car could multiply average annual use by car occupancy. The average annual use for conventional technology is from various sources(ICCT, 2012; Kittner et al., 2020; Q. Liu et al., 2019; Ramez Naam, 2016).

Table 2.3 Technical Inputs

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Fraction of BEV+PHEV market that is BEV	Percent	54% –69%	62%	8	8
CONVENTIONAL Car Occupancy	passengers/vehicle	1.39 –2.02	1.7	16	16
Average Annual EV Car Vehicle km	km/yr	10355 – 17178	13766	12	12

2.6 ASSUMPTIONS

Three overarching assumptions have been made for Project Drawdown models to enable the development and integration of individual model solutions. These are that infrastructure required for solution is available and in-place, policies required are already in-place, no carbon price is modeled, all costs accrue at the level of agency modeled, improvements in technology are not modeled, and that first costs may change according to learning. Full details of core assumptions and methodology will be available at www.drawdown.org. Beyond these core assumptions, there are other important assumptions made for the modeling of this specific solution. These are detailed below.

Assumption 1: The lifetime capacity for the solution are assumed the same as the conventional ICEVs.

The lifetime capacity for the conventional is from various sources (Choma & Ugaya, 2017; Hawkins et al., 2012; Lu, 2006; Zheng et al., 2019). Based on many sources (Hagman et al., 2016a; Hasan et al., 2021; Hawkins et al., 2012, 2013; Kara et al., 2017; Letmathe & Soares, 2017; Lu, 2006; Palmer, Tate, Wadud, & Nellthorp, 2018; Palmer et al., 2018; Sengupta & Cohan, 2017), the lifetime capacity for EVs is still 27% lower than ICEVs. However, EV development is still at early stage, and it is assumed that lifetime capacity will continue to increase with the technology development and reach parity with ICEVs.

Assumption 2: The learning rate of the conventional ICEVs is assumed zero.

Assumption 3: The car occupancy of an EV and an ICEV are assumed the same. The car occupancy of an ICEV are from various sources. While there are limited sources for the car occupancy of an EV. Since the seat for an ICEV and EV are similar, this report assumes that there is no difference between EV occupancy rate and ICEV occupancy rate.

2.7 INTEGRATION

The complete Project Drawdown integration documentation (will be available at www.drawdown.org) details how all solution models in each sector are integrated and how sectors are integrated to form a complete system. Those general notes are excluded from this document but should be referenced for a complete understanding of the integration process. Only key elements of the integration process that are needed to understand how this solution fits into the entire system are described here.

Each solution in the Transportation Sector was modeled individually, and then integration was performed to ensure consistency across the sector and with other sectors. These solutions require an integration

analysis chiefly to avoid double counting, as they may result in an overallocation of passenger or freight mobility to multiple modes at the same time, or incorrect distribution of passenger mobility to the urban or nonurban realms.

The integration process, while having several parts including ensuring consistency of inputs across the sector, was mainly concerned with limiting adoption of solutions where it was deemed necessary. The transport modes that were unaffected by any Drawdown solution such as motorbikes and intercity bus had their mobility share blocked so that it could not be allocated to any other modes, and then the remaining mobility demand was allocated according to priority of the modeled transport solutions.

Transport solution priority was loosely based on the Avoid-Shift-Improve framework where solutions that resulted in avoiding motorized mobility (walking, biking, telepresence) were classed as highest priority in their appropriate realm (walking is in the urban realm and telepresence is in the nonurban realm). Then the solutions that resulted in shifting of mobility to more efficient modes such as public transport or e-bikes were of second highest priority where space efficiency was qualitatively used as a classification metric. Finally, solutions that improved the efficiency of existing motorized modes were put in the third category with all car modes falling into this category.

For several variables, especially those relating to the conventional technology (ICEVs), discount rates, fuel prices, emissions factors, and mode shares, consistency across solutions was maintained by ensuring that the same values were used in different models needing those variables.

In addition to transport sector integration, there was an integration process across the grid and electricity efficiency solutions (buildings, transport, materials etc.) which adjusted for the double counting. Double counting of emissions reduction was a factor of using the reference grid emissions factors for electricity-based solutions. As grid solutions (Utility-scale Solar PV and others) are adopted, the grid gets cleaner and the impact of transport electrification solutions is amplified but not accounted for⁵. Grid solutions are adjusted to account for the increased impact as described in the Project Drawdown integration documentation. In the case of Carpooling, the integration of EV results in Carpooling working to decrease electricity demand so a cleaner grid actually results in a double counting of the emissions reduction. Therefore the grid integration removes the double counting effect.

Results in this report show already account for these integration effects.

⁵ Some solutions such as Electric Vehicles and High-Speed Rail increase the demand for electricity and reduce the demand for fuel.

2.8 LIMITATIONS/FURTHER DEVELOPMENT

As with any modeling effort, there are some limitations of the approach used. The primary one is that it is assumed the EV lifetime capacity is the same as ICEVs lifetime capacity. The EV lifetime capacity is shorter than ICEV lifetime capacity in the real world because of the limitation of battery technology. The current model could be further improved if considering dynamic fleet model of ICEVs and EVs with various lifetime distribution of different regions.

Another important limitation is the various car occupancy globally. Global averaging of car occupancies varies widely worldwide and is affected by various local and national circumstances. Data from the ICCT, albeit from a 2012 publication, indicate a range of car occupancies from 2.31 people per vehicle in India to 1.22 in Japan in 2010 (ICCT, 2012). This report collected 15 additional sources regarding ICEV car occupancy in China, U.S., Germany, Japan, and France, as well as global estimate. However, there is still limited sources on EV car occupancy. This report assumes that there is no differences for ICEVs and EVs regarding car occupancy.

3 RESULTS

3.1 ADOPTION

Below are shown the world adoptions of the solution in some key years of analysis in functional units and percent for the three Project Drawdown scenarios.

Table 3.1 World Adoption of the Solution

Solution	Units	Current Year (2018)	World Adoption by 2050		
			Plausible	Ambitious	Maximum
Carpooling	billion passenger-km	137.14	12,186.91	17,111.94	35,921.73
	(% Market)	0.2%	8.7%	15.2%	33.7%

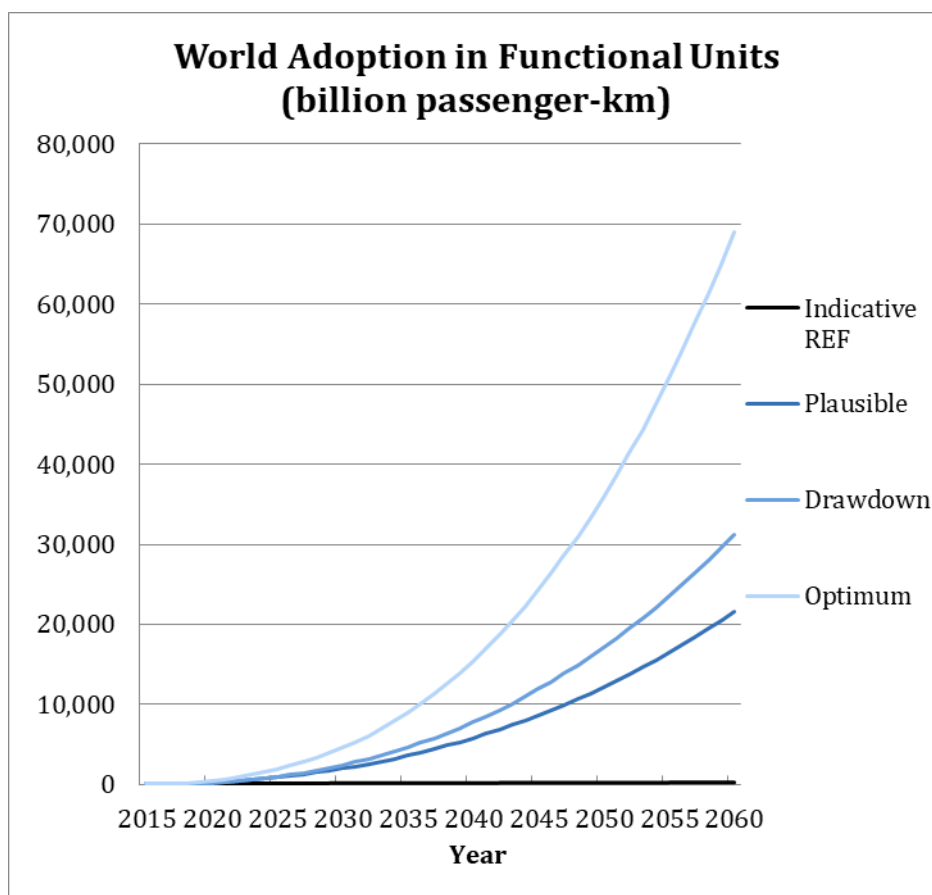


Figure 3.1 World Annual Adoption 2020-2050 in Billion Pkm

3.2 CLIMATE IMPACTS

Below are the emissions results of the analysis for each scenario which include total emissions reduction, atmospheric concentration changes, and sequestration where relevant. For a detailed explanation of each result, please see the Glossary (Section 6).

Table 3.2 Climate Impacts

Scenario	Maximum Annual Emissions Reduction	Total Emissions Reduction	Emissions Reduction in 2030	Emissions Reduction in 2050
	(Gt CO ₂ -eq/yr.)	Gt CO ₂ -eq/yr. (2020-2050)	(Gt CO ₂ -eq/year)	(Gt CO ₂ -eq/year)
<i>Plausible</i>	1.47	16.22	0.21	1.47
<i>Ambitious</i>	2.09	22.13	0.26	2.09
<i>Maximum</i>	4.42	45.32	0.51	4.42

The solution was integrated with all other Project Drawdown solutions and may have different emissions results from the models. This is due to adjustments caused by interactions among solutions that limit full adoption (such as by feedstock or demand limits) or that limit the full benefit of some solutions (such as reduced individual solution impact when technologies are combined).

Table 3.3 Impacts on Atmospheric Concentrations of CO₂-eq

Scenario	GHG Concentration Change in 2050	GHG Concentration Rate of Change in 2050
	PPM CO ₂ -eq (2050)	PPM CO ₂ -eq change from 2049-2050
Plausible	1.43	0.12
Ambitious	1.96	0.18
Maximum	4.03	0.38

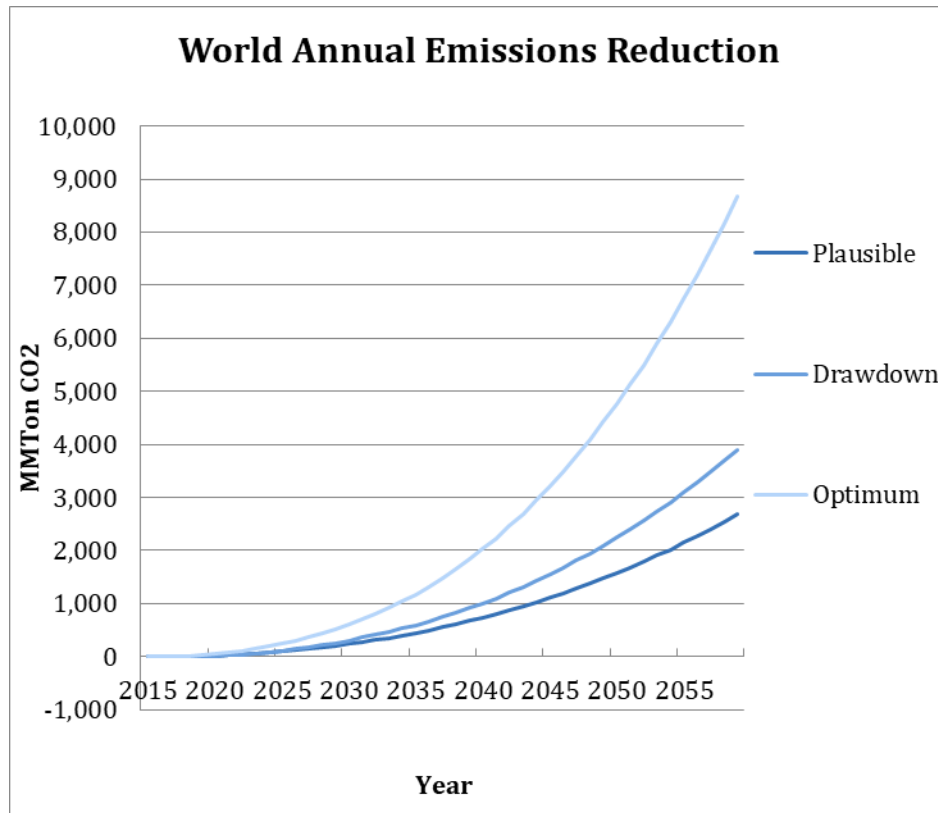


Figure 3.2 World Annual Greenhouse Gas Emissions Reduction

3.3 FINANCIAL IMPACTS

Below are the financial results of the analysis for each scenario. For a detailed explanation of each result, please see the glossary. Note, the drop off in the operations costs seen in Figure 3.3 is a result of the period of study. We only consider vehicles that will be in use by 2050 and we do not estimate additional implementation beyond 2050.

Table 3.4 Financial Impacts

Scenario	Cumulative First Cost	Marginal First Cost	Net Operating Savings	Lifetime Operating Cost Savings	Lifetime Cashflow Savings NPV (of All Implementation Units)
	2015-2050 Billion USD	2015-2050 Billion USD	2020-2050 Billion USD	2020-2050 Billion USD	Billion USD
Plausible	16,388.29	-594.43	5,119.84	8,357.27	2,434.94
Ambitious	22,552.92	-804.28	6,996.56	11,612.08	3,324.42
Maximum	46,560.63	-1,699.49	14,329.46	24,282.52	6,940.92

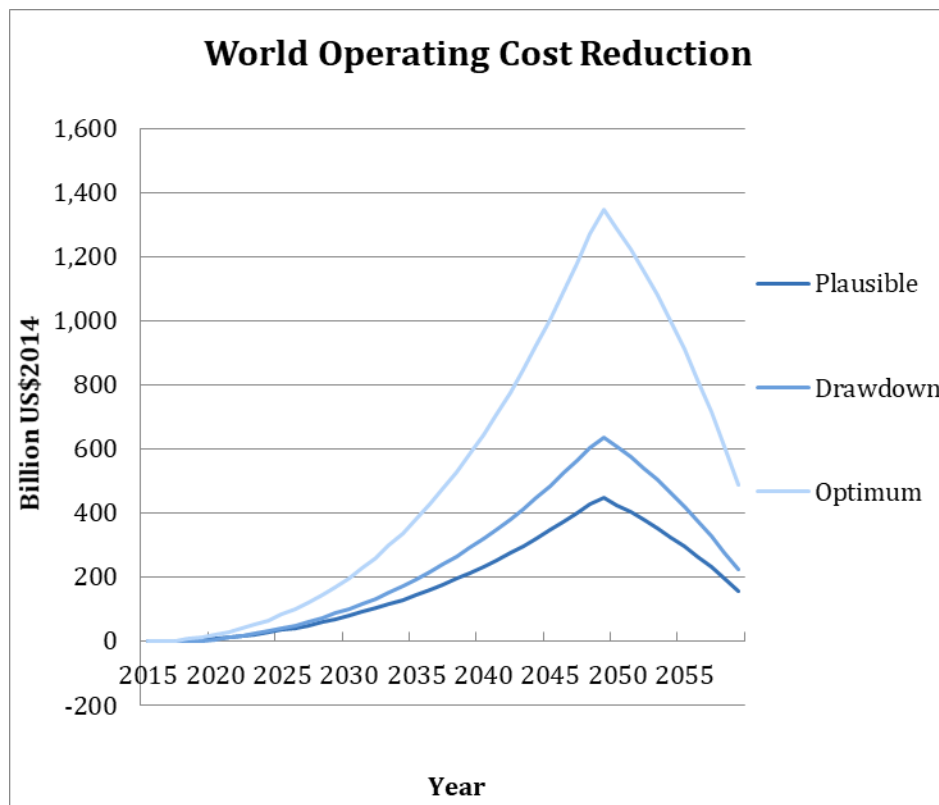


Figure 3.3 Net Profit Margin /Operating Costs Over Time

4 DISCUSSION

Travelers reduce emissions by using EVs. EVs will help reduce direct carbon emissions in the use phase immediately. Although EVs will lead to extra embodied emissions in the car production also power battery production, the increasing EV adoption will still offer big climate benefit because of higher efficiency than traditional ICEVs.

With a global trend towards EV for 9% of urban and all urban trips as defined in the Plausible (least aggressive) scenario by 2050, the emissions impact can be significant at 16.22Gt CO₂e over 30 years (2020-2050). In more aggressive scenarios (the Ambitious scenario in the model), the emission reduction over 30 years (2020-2050) are 45.32Gt. Overall the transport system is far less polluting if adopting more EVs in the future.

In addition to climate impacts there is some evidence that EVs contribute to air quality improvement because of declining toxic emissions from engines (e.g., NO_x, HC, and carbon monoxide emissions) and particle pollution.

The financial outcomes of increased EVs adoption depend on the first cost, operation cost, insurance cost, and fuel cost. Given the assumptions and projections of carpooling used for this report, the financial results presented in **Error! Reference source not found.** show the NPV of the EV solution to be \$3.3 trillion with a net operating savings of \$7.0 trillion from 2020 to 2050 for the Drawdown scenario. The significant net operating cost savings and lifetime cashflow savings from the model estimates hint at the enormous financial savings of EV use that many people often don't realize. For the Optimum scenario, the net operating cost savings and lifetime cashflow savings are high to \$14 trillion and \$7.0 trillion respectively over 2020 to 2050.

In the real world, some consumers may hesitate to buy an EV because of the higher first cost of EV and ignore the savings in other costs. The model results provide more evidence that EVs will offer big financial savings for consumers. This report demonstrated that EVs is an easy, cost-effective solution that has significant reductions in emissions.

4.1 LIMITATIONS

EVs cannot solve all passenger mobility issues since it is impossible to drive EVs for all urban and nonurban trips based on current technology. The driving range of EVs is still lower than traditional ICEVs. The charging station of EVs is still quite limited compared with the traditional gas station. The waiting time of charge an EV will last several hours, which is quite longer than that of traditional ICEVs. This will lead to

the inconvenience of EVs. The safety problem of EVs is another limitation. Exposure to the extremely high temperatures, EVs' batteries could explode. Besides, the battery recycling problems are another challenge and limitations for EVs adoption.

4.2 BENCHMARKS

The Bloomberg Global EV Outlook modeled the projections of EV stocks (Bloomberg NEF, 2020). The projections consider increasing EV stocks globally by 2040.

The IEA Global EV Outlook Sector modeled the projection of EV stock share (IEA, 2021b). The projections consider increasing EV stocks by 2030.

The OPEC World Oil Outlook modeled the projection of EV stocks (OPEC, 2020). The projections consider increasing EV stocks by 2045.

This report use number of pkm as the implementation unit to quantify the climate and financial impact. The EV stocks for the PDS1-3 scenarios are converted by dividing the annual use of EVs.

Table 4.1 Benchmarks

Source and Scenario	EV stock in 2030	EV stock in 2040	EV Stock in 2050
(IEA, 2021b)	124 million		
(Bloomberg NEF, 2020)	116 million	535 million	
(OPEC, 2020)	81 million	325 million	
Project Drawdown – Plausible Scenario (PDS1)	85 million	248 million	519 million
Project Drawdown – Drawdown Scenario (PDS2)	103 million	332 million	729 million
Project Drawdown – Optimum Scenario (PDS3)	195million	657 million	1531 million

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6 GLOSSARY

Adoption Scenario – the predicted annual adoption over the period 2015 to 2060, which is usually measured in **Functional Units**. A range of scenarios is programmed in the model, but the user may enter her own. Note that the assumption behind most scenarios is one of growth. If for instance a solution is one of reduced heating energy usage due to better insulation, then the solution adoption is translated into an increase in use of insulation. There are two types of adoption scenarios in use: **Reference (REF)** where global adoption remains mostly constant, and **Project Drawdown Scenarios (PDS)** which illustrate high growth of the solution.

Approximate PPM Equivalent – the reduction in atmospheric concentration of CO₂ (in **PPM**) that is expected to result if the **PDS Scenario** occurs. This assumes a discrete avoided pulse model based on the Bern Carbon Cycle model.

Average Abatement Cost – the ratio of the present value of the solution (**Net Operating Savings** minus **Marginal First Costs**) and the **Total Emissions Reduction**. This is a single value for each solution for each **PDS Scenario**, and is used to build the characteristic “*Marginal Abatement Cost*” curves when Average Abatement Cost values for each solution are ordered and graphed.

Average Annual Use – the average number of functional units that a single implementation unit typically provides in one year. This is usually a weighted average for all users according to the data available. For instance, total number of passenger-km driven by a hybrid vehicle in a year depends on country and typical number of occupants. Global weighted averages are taken for this input. This is used to estimate the **Replacement Time**.

Car Occupancy – the average number of passengers riding in a car during trips. This should exclude drivers who are not also passengers (such as taxi drivers).

Cumulative First Cost – the total **First Cost** of solution **Implementation Units** purchased in the **PDS Scenario** in the analysis period. The number of solution implementation units that are available to provide emissions reduction during the analysis period is dependent on the units installed prior to the analysis period, and hence all implementation units installed after the base year are included in the cumulative first costing (that is 2015-2050).

Direct Emissions – emissions caused by the operation of the solution, which are typically caused over the lifetime of the solution. They should be entered into the model normalized per functional unit.

Discount Rate- the interest rate used in discounted cash flow (DCF) analysis to determine the present value of future cash flows. The discount rate in DCF analysis takes into account not just the time value of money, but also the risk or uncertainty of future cash flows; the greater the uncertainty of future cash flows, the higher the discount rate. Most importantly, the greater the discount rate, the more the future savings are devalued (which impacts the financial but not the climate impacts of the solution).

Emissions Factor– the average normalized emissions resulting from consumption of a unit of electricity across the global grid. Typical units are kg CO₂e/kWh.

First Cost- the investment cost per **Implementation Unit** which is essentially the full cost of establishing or implementing the solution. This value, measured in 2014\$US, is only accurate to the extent that the cost-based analysis is accurate. The financial model assumes that the first cost is made entirely in the first year of establishment and none thereafter (that is, no amortization is included). Thus, both the first cost and operating cost are factored in the financial model for the first year of implementation, all years thereafter simply reflect the operating cost until replacement of the solution at its end of life.

Functional Unit – a measurement unit that represents the value, provided to the world, of the function that the solution performs. This depends on the solution. Therefore, LED Lighting provides petalumen-hours of light, Biomass provides tera-watt-hours of electricity and high speed rail provides billions of passenger-km of mobility.

Grid Emissions – emissions caused by use of the electricity grid in supplying power to any operation associated with a solution. They should be in the units described below each variable entry cell. Drawdown models assume that the global electric grid, even in a Reference Scenario, is slowly getting cleaner, and that emissions factors fall over time resulting in lower grid emissions for the same electricity demand.

Implementation Unit – a measurement unit that represents how the solution practice or technology will be installed/setup and priced. The implementation unit depends on the solution. For instance, implementing electric vehicles (EV) is measured according to the number of actual EV's in use, and adoption of Onshore Wind power is measured according to the total terawatts (TW) of capacity installed worldwide.

Indirect Emissions – emissions caused by the production or delivery or setup or establishment of the solution in a specified area. These are NOT caused by day to day operations or growth over time, but they should be entered into the model normalized on a per functional unit or per implementation unit basis.

Learning Rate/Learning Curve - Learning curves (sometimes called experience curves) are used to analyze a well-known and easily observed phenomenon: humans become increasingly efficient with experience. The first time a product is manufactured, or a service provided, costs are high, work is inefficient, quality is marginal, and time is wasted. As experience is acquired, costs decline, efficiency and quality improve, and waste is reduced. The model has a tool for calculating how costs change due to learning. A 2% learning rate means that the cost of producing a *good* drops by 2% every time total production doubles.

Lifetime Capacity – this is the total average functional units that one implementation unit of the solution or conventional technology or practice can provide before replacement is needed. All technologies have an average lifetime usage potential, even considering regular maintenance. This is used to estimate the **Replacement Time**, and has a direct impact on the cost to install/acquire technologies/practices over time. E.g. solar panels generate, on average, a limited amount of electricity (in TWh) per installed capacity (in TW) before a new solar panel must be purchased. Electric vehicles can travel a limited number of passenger kilometers over its lifetime before needing to be replaced.

Lifetime Operating Savings – the operating cost in the PDS versus the REF scenarios over the lifetime of the implementation units purchased during the model period regardless of when their useful life ends.

Lifetime Cashflow NPV – the present value (PV) of the net cash flows (PDS versus REF) in each year of the model period (2015-2060). The net cash flows include net operating costs and first costs. There are two results in the model: Lifetime Cashflow NPV for a Single **Implementation Unit**, which refers to the installation of one **Implementation Unit**, and Lifetime Cashflow NPV of All Units, which refers to all **Implementation Units** installed in a particular scenario. These calculations are also available using profit inputs instead of operating costs.

Load Factor – The percentage of total possible passengers that a vehicle carries, which is usually calculated by dividing the number of passengers carried by the number of seats in the vehicle (car, train, bus, or plane).

Marginal First Cost – the difference between the **First Cost** of all units (solution and conventional) installed in the **PDS Scenario** and the **First Cost** of all units installed in the **REF Scenario** during the analysis period. No discounting is performed. The number of solution implementation units that are available to provide emissions reduction during the analysis period is dependent on the units installed prior

to the analysis period, and hence all implementation units installed after the base year are included in the cumulative first costing (that is 2015-2050).

Net Annual Functional Units (NAFU) – the adoption in the PDS minus the adoption in the REF in each year of analysis. In the model, this represents the additional annual functional demand captured either by the solution in the **PDS Scenario** or the conventional in the **REF Scenario**.

Net Annual Implementation Units (NAIU) – the number of **Implementation Units** of the solution that are needed in the PDS to supply the **Net Annual Functional Units (NAFU)**. This equals the adoption in the PDS minus the adoption in the REF in each year of analysis divided by the average annual use.

Net Operating Savings – The undiscounted difference between the operating cost of all units (solution and conventional) in the **PDS Scenario** minus that of all units in the **REF Scenario**.

Operating Costs – the average cost to ensure operation of an activity (conventional or solution) which is measured in 2014\$US/**Functional Unit**. This is needed to estimate how much it would cost to achieve the adoption projected when compared to the **REF Case**. Note that this excludes **First Costs** for implementing the solution.

Payback Period – the number of years required to pay all the **First Costs** of the solution using **Net Operating Savings**. There are four specific metrics each with one of **Marginal First Costs** or **First Costs** of the solution only combined with either discounted or non-discounted values. All four are in the model. Additionally, the four outputs are calculated using the increased profit estimation instead of **Net Operating Savings**.

PDS/ Project Drawdown Scenario – this is the high growth scenario for adoption of the solution

PPB/ Parts per Billion – a measure of concentration for atmospheric gases. 10 million PPB = 1%.

PPM/ Parts per Million – a measure of concentration for atmospheric gases. 10 thousand PPM = 1%.

REF/ Reference Scenario – this is the low growth scenario for adoption of the solution against which all **PDS scenarios** are compared.

Regrets solution has a positive impact on overall carbon emissions being therefore considered in some scenarios; however, the social and environmental costs could be harmful and high.

Replacement Time- the length of time in years, from installation/acquisition/setup of the solution through usage until a new installation/acquisition/setup is required to replace the earlier one. This is calculated as the ratio of **Lifetime Capacity** and the **Average Annual Use**.

TAM/ Total Addressable Market – represents the total potential market of functional demand provided by the technologies and practices under investigation, adjusting for estimated economic and population growth. For this solutions sector, it represents world and regional total addressable markets for electricity generation technologies in which the solutions are considered.

Total Emissions Reduction – the sum of grid, fuel, indirect, and other direct emissions reductions over the analysis period. The emissions reduction of each of these is the difference between the emissions that would have resulted in the **REF Scenario** (from both solution and conventional) and the emissions that would result in the **PDS Scenario**. These may also be considered as “emissions avoided” as they may have occurred in the REF Scenario, but not in the PDS Scenario.

Transition solutions are considered till better technologies and less impactful are more cost effective and mature.

TWh/ Terawatt-hour – A unit of energy equal to 1 billion kilowatt-hours

Well-to-wheel/WTW– A modified life cycle energy pathway representing the path of energy from the well, where hydrocarbons are extracted (crude oil), through processing, to distribution (stations), to vehicle tanks and then finally to combustion in engines to power wheel movement. WTW Analysis = WTT (well-to-tank) analysis + TTW (tank-to-wheel) analysis. This type of analysis excludes emissions and energy for the processing facilities, building vehicles or end of life processing. Note that this term is also used when describing alternative fuel vehicles such as electric cars in order to allow balanced comparison of efficiencies.