

TECHNICAL ASSESSMENT FOR ELECTRIC BICYCLES (E-BIKES)

SECTOR: TRANSPORTATION

AGENCY LEVEL: INDIVIDUAL

KEYWORDS: CYCLING, BATTERY TECHNOLOGY, PEDELECS

VERSION 2 (JULY 2021)

Copyright info

© 2022 by Project Drawdown

Suggested citation

Allard, R., Jones, H., Chen, W., Covis, L., & Frischmann C.J (2022). Electric Bicycles. Project Drawdown

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

DRAWDOWN

27 GATE 5 RD., SAUSALITO, CA 94965

info@drawdown.org

www.drawdown.org

TABLE OF CONTENTS

List of Figures	IV
List of Tables.....	IV
Acronyms and Symbols Used	V
Executive Summary.....	VII
1 Literature Review	8
1.1 State of electric bikes.....	8
1.1.1 E-Bike Design and Aesthetics.....	9
1.1.2 Throttle vs. Pedal Assist.....	11
1.1.3 E-bike definition and regulations.....	11
1.1.4 Battery type	13
1.1.5 Electric Bicycles and Climate Change.....	17
1.2 Adoption Path	18
1.2.1 Current Adoption.....	19
1.2.2 Trends to Accelerate Adoption.....	20
1.2.3 Barriers to Adoption	22
1.2.4 Adoption Potential.....	23
1.3 Advantages and disadvantages of E-Bikes	24
1.3.1 Similar Solutions	24
1.3.2 Arguments for Adoption	24
1.3.3 Additional Benefits and Burdens.....	25
2 Methodology.....	25
2.1 Introduction.....	25
2.2 Data Sources	27
2.2.1 Total addressable Market	27
2.2.2 Adoption Projections	27

2.2.3	Inputs	27
2.2.3.1	Financial Variables	27
2.2.3.2	Emissions Reduction Variables	28
2.2.3.3	Additional Variables	28
2.3	Total Addressable Market / TAM	29
2.4	Adoption Scenarios	29
2.4.1	Reference Case / Current Adoption	30
2.4.2	Project Drawdown Scenarios	30
2.5	Inputs	30
2.5.1	Climate Inputs	30
2.5.2	Financial Inputs	32
2.5.3	Technical Inputs	34
2.6	Assumptions	36
2.7	Integration	36
2.8	Limitations/Further Development	37
3	Results	38
3.1	Adoption	38
3.2	Climate Impacts	39
3.3	Financial Impacts	41
4	Discussion	42
4.1	Limitations	43
4.2	Benchmarks	43
4.3	Summary	44
5	References	45
6	Glossary	55

LIST OF FIGURES

Figure 1.1 The original e-bike schematic from Ogden’s patent. The fundamental design of e-bikes has changed little since 1895, featuring the same three components: bicycle frame, battery pack, electric motor in bottom bracket or wheel hub.....	9
Figure 1.2 Mode substitution by electric bikes across studies. From (Bigazzi & Wong, 2020)	23
Figure 3-1 World Annual Adoption 2020-2050.....	39
Figure 3.2 World Annual Greenhouse Gas Emissions Reduction	40
Figure 3.3 Operating Costs Over Time.....	42

LIST OF TABLES

Table 1 E-bike Regulations around the World (Fishman & Cherry, 2015; Sun, 2020).....	12
Table 1.2 Comparison of SLA and LIB batteries from (Wenqiu Liu et al., 2021; Sun, 2020)	15
Table 1.3 Current Global Modal Share and Adoption of E-bike in billion PKM.....	20
Table 1.4 Current Global E-bike use by region.....	20
Table 1.5 Urban Passenger Mode Comparison	25
Table 2.1 Global and Regional TAM, in billion PKM	29
Table 2.1 Climate Inputs.....	31
Table 2.2 Financial Inputs for Conventional Technologies	33
Table 2.3 Financial Inputs for Solution	33
Table 2.4 Technical Inputs Conventional Technologies.....	34
Table 2.5 Technical Inputs Solution.....	34
Table 2.7 Technical Inputs Solution.....	35
Table 3.1 World Adoption of the Solution.....	38
Table 3.2 Climate Impacts	39
Table 3.3 Impacts on Atmospheric Concentrations of CO ₂ -eq	40
Table 3.4 Financial Impacts	41
Table 4.1 Benchmarks	44

ACRONYMS AND SYMBOLS USED

- **Ah**– Amp-hour
- **BC** – indicates battery cycles,
- **BCA** – indicates e-bike battery capacity,
- **BTS** – Bureau of Transportation Statistics
- **CAGR** – Compund Annual Growth Rate
- **CO₂/CO₂/CO₂e/ CO₂e** – Carbon Dioxide/ Carbon Dioxide Equivalent
- **E-bikes** – Electric bicycles
- **EPAC** The Electrically Power Assisted Cycles (
- **EV** – Electric Vehicle
- **EVs** – Electric Vehicles
- **GHG** – Greenhouse gas
- **GHG** –Greenhouse gas
- **Gt** – Gigatons
- **ICCT** – International Council on Clean Transportation
- **ICE** – Internal Combustion Engine
- **IEA** – International Energy Agency
- **IPCC** – Intergovernmental Panel on Climate Change
- **ITDP** – The Institute for Transportation and Development Policy
- **ITF** – Internaitonal Transportation Forum
- **Kg** – Kilogram
- **km**– Kilometer
- **kWh** – Kilo-Watt-hour
- **MWh**– Megawatt Hours of Installed Battery equivalent
- **OECD** – Organisation for Economic Co-operation and Development
- **PDS** – Project Drawdown Scenario
- **PKM** – Passenger-kilometer
- **R** – indicates riders per e-bike,
- **REF** – Reference (Scenario, of Project Drawdown)
- **RRS**-Reduction and Replacement Solutions
- **SLA** – Sealed Lead Acid
- **TAM** – Total Addressable Market

- ***UCD*** – University of California at Davis
- ***UK*** – United Kingdom
- ***V*** – volts
- ***Wh*** – Watt-hour
- ***WR*** – indicates battery work rate
- ***ZEZ*** – Zero Emission Zones

EXECUTIVE SUMMARY

Electric bicycles (e-bikes) offer many of the same benefits as traditional bicycles, especially ease and versatility of mobility for urban commuters, but e-bikes have benefits that conventional bikes cannot match. By making it possible to traverse steep hills or cover long distances with little effort, e-bikes make it possible for elderly or physically disabled people to make active, low-carbon transportation choices. These benefits however are not free. E-bikes cost more than traditional bikes and their users must be conscious about how they dispose of expired batteries. E-bike battery manufacturing and charging also lead to higher carbon dioxide emissions than traditional bikes.

The Reduction and Replacement Solutions (RRS) model was used to evaluate the impacts of increased e-bike usage around the world from 2014 to 2060 with primary results being reported here for the period 2020-2050. The current adoption of e-bikes was found to be about 1% of the total addressable market globally with higher adoption rates in Asia.

Projections of rapidly increasing e-bike sales from market and policy research firms are coupled with transportation scholarship to estimate growth in actual passenger-kilometers travelled. This number is then compared to the travel that would have happened in the absence of e-bikes—much of this coming from automobiles, public transportation, and traditional bikes. The net cost and carbon emissions are calculated based on current mode share splits and how those splits may shift in the next thirty years.

The model is based on five main sources for e-bike statistics: International Transportation Forum Transport Outlook, Guidehouse Research's Global Electric Bike Market report, the Institute for Transportation and Development Policy's Global High-Shift Cycling scenario, a peer reviewed paper from Transportation Research, and Navigant Research's Market Report. Based on these sources, current adoption is estimated to be 289 billion passenger-kilometers (PKM) of electric bicycling around the world, with the great majority of those PKM coming from China. The model then projects e-bike PKM to increase to over 1663 billion PKM by 2050, approximately 3.3% of the total estimated market for urban PKM. This growth will be driven by adoption in the Latin America and Middle East and Africa regions. .

The results of the analysis show that e-bikes represent a net financial benefit for the individuals who purchase them, as well as a net greenhouse gas (GHG) benefit for the globe. Given the projections described above and the emissions factors of different travel modes, e-bikes could prevent the release of 1.54 cumulative gigatons of carbon dioxide-equivalents and save consumers \$1207 billion in savings over the lifetime of the purchased e-bikes. Significant factors in these calculations are the carbon intensity and price of electric bikes. As these e-bikes become less expensive, the benefits from e-bikes will grow. However, a large increase in the use of lithium-ion batteries in e-bikes will necessitate large-scale production and battery recycling methods.

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, 2018)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, 2018). 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 BIKES

E-bikes are the most common and fastest-selling alternative-fuel vehicles on the planet (A. J. Hawkins, 2019). This solution report will focus on the role, impact, and viability of e-bikes on meeting global travel needs while reducing greenhouse gas (GHG) emissions and lowering expenses for individuals. Because e-bikes use energy from batteries, they are more expensive than traditional bicycles and do not reduce GHG emissions to the same extent. This report will explore and quantify the pollution reductions and financial savings associated with replacing automobiles, motorcycles, public transportation, and walking and bicycling with e-bikes.

Traditional bicycles are a well-known form of transportation around the world. As a non-emitting form of transportation, they have a high potential impact on climate change. The effects of increased bicycling are explored in another Drawdown solution report.

E-bikes work on the same basic principle as traditional bicycles: a crank turns a chain, turning a wheel. E-bikes differ in that they feature a battery pack and an electric motor that can help turn the crank or wheel

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

(depending on where the motor is mounted). This report does not consider scooters or e-mopeds, and focuses on e-bikes that have foot pedals to propel the bicycle when the motor is not engaged.

The first e-bike patent was filed in the United States in 1895, shortly after introducing the “safety bike” design (United States Patent No. US552271A, 1895). Since then, e-bikes’ fundamental design has changed little, but recently costs have begun to fall, and ancillary design features have multiplied. With motorized assistance, e-bikes can travel faster, farther, and across more varied topography than traditional bikes, making them an appealing travel mode choice for people with disabilities or difficult commutes. Researchers have found that access to e-bikes can extend the physical activity years of seniors and have shown that e-bike riders enjoy many of the physiological benefits of traditional bicycling (Johnson & Rose, 2015).

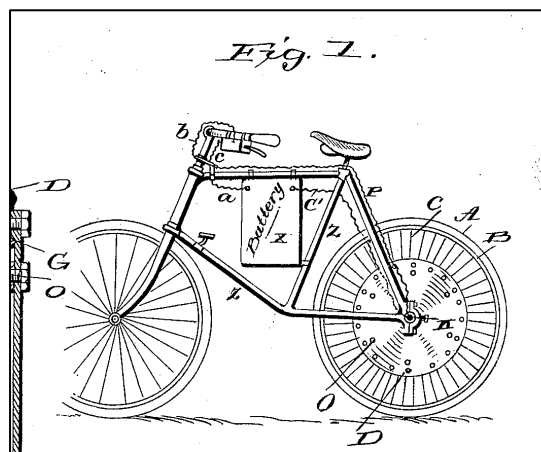


Figure 1.1 The original e-bike schematic from Ogden’s patent. The fundamental design of e-bikes has changed little since 1895, featuring the same three components: bicycle frame, battery pack, electric motor in bottom bracket or wheel hub.

1.1.1 E-Bike Design and Aesthetics

E-bikes come in various styles and designs globally, including bicycle-style e-bikes and scooter-style e-bikes (Fishman & Cherry, 2015). The bicycle-style e-bikes look like traditional bicycles with a large hub and attached battery pack (Figure 3a-b). Figure 3a shows the type of e-bikes that are popular in Asia. The Electrically Power Assisted Cycles (EPAC Bicycles) are intermediate bicycles between traditional bicycles and bicycle-style e-bikes (Figure 3b). They are significantly lighter than bicycle-style e-bikes and preferred by some sportsmen. According to the requirements of Japanese and European standards, electric-assisted bicycles do not use throttle handlebars to power the bicycle but require a person to pedal it. The electric motor cannot generate auxiliary power independently, determined by the pedal action and associated generated signal (Hu & Qiu, 2019).

The scooter-style e-bikes could also be divided into electric mopeds (Figure 3c) and electric motorcycles (Figure 3d). Electric mopeds look like motorized scooters with pedals (or without pedals for some models) with a limited speed of less than 50km/hour and still look like futuristic motorcycles. Electric motorcycles are special e-bikes popular in China and Southeast Asia without pedals and speed up to over 50km/hour (Fishman & Cherry, 2015; Sun, 2020). Although scooter-style e-bikes are popular in China, they were prohibited and regulated like traditional bikes with the new national standard.



Figure 1.1 Two styles of electric bikes, bicycle-style e-bikes and scooter-style e-bikes (Sohu, 2019; Yong & Guan, 2020).

The design features sometimes provide additional functionality, such as electronic screens that show power readings or electric mountain bikes with advanced suspension systems. Another style element of e-bikes has to do with the placement of the motor and battery pack. The battery, the heaviest part of the bike, can be mounted in the frame or above the rear wheel. The motor is often mounted in the frame's bottom bracket (near the crank) or in one of the wheel hubs. Consumers can also purchase and install modular e-bike conversion kits with a motor and battery pack installed inside the front or rear wheel which are not included in this report. These design elements affect the bicycle's weight distribution but mostly have an aesthetic rather than functional effect.

1.1.2 Throttle vs. Pedal Assist

In addition to aesthetic styles, e-bikes come with a variety of functionalities. The biggest functional distinction among e-bikes is whether they have full-throttle power or only pedal-assist power. Full throttle power allows the rider to turn a throttle or push a button on the handlebars, and the electric motor will move the bike without the rider pedaling. If the rider chooses to pedal, the bicycle will move faster. Pedal-assist e-bikes (or EPAC Bicycles) differ in that the motor engages only when the rider turns the pedals (Hu & Qiu, 2019). In most cases, the rider can choose the amount of assistance that the motor provides the pedals, and in this way, climbing hills or covering long distances becomes much easier. Most scooter-style e-bikes operate on-throttle power and, in many cases, function like low-power electric scooters rather than bicycles.

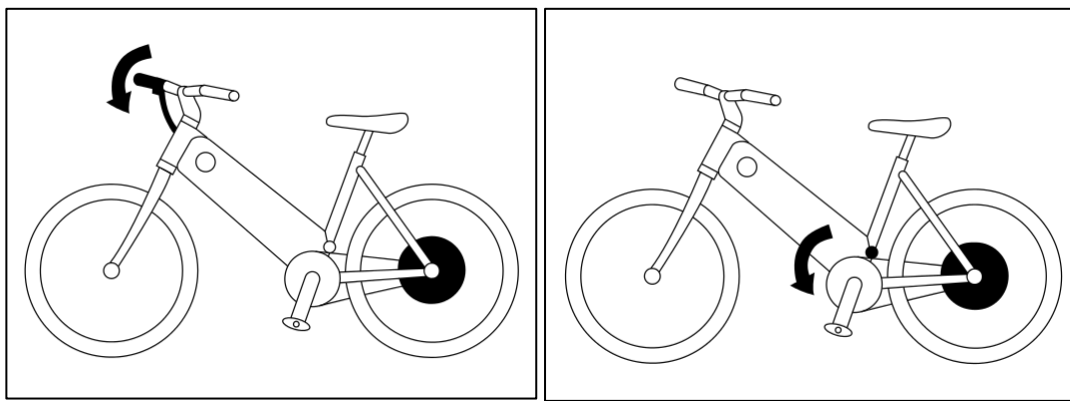


Figure 1.2 Throttle Power and Pedal Assist E-bike Diagrams. https://en.wikipedia.org/wiki/Electric_bicycle#/media/File:E-Bike.svg

1.1.3 E-bike definition and regulations

E-bikes have become popular in Asia since 2000, and then in Europe and America recently, governments are in the early stages of determining how to regulate them (Fishman & Cherry, 2015) because of the various forms and functions of e-bikes. E-bikes could be the simple motor attachments on conventional bikes or the models that can achieve 80 kilometers per hour.

For this report, an e-bike is defined as a two-wheeled vehicle that can be propelled by human power through a pedal and crank system and with an electric motor and battery (Figure 3a-b). Electric mopeds and electric motorcycles are not included in this report. Some jurisdictions, including some large cities in China, have banned many e-bike models (especially electric motorcycles) for safety reasons under new national standards in 2019 (C. Cherry & Cervero, 2007; Sun, 2020). The new national standard for e-bikes in China clearly states the limitation of the maximum speed (25km/h), maximum weight (55kg), maximum motor capacity (400W), and pedals. Under the new national standard regulations, most previous e-bikes models

in China were banned and will be gradually replaced, which will result in an increasing trend of e-bikes sales in China (Sun, 2020).

Policies that regulate e-bikes will also need to adapt to changing technology to avoid restraining the market. In the late 1990s, Chinese officials subsidized e-bikes to limit gasoline-powered scooters and motorcycles. This strategy worked, as evidenced by the rapid rise in e-bike purchases, but a similar strategy in Taiwan did not lead to a similar rise in e-bike adoption (Yang, 2010). Nevertheless, e-bikes' future in China is still uncertain due to various local government attitudes, policies, and unaddressed safety problems (Gu, Kim, & Currie, 2020).

A more sustainable and globally applicable policy strategy would enforce standards that would reduce consumers' and producers' guesswork about what an e-bike is and where and when it is allowed. As mentioned, some jurisdictions in China have banned e-bikes out of safety concerns. Globally, e-bikes are treated differently everywhere, limiting the ability of manufacturers to sell their goods widely. E-bike sales would benefit from standardized regulations dealing with the definitions of e-bikes, motor power limitations, weight limits, and functionality. The table below illustrates the diversity of rules that govern what an e-bike is and what it is allowed to do.

Table 1 E-bike Regulations around the World (Fishman & Cherry, 2015; Sun, 2020)

Country	Power Limit	Throttle Power Allowed?	Pedal Assist Allowed?	Maximum Speed under Power Assistance	Other Conditions and Comments
USA	750 W	Yes	Yes	32 kph	Operable pedals required
Canada	500 W	Yes	Yes	32 kph	Power assistance only above 3 kph
EU	250 W	No	Yes	25 kph	Power assistance only when pedaling
EU	250-1000W	Yes	Yes	25kph	Power required but generally throttle powered
Japan	250 W	No	Yes	24 kph	Max assistance at 15 kph declining to zero above 24 kph
China	400W	Yes	Yes	25 kph	The weight of whole e-bike is less than 55kg and battery voltage is less than 48V

Country	Power Limit	Throttle Power Allowed?	Pedal Assist Allowed?	Maximum Speed under Power Assistance	Other Conditions and Comments
Australia	200-250 W	Yes	Yes	Not specified	Operable pedals required. Power (electric or IC) must be auxiliary, not the main source of power

In addition to the e-bikes themselves, regulatory structures will need to be applied to battery recycling. As discussed, Lithium-ion battery recycling is a nascent practice, which means that the companies involved are likely trying different strategies to be profitable. These companies would welcome clear standards to ensure that they do not lock-in practices that will later be banned. An example of what could happen if regulations are not specified and enforced in China, where authorities found Sealed Lead Acid (SLA) batteries recyclers operating under dangerous conditions and subsequently closed almost all legally authorized facilities (Fu, 2013) Putting in place clear rules and oversight procedures would ensure that recycling companies have the capacity to process the potentially large number of expired Li-ion batteries that e-bikes will produce in the coming decades.

1.1.4 Battery type

The range that e-bike batteries can assist or drive bicycles is usually expressed in Watt-hours (Wh). However, most batteries do not list their Wh capacity. Instead, this can be determined by multiplying the displayed number of volts (V) by the number of amp-hours (Ah). For example, a 12V battery with 10 Ah would yield 120 Wh of energy. This corresponds to roughly 10 kilometers (km) of assistance in most cases.

$$V \times Ah = Wh$$

For the purposes of analyzing the greenhouse gas (GHG) emissions impact of e-bikes, the most important distinction is the battery chemistry that powers the motor. There are two main types of battery chemistry: Sealed Lead Acid (SLA) and Lithium-ion. Nickel Metal Hydride batteries are also used in some e-bikes but have a tiny market share. This report assumes that Nickel Metal Hydride batteries are similar to lithium-ion and does not specify them. There are also several types of Lithium-ion battery chemistries with slightly different usage characteristics. However, the differences between all Lithium batteries are small enough to be considered as one type of Lithium-ion batteries in this report.

Globally Lithium-ion batteries have the largest share of the market today (Fortune Business Insights, 2020; Markets and Markets, 2020). In China, the largest growing market for e-bikes, the Lithium-ion battery

market share is different. SLA batteries had over 90% of the market before 2017 due to Lithium-ion battery technology limitations and a much lower price. Although the Lithium-ion batteries' market increases recently with lithium-ion battery technology development and decreasing Lithium-ion battery price, its share was still only 16% of China's e-bike market in 2019. The market share of Lithium-ion batteries is relatively lower than SLA worldwide. China accounts the biggest e-bike market share and most consumers are sensitive to the e-bike price. The SLA battery and Lithium-ion battery price was 500 CNY/kWh and 1600 CNY/kWh in 2017, but the price decreased to 400CNY/kWh and 700CNY/kWh in 2019, respectively. These price changes along with further technology development will propel Lithium-ion batteries to dominate the Chinese battery market in the future (Foresight Industrial Research Institute, 2020; Sun, 2020). The diffusion of more Li-on batteries will improve +-- energy efficiency due to the better charge-discharge efficiency than SLA batteries. SLA batteries for e-bikes have a charge-discharge efficiency of approximately 82.5%, while Li-on batteries are a bit higher ranging from 85% to 95% (Wenqiu Liu, Liu, Liu, & Cui, 2021).

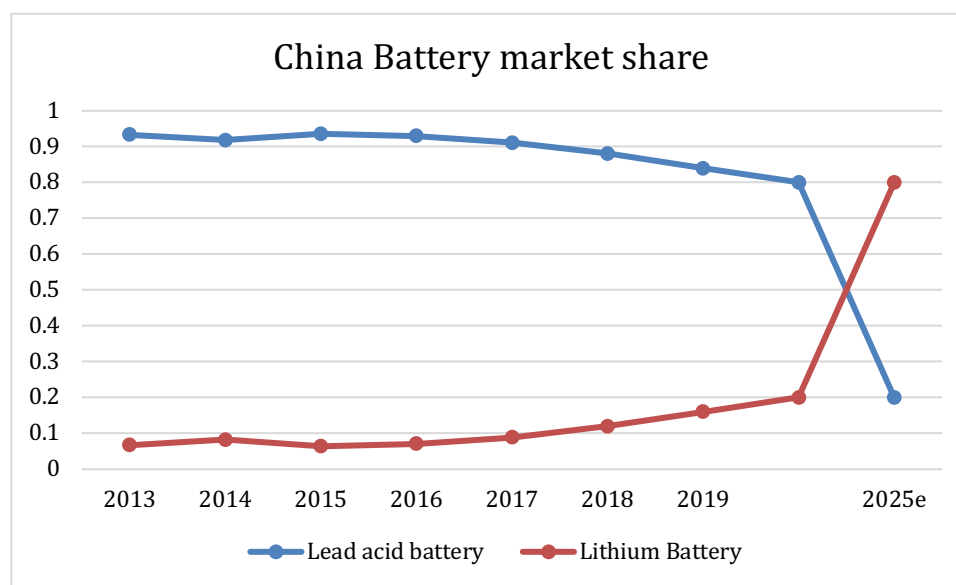


Figure 1.3 E-bike battery market share China (Foresight Industrial Research Institute, 2020; Sun, 2020)

1.1.4.1 Sealed Lead Acid Batteries

Historically, the most common type of battery used in electric bikes worldwide was SLA battery; however, they will be gradually be abandoned by the market because of governments' stringent norms for Lithium-ion batteries. SLA batteries represented roughly 91% of the batteries in e-bikes in China before 2017. SLA batteries have an energy density of about 28-40 Wh per kilogram (kg), which is smaller than Li-on batteries. The average battery capacity is 458 Wh per e-bike, which means the average SLA battery weight is 11-16kg per e-bike. In theory, the cycle life of SLA batteries is around 500 cycles, but, in reality, SLA batteries

cycle life is only 350 cycle, when there are only 80% of the depth of discharge (Wenqiu Liu et al., 2021). SLA batteries have one advantage: they lose relatively little of their charge when not in use (about 40% of their charge after one year). Other battery types may lose this much of their charge after a few weeks or months of no use.

The booming e-bikes in China also led to the fast development of the SLA batteries industry and to enormous environmental problems due to heavy metal pollution (Wei Liu, Chen, & Tian, 2016). Strict regulation was implemented and helped accelerate the clean production of SLA batteries. Now, the SLA battery industry utilizes the cadmium-free technology (Ministry of Industry and Information Technology of the People's Republic of China, 2012) to make SLA batteries at the lowest toxic potential (Wenqiu Liu et al., 2021). In spite of these new standards, serious environmental problems (like lead released into ground water) were being caused by chemical releases from SLA batteries and new government regulation was implemented in 2019 to start shifting over to Lithium-ion batteries (Fortune Business Insights, 2020; Markets and Markets, 2020).

SLA batteries are highly recyclable because their metal and chemical components can be relatively easily separated, rehabilitated, and sold for a profitable price to make new batteries. Because of the high recyclability, most SLA batteries around the world are recycled rather than sent to landfills where they would cause environmental damage. SLA recycling rates have been found to be nearly 100% in the USA (Recycling Today, 2017)

Table 1.2 Comparison of SLA and LIB batteries from (Wenqiu Liu et al., 2021; Sun, 2020)

Characteristics	SLA battery	Lithium-ion battery
Energy intensity	28-40wh/kg	120-180wh/kg
Safety	High	Relatively low
Distance per charge	Low	Medium
Technology maturity	High	Low
Lifetime	1-1.5 years	4-5 years
Theoretical charge cycle	500 cycles	1000-2000 cycles
Capability	Low	High
Fast charging technology	Support	Not support

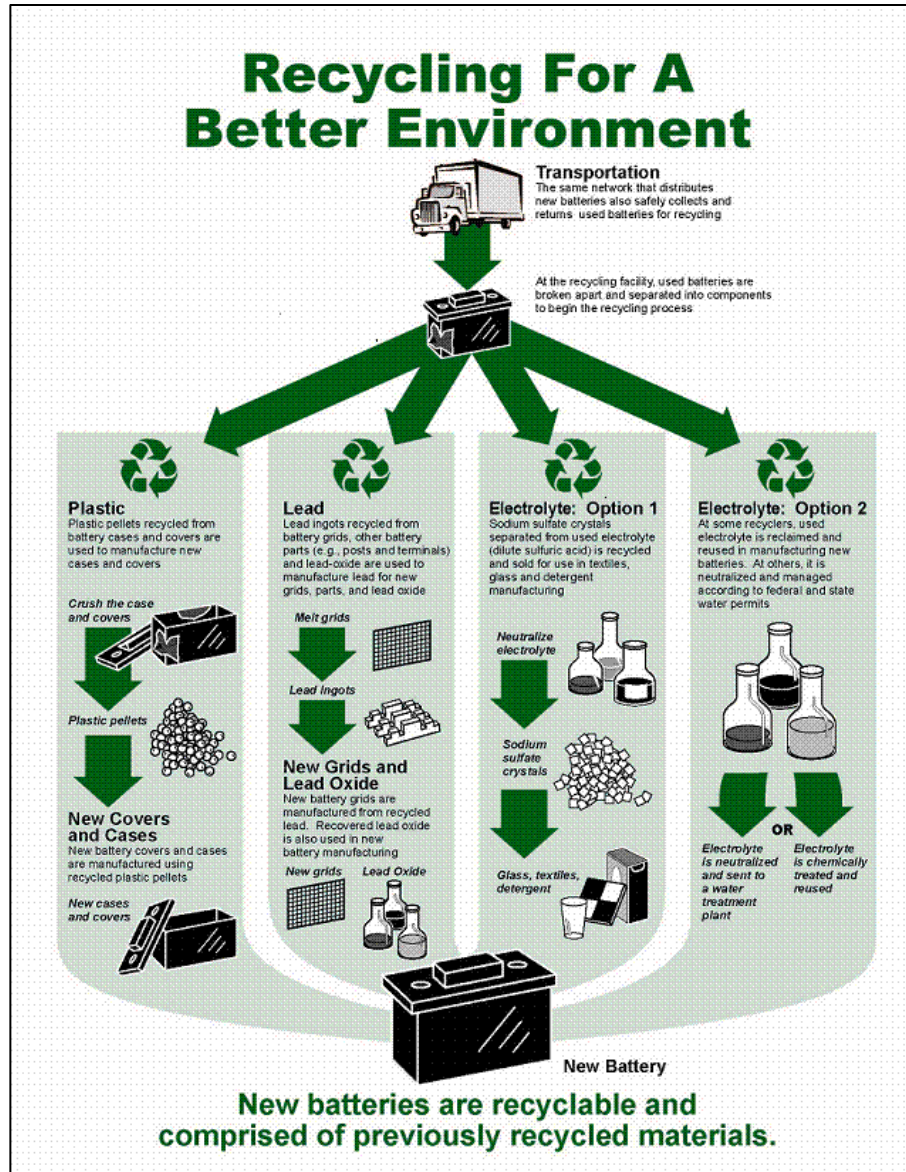


Figure 1.4 The SLA recycling process.(Battery Council International, 2014)

1.1.4.2 Lithium-ion Batteries

In Europe and the United States, the world's second and fourth-largest bicycle markets, SLA batteries are uncommon and Lithium-ion batteries are the prevalent battery type (Markets and Markets, 2020; Guidehouse, 2020; Fortune Business Insights, 2020). There are several types of Lithium-ion chemistry batteries, but their effects on this analysis are negligible. Batteries with other chemistry types, such as nickel-cadmium, are also similar enough and represent a small enough market that they will be considered in the same categories as Lithium-ion batteries.

Lithium-ion batteries have an energy density of 120-180 Wh per kg, much higher than SLA batteries. With an average capacity of 458 Wh, Lithium-ion batteries' weight is only 22-23% of the SLA batteries for the same energy storage. Moreover, Lithium-ion batteries can be recharged several hundred times (up to 2,000 in some circumstances), meaning that they last longer and provide many more passenger kilometers (PKM) of assistance.

Lithium-ion batteries have higher energy intensity than SLA batteries, and they used to cost significantly more as well, but the gap is narrowing. In China, the cost of SLA batteries was about \$0.8/Wh and Lithium-ion batteries cost \$244/kWh on average in 2017. In contrast, the price of SLA batteries and Lithium-ion batteries declined to \$61/kWh and \$107/kWh in 2019 (Sun, 2020). Now Lithium-ion batteries cost is only 1.8 times the cost of SLA batteries, but it can provide upwards of 4 times the lifetime PKM. Globally, the average price of Lithium battery pack including cell and the pack decreases by 85% within nine years (from 2010-2018) and will continue to fall to \$62/kWh by 2030 based on the estimation of BloombergNEF (Rapier, 2019).

Lithium-ion batteries' recyclability depends on the demand for the batteries' raw components and the simplicity of the process for separating those components. The current recycling rate of lithium-ion batteries varies in different regions. In some industry reports, the recycling rate is approximately 30%, while in the European Union and Japan, the recycling rate of Lithium-ion batteries reaches 45% and 80%, respectively (Wenqiu Liu et al., 2021). To date, most Lithium-ion companies are located in Asia, where they play a significant role in manufacturing batteries. It should be noticed that more startups in North America and Europe startup join the game and gradually make more efforts to make such labor-intensive and dirty recycling processes more high-efficient, automate, and streamline (Jean, 2021). This will further increase the recycling rate in the future.

1.1.5 Electric Bicycles and Climate Change

Traditional bikes reduce GHG emissions by replacing motorized transport with non-motorized and therefore non-emitting transport. Although e-bikes consume more materials and energy than traditional bikes, the associated direct and indirect carbon impact is still far smaller than cars. Studies show that e-bikes could substitute public transport (33%), traditional bicycle (27%), car (24%), and walking (10%), respectively (Bigazzi & Wong, 2020).

The potential climate change depends on reducing PKM from transport modes with more energy or carbon impacts. E-bikes consume electricity as partial power to provide passenger-kilometer service, but the carbon

emissions per MJ power are much lower than internal combustion vehicles due to the lower energy efficiency. Even compared with electric cars, e-bikes are also more efficient and only require approximately 10% of their electricity per vehicle kilometers (Cherry et al., 2016). Therefore, e-bikes use cleaner and less fuel than private and public motorized transportation. However, e-bikes also displace PKM from traditional bikes and walking, which require no fuel. The more e-bikes draw from these transport modes, the lower their net GHG impact will be.

1.2 ADOPTION PATH

E-bikes have gradually become popular globally, especially in China and Europe because of the lower price than cars and motorcycles, low dependence on fossil fuels, and low electricity consumption (C. R. Cherry et al., 2016; Fishman & Cherry, 2015). Compared with electric cars, e-bikes play a big role in providing passenger demand due to the large stock worldwide. There are approximately 350 million electric two/three-wheelers, and most of them are in China (*Global EV Outlook 2020*, 2020).

Figure 1.5 shows the global and regional e-bike market size from 2011 to 2019. The global e-bike sales worldwide remained fairly steady at approximately 34 million units annually from 2011 to 2019 (Fishman & Cherry, 2015; Sun, 2020). During this period, China played the biggest role in the global e-bike market even though its share decreased from 94% in 2011 to 85% in 2019 because of the localized bans on e-bikes in some cities and increasing use in other countries. The EU is the second largest market for e-bikes with an increasing market share that rose to 7% in 2019. Sequentially, the market share in Japan and the U.S. increased in recent years but only accounted for 2% and 1%, respectively. The e-bike is still not a common mode of transport in the U.S. (Fyhri, Heinen, Fearnley, & Sundfør, 2017). It should be noted that the reason for the most significant share in China is mainly due to the definition of e-bikes. In China, e-bikes include e-bikes, electric mopeds, and electric motorcycles.

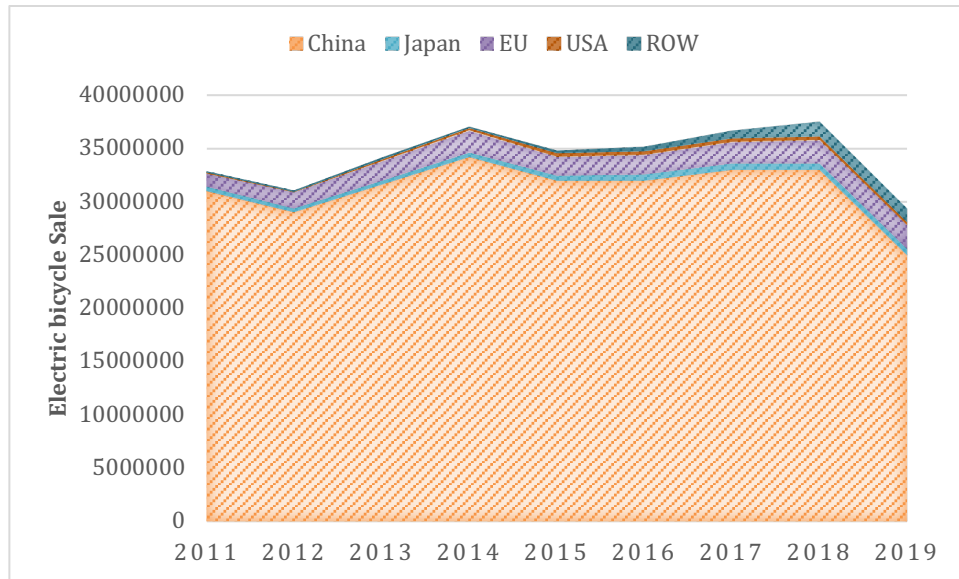


Figure 1.5 The global market size from 2011 to 2019.

1.2.1 Current Adoption

The current modal share of e-bikes is determined based on the percentage of urban PKM done using e-bikes. Adoption projections are gathered from as many credible sources as possible. Sources include highly renowned and respected institutions, a university that specializes in transportation and a commercial market research firm (Guidehouse, 2020; Navigant Research, 2016; OECD/ITF, 2021; UC Davis, Fulton, & Mason, 2015). The current adoption of e-bikes is estimated by calculating the average based on these sources. Current modal share can be seen in Table 1.3. Table 1.4 shows e-bike use by region based on ITF (OECD/ITF, 2021).

The International Transport Forum (ITF) reports mode share of urban passenger transport in its Outlook report that it publishes every other year. The ITF reports urban passenger mode share for private bikes and shared bikes. The other data sources were used to estimate the shares belonging to e-bikes and traditional bikes. The ITF also provides mode share in three different scenarios. Active modes are expected to increase in all scenarios (OECD/ITF, 2021). The ITF e-bike mode share based on its urban passenger travel demand was substantially lower than all of the other sources. Given that its data comes directly from the governments of its member countries it is considered a trusted source.

The Institute for Transportation and Development Policy (ITDP), in cooperation with the University of California, Davis, produced a comprehensive global estimate of transportation mode shares and PKM through 2050. In ITDP's estimate of a high-shift to sustainable transportation, e-bikes quickly become a

significant portion of urban PKM travelled, ITDP uses global e-bike sales figures average person-KM travel rates to reach their conclusion (UC Davis et al., 2015).

Guidehouse Insights, a global market analysis firm, provides estimates of e-bike sales to 2030. They predict that sales of e-bikes will rise by a 1.7% compound annual growth rate (CAGR) from 2020 to 2030. This means 37.5 million e-bikes were sold in 2020 and 44.4 million will be sold in 2030 for a total of 200 million from 2020 to 2025 and 450 million from 2020 to 2030. The growth in sales will come from the United States, countries in Western Europe and Australia, India, Japan, New Zealand, Singapore, Vietnam in Asia (Guidehouse, 2020).

Navigant Research, a global market analysis firm, provides estimates of e-bike sales to 2025. Navigant estimates that Lithium-ion battery technology advancement will lead to strong sales in Europe and the United States, even as SLA battery e-bike sales in China would decline. Specifically, Navigant predicts that China's market share will shrink from 95% to 88% of global e-bike sales by 2025. E-bike sales are set to increase from 35 million to 57 million units globally in that time (Navigant Research, 2016).

Table 1.3 Current Global Modal Share and Adoption of E-bike in billion PKM

	Percent (%)	Billion PKM
Current Adoption	0.96%	288.5

Table 1.4 Current Global E-bike use by region

Region	Percent (%)
OECD 90	18.2%
Eastern Europe	1.9%
Asia (Sans Japan)	59.9%
Middle East and Africa	6.6%
Latin America	13.3%
Total	100%

1.2.2 Trends to Accelerate Adoption

1.2.2.1 Battery

There has been a trend toward the use of Lithium-ion batteries in e-bikes. The price of these batteries has decreased substantially making e-bikes more affordable with the added benefits of higher battery power

density translating into having a longer range (reducing range anxiety) and being lighter, cheaper and having a better life cycle. They also perform better in extreme weather conditions improving usability in some geographical markets.

1.2.2.2 Demographics

There is a trend toward urbanization which increases the commuter population which in turn increases congestion. Modes such as e-bikes that can avoid congestion are increasing in popularity, and could potentially help people shift from driving and public transport to cycling, which would also result in congestion reduction (Bakker, 2018)

The aging population in many parts of the world are looking for alternatives to walking and conventional cycling due to health reasons and cars due to environmental reasons but still want health and environmental benefits. E-bikes are an increasingly popular option for the aging population.

The recent trend of telecommuting or work-from-home is lowering need for car use for commuting and there is a trend towards using e-bikes for errands such as grocery shopping and for transporting children.

1.2.2.3 Environment

E-bikes could potentially help people shift from driving and public transport to cycling because they are flexible and fast – which would reduce congestion (Bakker, 2018) and increase carbon emission savings (C. R. Cherry et al., 2016)(McQueen, MacArthur, & Cherry, 2020). The environmental impact of e-bikes (both indirect emissions and direct emission) is much lower than internal combustion engine cars (even electric cars) that provide the same service. The carbon intensity gaps between e-bikes and other motorized modes, and replacing PKM will bring more carbon benefits, which will encourage more people implement e-bikes.

1.2.2.4 Health and Physical Fitness

As there is a move towards being more active and healthy. Compared with conventional bikes, electric bikes make it easier to bike farther, faster, and across more challenging terrain. E-bikes ease the stress on the body and make it possible for people with physical limitations, especially for older people, to use bikes. Therefore, e-bikes implementation would increase the cycling rate, and thus, contribute to additional health benefits for society (Bigazzi & Wong, 2020; Fyhri et al., 2017). Studies show that people who regularly commuted on e-bikes had improved health outcomes compared to inactive commuting options (e.g., driving a car). Although these study subjects did not see a cardio-vascular efficiency improvement, they significantly increased muscle strength. This study suggests that many of the benefits of physical activity can accrue to e-bike users despite having assistance from an electric motor (de Geus, Kempenaers, Lataire, & Meeusen, 2013).

1.2.2.5 Policies and Regulations

Many cities are introducing regulations requiring Zero emission vehicles and making Zero Emission Zones (ZEZ) in city centers. E-bikes are considered Zero emission vehicles so they are allowed in ZEZ and due to their small size can enter roads closed to cars.

Many governments are offering incentive programs through subsidies and grants. The UK, Scotland, Sweden, Paris (ended but likely to reoccur), British Columbia in Canada and California, Vermont (2 programs) and Austin, TX in the US have all introduced incentives.

1.2.2.6 Fleet Decarbonization

As pressure to decarbonize increases, e-bikes will be increasingly used for transporting cargo. Many logistics and delivery companies are looking to decarbonize their fleet, particularly for last-mile deliveries. E-bikes fit this need and cost less to buy and operate than traditional delivery trucks (Bernhard, 2020; Center for Research into Energy Demand Solutions, n.d.; Nocerino, Colorni, Lia, & Luè, 2016).

1.2.3 Barriers to Adoption

1.2.3.1 Economic barriers

Compared with conventional bikes, e-bikes costs are much higher, which will influence the adoption. The market reports estimate that an average e-bike in China costs \$237, while the average e-bike price is \$3,087 and \$2,018 in Europe and the US (Sun, 2020). In addition to the cost of purchase and charging, many consumers will also need to pay a fee to recycle their Lithium-ion batteries as long as the process remains unprofitable. These extra costs of e-bikes and battery recycling may hinder the potential adoption of e-bikes.

1.2.3.2 Safety barriers

E-bike accidents sometimes occur due to higher speeds (Haustein & Møller, 2016). Additionally, sometimes older people are not able to maintain balance because of e-bikes' heavy weight (Van Cauwenberg, de Geus, & Deforche, 2018). These potential safety problems make future development unclear (Gu et al., 2020). The local governments in different cities in China have different attitudes to e-bikes and some cities even banned the e-bike on-road (Sun, 2020). The negative attitude of some local governments may hurt the potential development of e-bikes in China in the future.

1.2.3.3 Other barriers

The implementation of e-bikes results in additional demand for SLA and Lithium-ion batteries and generates several additional problems. Firstly, the Lithium-ion batteries' demand with increasing e-bikes sales will lead to increased demand for critical materials (e.g., Lithium, Cobalt, Manganese etc.). Secondly, the production stage energy consumption and carbon footprint are higher than for conventional bikes

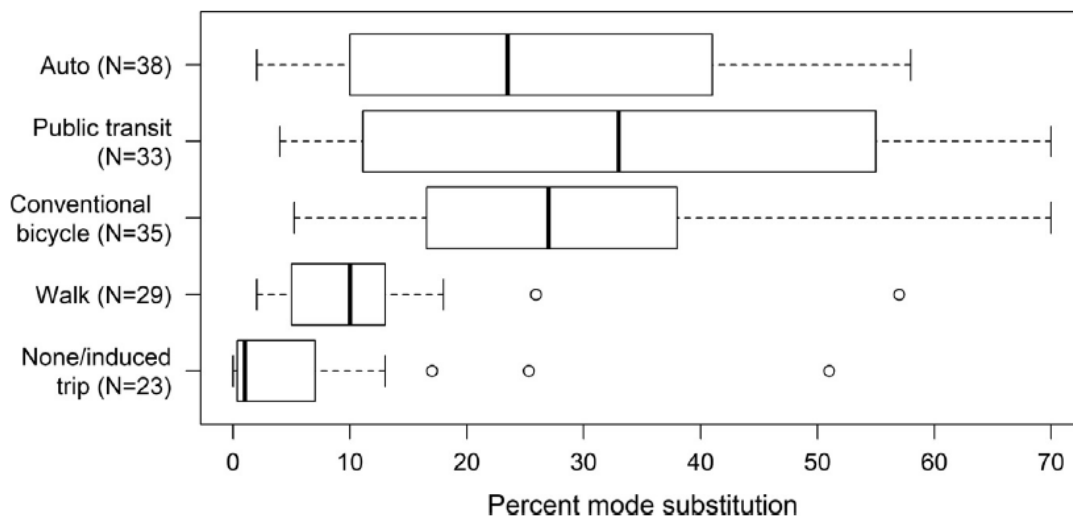
(Mellino et al., 2017). Thirdly, if battery recycling problems are not addressed to ensure proper recycling, e-bike use could contribute to severe environmental problems (Jean, 2021).

1.2.4 Adoption Potential

The adoption potential for e-bikes is high. The increasing availability of shared e-bikes makes the cost comparable to public transit per trip and increases their accessibility. The potential is limited by urban passengers that do not want to use an active mode of transport. However, as passengers are concerned with the close proximity of users of public transit, many individuals are choosing outdoor modes -including e-bikes - as a good substitution. For those urban passengers that steadfastly use only private car, increasing regulations such as ZEZs and decreasing parking spaces will influence their mode choice. E-bikes are not expected to ever overtake public transit or private car by mode share but large gains in adoption can be made.

A recent review paper has a meta-analysis on mode substitution of different transport modes by e-bike based on 24 published research papers (Bigazzi & Wong, 2020). It reveals that the substitution rate by e-bike is public transport (33%), traditional bicycle (27%), automobile (24%), and walking (10%) (as shown in Figure 1) (Bigazzi & Wong, 2020).

Figure 1.2 Mode substitution by electric bikes across studies. From (Bigazzi & Wong, 2020)



1.3 ADVANTAGES AND DISADVANTAGES OF E-BIKES

1.3.1 Similar Solutions

Solutions that are similar to or can replace e-bikes are all other modes that serve the urban passenger market. These modes include car, public transit, conventional bike, walking, e-kick scooters and e-mopeds. All but the last two modes (which are considered motorized 2/3 wheelers) are current Drawdown Solutions (car use encompasses three solutions—electric cars, hybrid cars, and carpooling).

1.3.2 Arguments for Adoption

E-bikes are a good mode choice for urban passenger transit. It is an important component of the mix of mode choices and has the ability to shift use from modes with higher emissions. The solution's advantages and disadvantages are better understood when compared to the other available urban passenger mode choices (note: 2/3 wheelers are not currently Drawdown solutions and will not be evaluated in this assessment).

For example, E-bikes enable some use from riders, such as older, less physically fit or live in a hilly environment, which may not use traditional bicycles (Fyhri et al., 2017; Hoj et al., 2018).

They cost more than conventional bikes and walking, but cost much less than cars. It is difficult to compare the cost of an e-bike to public transit as the e-bike cost must be amortized by PKM over the life of the bike and the cost of public transit is the cost to the user, not the builder or operator. However, the costs per trip are similar and even more so when comparing the cost of shared e-bikes to public transit.

While e-bikes produce more emissions than walking and conventional bikes, they emit significantly less than cars. It is difficult to compare to the composite mode of public transit, however metro is one of the least polluting modes per PKM, and many buses are now electric. Yet, indirect emissions from manufacturing the different vehicles used by each mode should also be taken into account. Generally, E-bikes use about the same materials as conventional bikes, save for the battery which uses critical materials such as lithium, cobalt, and manganese. E-bikes use drastically less materials than cars. When comparing amortized materials per lifetime PKM for e-bikes and public transit (excluding infrastructure) they are in line (ITF/OECD, 2020).

The solution is much faster than a conventional bike and walking. In congestion, which is common in the urban passenger market that is modeled, e-bikes can go as fast or faster than cars. Again, the comparison to public transit is complex depending on whether access and egress times are included and whether the type of public transit is effected by congestion. E-bikes are usually selected over public transit when it is perceived as faster or congestion is a factor (Astegiano, Fermi, & Martino, 2019).

E-bikes require more physical activity than car or public transit. However, the solution requires less physical effort than walking or conventional bike.

The space efficiency of e-bikes, conventional bikes and walking are significantly less than that of cars. Comparing the solution to the public transit composite is complex as a bus can take up the same space as a car but dedicated lanes for buses or trams (or even bikes) take up less space as cars usually have multiple lanes.

1.3.3 Additional Benefits and Burdens

Additional benefits of e-bikes include improvements to health and positive impacts on the local economy as bike users tend to shop in their local community (Arancibia et al., 2019).

Any rebound effects of induced trips is not a burden as the marginal emissions are small and it could contribute to decreasing the emissions over the life cycle depending on use.

Burdens are that the higher speeds of e-bikes can contribute to safety and that batteries must be recycled along with the extraction of critical materials.

Table 1.5 Urban Passenger Mode Comparison

	User Costs	Emissions	Speed	Physical Effort	Congestion	Space Efficiency
E-Bike	Low	Low	High	Medium	Low	Low
Conventional Bike	Low	None	Medium	High	Low	Low
Car	High	High	Medium	Low	High	High
Public Transit	Low	Low	High	Low	Low	Medium
Walking.	Low	None	Low	High	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 functional unit of the analysis is billion PKM and the implementation unit is Megawatt Hours of Installed Battery equivalent (MWh(i)). This implementation unit is chosen because e-bikes have different designs, battery types and sizes and prices; therefore, using MWh(i) better estimates the impact of e-bikes rather than using the number of bicycles or global sales. The agency level is individual meaning that the costs are analyzed from a user perspective (rather than at the e-bike manufacturer for example) because the individual makes the choice of which mode to use and can take into account both costs and emissions of each mode.

The Total Addressable Market (TAM) covers all demand for the function provided by the solution e.g. if the solution focuses on e-bike usage, the TAM is global demand for urban passenger travel including conventional technologies and practices and emerging solutions. Most reports available in the literature exclude non-motorized trips when calculating urban modal share. There are two reasons for this. First the modal share is calculated through PKM, and therefore the smaller trip distance of a non-motorized trip results to a much smaller share. Second, non-motorized trips are much harder to record and predict. The TAM has been increased to account for the non-motorized PKM.

The Project Drawdown Scenario, (PDS), shows a slow increase of the modal share of e-bikes in urban environments as the total number of PKM slowly grows. The increased number of e-bike PKM will come from some newly generated trips, but mostly from mode switch mainly from car, conventional bike and public transit.

The conventional technology in this model is defined as all modes used for urban passenger travel, more specifically Cars (ICE and others proportionally), Motorized 2/3 Wheelers, Public Transit, traditional Biking and Walking. Since hybrid, electric, or other engine vehicles sum up to only a few percent of the global car fleet, they will not be considered in this approach.

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.

2.2 DATA SOURCES

Data from multiple sources were compiled to construct this model, with an emphasis on recent, credible, and peer-reviewed methodology. The data sources used for the model have been divided in three main sections: Total Addressable Market (TAM), Adoption Projections, and Variable Inputs.

2.2.1 Total addressable Market

The Total Addressable Market (TAM) covers all demand for the function provided by the solution. For e-bikes solution, TAM is defined by world urban passenger kilometers made by all modes of passenger transport. Global TAM was projected based on data from International Energy Agency, International Council on Clean Transportation and ITDP-UC Davis (IEA, 2016; The International Council on Clean Transportation, 2012; UC Davis et al., 2015). Regional data come from ITDP-UC Davis (UC Davis et al., 2015).

2.2.2 Adoption Projections

Adoption projections are gathered from many credible sources. Sources include Astegiano et al., Guidehouse Research, International Transport Forum, ITDP-UC Davis and Navigant Research (Astegiano et al., 2019; Guidehouse, 2020; Navigant Research, 2016; OECD/ITF, 2021; UC Davis et al., 2015).

2.2.3 Inputs

Inputs are used in the Variable Meta-Analysis (VMA) and are updated to reflect current conditions at each update. The VMA is used to collect data and to construct meta-analyses of data points in order to make the assessments more robust. All variables used in the analysis are documented here.

2.2.3.1 Financial Variables

- Conventional first costs by mode are mostly reported at the regional level from (An, Xiaochong, Feifei, Bin, & Longyu, 2013; UC Davis et al., 2015).
- Solution first costs data including the learning rate come from various sources including (eBicycles, 2021a, 2021b; ITDP, 2019; Sun, 2020; Weiss, Cloos, & Helmers, 2020; Weiss, Zerfass, & Helmers, 2019),
- The solution lifetime capacity data come from (Energuide, 2020).
- The solution average annual use is calculated based on data from (C. Cherry & Cervero, 2007).
- Conventional variable operating costs by mode are mostly reported at the regional level and come from (An et al., 2013; UC Davis et al., 2015).

2.2.3.2 Emissions Reduction Variables

- Conventional and solution electricity and fuel consumed calculations are based on data from (UC Davis et al., 2015, 2015).
- Indirect emissions for conventional and solution data come from (ITF/OECD, 2020; Mellino et al., 2017).

2.2.3.3 Additional Variables

- Average car occupancy comes from a variety of sources including (Center for Sustainable Systems University of Michigan, 2020; Environmental and Economic Policy Research Center of the Ministry of Ecology and Environment, 2018; ITF/OECD, 2020; H. Liu et al., 2017; McQueen et al., 2020; Schäfer & Yeh, 2020).
- Average car lifetime data come from several sources such as peer reviewed sources (T. R. Hawkins, Gausen, & Strømman, 2012; ITF/OECD, 2020; NHTSA, 2006; Zheng et al., 2019).
- The household discount rate is based on data from peer reviewed sources (Koster & Pinchbeck, 2018; Li & Pizer, 2018, 2021; Martin, Markhvida, Hallegatte, & Walsh, 2020).
- Average annual PKM per car data come from a peer reviewed source (ITF/OECD, 2020; Odyssee-Mure, 2019; Ou et al., 2020).
- The first cost of ICE car data is based on (Carnext, 2019; Carview, 2019; Coren, 2019; Feijter, 2018a, 2018b; Gasnier, 2019; Hu, 2019a, 2019b; IEA, 2019; IEA & ICCT, 2019; ITDP, 2019; H. Liu et al., 2017; Lutney & Nicholas, 2019; Mock, 2018; Ning, 2018; Tate, 2019; Wang, 2018).
- Average e-bike PKM per year data comes from (C. Cherry & Cervero, 2007; ITF/OECD, 2020; UC Davis et al., 2015).
- E-bike battery size data come from (Weiss et al., 2020) which includes multiple data points from many countries.
- The e-bike work rate data come from (Weiss et al., 2020) which includes multiple data points from many countries and from (Lin, 2019).
- The percentage of e-bike rides with two riders data is based on expert assumptions from the Project Drawdown team and (China Urban Public Transport Association, 2013; ITF/OECD, 2020).
- The conventional fuel consumed per PKM data is from several sources some of which have multiple data points for many countries (Bieker, 2020; ITF/OECD, 2020; Schäfer & Yeh, 2020; Wu et al., 2019).
- Car maintenance costs per functional unit are from (AAA, 2019; Bartlett, n.d.; BTS, 2019; Masson, 2018).

- Car insurance costs data come from (AAA, 2019; Hagman, Ritzén, Stier, & Susilo, 2016; Masson, 2018; Norman, 2021).

2.3 TOTAL ADDRESSABLE MARKET / TAM

The Total Addressable Market (TAM) covers all demand for the functional transportation units provided by the solution. For the e-bikes solution. The values shown represent the average from all the sources listed in Data Sources (Table 2.1). The global TAM more than doubles throughout the study period. The growth comes mainly from the Middle East and Africa region, where the TAM is almost 4 times bigger; and Asia, where the TAM more than doubles by 2050. In Latin America the TAM grows by about 90%.

Table 2.1 Global and Regional TAM, in billion PKM

Drawdown Region	2015	2030	2045	2050
World	28,321	40,744	53,694	58,574
OECD90 ³	9,528	10,012	9,986	10,029
Eastern Europe	1,263	1,362	1,352	1,356
Asia (sans Japan)	9,386	15,360	21,017	22,802
Middle East and Africa	2,828	4,329	7,172	8,499
Latin America	2,717	3,881	4,861	5,150

2.4 ADOPTION SCENARIOS

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

³ The Organisation for Economic Cooperation and Development, with membership as at the end of 1990 (this was chosen to match the AMPERE model used by the IPCC and developed by the International institute for Applied Systems Analysis (IIASA). See www.iiasa.ac.at)

2.4.1 Reference Case / Current Adoption

This model defines the REF adoption scenario as a fixed percentage of TAM over the modeling period, using the percentage of adoption in the base-year as the fixed percentage of TAM projecting forward which is 0.96%.

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.

2.4.2.1 Plausible Scenario

This scenario assumes that e-bikes use continues to grow without any major interventions which uses the baseline TAM predictions and the baseline adoption predictions as inputs.

2.4.2.2 Drawdown Scenario

In this scenario, e-bike use is expected to grow as a percent of total bicycle PKM which are also increasing. The conservative TAM and adoption predicts are used.

2.4.2.3 Optimum Scenario

This scenario assumes that there are incentives for e-bikes, the percent of e-bikes of total bicycles is increasing and that there is a shift towards bicycling for commuting and shopping. The ambitious TAM adoption predictions are used.

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

This section addresses the environmental inputs of the model. These can be either direct emissions, through fuel combustion or the electricity grid, or indirect, through the construction of the vehicles.

2.5.1.1 Direct Emissions

Direct emissions can come from fuel combustion or from electricity consumption. Certain assumptions regarding the technologies are made to calculate them. All cars are ICE cars, therefore conventional has only fuel-combustion related emissions. On the other hand, e-bikes use grid electricity. Therefore the solution has both types of direct emissions.

For ICE cars, the input required is the average liters of fuel required per PKM. This information has also been used for the calculation of the operational cost of cars. It is calculated by dividing the average fuel consumption by the average car occupancy.

To calculate the reduction obtained by the solution technology, one estimates how much fuel or electricity would be saved by switching a car, public transit or 2/3 wheeler PKM to an e-bike PKM. Conventional travel mode energy use was converted to liters of gasoline equivalent based on a weighted average of mode share.

Rail mass transit modes, namely subway, light rail, and commuter rail, use grid electricity to function. Furthermore, a small percent of buses and minibuses are electric or hybrid. Therefore the amount of energy consumed per trip is estimated, to estimate the respective emissions for electricity production. Calculations from the Drawdown team have been used for all these figures.

To account for solution emissions from e-bike PKM, the model derives the MWh(i) required to achieve that mobility. The emissions from these MWh are calculated based on regional projections of CO₂-e emissions factors from 2014 to 2050 calculated with Drawdown-wide assumptions on electricity generation mixes.

2.5.1.2 Indirect Emissions

Indirect emissions from vehicle manufacturing must also be taken into account. Figures from various sources, related with the CO₂e emissions generated to produce an ICE car, 2/3 wheeler or a mass transit vehicle (bus and rail), are used to calculate these emissions per PKM.

Table 2.2 Climate Inputs

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Electricity Consumed per Functional Unit - CONVENTIONAL	<i>Twh per Billion PKM</i>		0.004	1	1
Total Energy Used per Functional Unit - SOLUTION	<i>Twh per Billion PKM</i>		0.006	1	1
Fuel Consumed per Functional Unit - CONVENTIONAL	<i>Liter/ Billion PKM</i>		33,665,812	1	1
Indirect CO ₂ Emissions per	<i>t CO₂-eq/ Billion PKM</i>	6,207-25,141	15,674	7	1

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
CONVENTIONAL Functional Unit					
Indirect CO2 Emissions per SOLUTION Unit	<i>t CO2-eq/ Billion PKM</i>	4,579-13,000	4,579	2	2

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

This section addresses the financial inputs of the model, by splitting them to first and operational cost. The costs have been converted to US\$2014 based on inflation.

2.5.2.1 First Costs

E-bikes replace a range of modes, so the existing (non-e-bike) modeshares are used as a composite conventional alternative that is replaced by each 1 MWh(i) unit of e-bike. Regional usage and cost data on Public transit, traditional bicycle, motorbike (2/3 Wheeler) were combined with private car data to estimate the amortized first cost for this composite conventional alternative. A bottom-up approach was used since modeshare and costs vary greatly by region.

The composite conventional cost takes into account the first costs for each mode normalized by the mobility that it provides (i.e. amortized⁵), and combined according to the current non-e-bike mode shares. The conversion multiplies the cost per PKM by the number of PKM that 1 MWh(i) can generate in a year (see solution first cost).

The first cost for the solution e-bike is defined as dollars per MWh(i) of battery. It is based on the purchase price of e-bikes that has been weighted by battery type and region. The principles of the calculations are based upon the assumptions that one MWh of installed battery pack (1 MWh(i)) provides batteries for

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.

⁵ The conventional technologies use amortization of costs meaning that the lifetime is reduced to allow combination of the costs into a single compound unit (40%- car, 3% -bike etc). This is a theoretical Mobility as a Service (MaaS) package that users buy to receive all types of mobility in a specified ratio. The users pay to join the service (i.e. First Cost), then pay for each PKM travelled (i.e. Variable Operating Cost), and possibly pay for each trip independent of length (would be Fixed Operating Cost - not used). But as it's a service, there is no "lifetime".

around 2200 bikes (each with 458 Wh packs), with each e-bike assumed to run a fixed average number of PKM per year which means that 1 MWh of battery packs allows for just over 6 million PKM per year. The battery size is another input and therefore the average size changes as does the average PKM per year.

2.5.2.2 Operational Cost Factors

Conventional operating and maintenance costs include fuel costs (if any) are on a \$2014/PKM basis and are regionalized and weighted by mode share. The bottom-up approach is used due to the differences in mode share and costs across the regions. ICE cars carry the additional fixed expense of insurance to the user. Solution operating and maintenance costs assume that e-bikes have no additional maintenance costs beyond electricity costs, which are captured in another input on Advanced Controls.

2.5.2.3 Learning Rate Factor

A recent study found that the battery prices have a learning rate of 6% (Weiss et al, 2019). Given the differences between producing large automobile battery packs and smaller packs for e-bikes, this report assumes that estimate as a conservative rate. The conventional efficiency rate is very close to zero.

2.5.2.4 Discount Rate

The household discount rate of 3.2% was used based on the average of 3 sources reporting global household discounting.

Table 2.3 Financial Inputs for Conventional Technologies

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
First costs (Conventional)	<i>US2014\$/MWh(i)</i> (<i>MWh of Installed Battery equ.</i>)	\$149,098-\$199,125	\$174,111	5	2
Variable Operation and Maintenance Costs (Conventional)	<i>US2014\$/Billion PKM</i>	\$52,537,966-\$56,288,575	\$54,413,271	5	2
Fuel Price (Conventional)	<i>US2014\$/liter</i>		\$1.04		
Learning Rate Factor (Conventional)	%	0%	0%	1	1

Table 2.4 Financial Inputs for Solution

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
First costs (Solution)	<i>US2014\$/MWh(i)</i> <i>(MWh of Installed Battery equ.)</i>	\$4,896-\$1,512,846	\$491,576	23	4
Learning Rate Factor (Solution)	%	6%	6%	1	1

2.5.3 Technical Inputs

Besides strictly climate and financial inputs, several general variables were used in the analysis which had important impacts on both the climate and financial results.

2.5.3.1 Replacement Factors

The Conventional Implementation unit (a composite of multiple modes) is costed using amortization of individual modes, and, therefore, is only relevant for a defined number of PKM produced each year. The conventional average annual use and the lifetime capacity are therefore the same and is one year.

For the solution average annual use, the use rate of e-bikes is estimated by using a bottom-up approach: daily use is converted into annual use and then is divided by installed battery capacity, weighted by battery size. Solution lifetime capacity is weighted by size and type of battery and is roughly 11 years.

Table 2.5 Technical Inputs Conventional Technologies

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Lifetime Capacity (Conventional)	<i>years</i>	1	1	1	1
Average Annual Use (Conventional)	<i>hours</i>	1	1	1	1

Table 2.6 Technical Inputs Solution

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Lifetime Capacity (Solution)	<i>years</i>	11	11		

2.5.3.2 Technical Factors

Other variables were used in the calculations for the climate, financial and replacement factors. They are listed below.

Table 2.7 Technical Inputs Solution

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Average Car Occupancy	Persons/vehicle	1.39-2.04	1.72	15	6
Average Car Lifetime	PKM	257,654-442,266	349,960	14	4
Discount Rates - Households	Percent	3.0%-3.4%	3.2%	3	4
Average Annual Passenger-km per Car	PKM/yr	18,996-23,649	21,323	13	3
First Cost of ICE Car	US2014\$/vehicle	\$14,822-\$27,564	\$21,193	16	17
Average Bike Pass-km per Year	PKM/year	2,306-3,240	2,773	3	3
E-bike Battery Size	Wh(i) (installed capacity)	409-508	458	7	1
E-bike Work Rate	Wh(e)/bike-km (Wh of electricity/bike-km)	4.1-9.0	6.5	7	2
Percentage of E-bike Rides with 2 Riders	Percent	5%-15%	10%	2	2
Fuel Consumed per PKM - CONVENTIONAL	Liter/ Billion PKM	35,867,431-75,318,483	55,592,957	8	4
Car Maintenance Cost per Functional Unit	US2014\$/Billion PKM	\$32,901,151-\$36,099,511	\$34,500,33	4	4
Car Insurance Costs	US2014\$/Billion PKM	\$13,524,155-\$32,086,196	\$32,086,196	6	4

2.6 ASSUMPTIONS

Six 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: Travel mode fuel efficiencies remain constant through 2050

Assumption 2: LDV, Motor 2W, Urban bus, and Mini bus use liquid fuel and electricity

Assumption 3: BRT uses only liquid fuel

Assumption 4: Minibus, Metro, Tram, Commuter rail and e-bike use only electricity

Assumption 5: Walking and cycling use no fuel.

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 (including Walkable Cities and Bike Infrastructure) was modeled independently and integration was performed to ensure consistency within the sector. Intra-sectoral integration of the transportation solutions was based on two main components:

- **TAM/Adoption Consistency:** Ensuring that all solutions that are in the same “market” use the same TAM data, use consistent market shares, and have projected adoptions that do not exceed the total projected demand
- **Variable Consistency:** Ensuring that all variables that are used in several solutions have the same values.

The total motorized and non-motorized transport demand (TAM) was collected and synthesized from several sources in functional units (mostly passenger-km and ton-km), then classified according to type (urban passenger, non-urban passenger, and all freight). The TAM was then assigned to each solution according to the service that the solution technology provides. The TAM served as the upper limit of the sum

of adoptions of the modeled solutions. Additionally, some reasonable bounds that were lower than the TAM were placed on adoptions to represent the technologies not affected by the matrix of solutions of Project Drawdown (such as 2-wheelers, intercity bus, and conventional rail).

To determine the new mode shares as adoption grew independently in the models, a simplified approach was used. Solutions were prioritized according to their impact on the climate/environment and efficiency (in space, energy and cost terms). Higher priority solutions were allocated larger proportions of their total individual projected adoption than lower priority ones. Put another way, if the sum of all projected adoptions exceeded the limit discussed above, then in reverse order of priority, and until that was no longer the case, the projected adoption of each solution was reduced until either the relevant bound was no longer exceeded or the adoption was zero. In practice, this mostly affected the Hybrid Cars solution, and to a lesser extent Electric Vehicles which were (respectively) the lowest and second lowest priority solutions in the urban and non-urban passenger TAM's. The adjusted adoption projections are then used in the individual solution models and in the technical report. Therefore the adoptions shown in this report already account for integration.

For several variables, especially those relating to the conventional technology (ICE cars), 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 intra-solution integration within the transport sector, there was an integration process across the grid solutions and the 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 efficiency solutions is reduced (where they reduce electricity demand) or increased (where they increase electricity demand⁶). Grid solutions are adjusted to remove the double counting as described in the Project Drawdown integration documentation.

2.8 LIMITATIONS/FURTHER DEVELOPMENT

The main limitation of the e-bike model is the inconsistency of what the adoption measures. The adoption data is usually reported in different units of measurement such as number of e-bikes sold or bicycle PKM that include both conventional and electric. Adjustments are made based on the different studies to arrive at e-bike PKMs.

⁶ Some solutions such as Electric Vehicles and High-Speed Rail increase the demand for electricity and reduce the demand for fuel.

The model would benefit greatly from more regional adoption data since current results are based on only 2 sources for regional projections. Another important variable in this model is conventional functional unit which is measured as a composite index of all modes replaced which can be difficult to comprehend.

3 RESULTS

3.1 ADOPTION

Below are shown the global adoption of the solution functional units and percent for the three Project Drawdown scenarios.

Table 3.1 World Adoption of the Solution

Solution	Units	Base Year (2014)	World Adoption by 2050		
			Plausible	Drawdown	Optimum
Electric bicycles	<i>Billion PKM</i>	288.50	1443.64	1663.36	1693.97
	<i>(% market)</i>	1.0%	2.0%	3.2%	3.3%

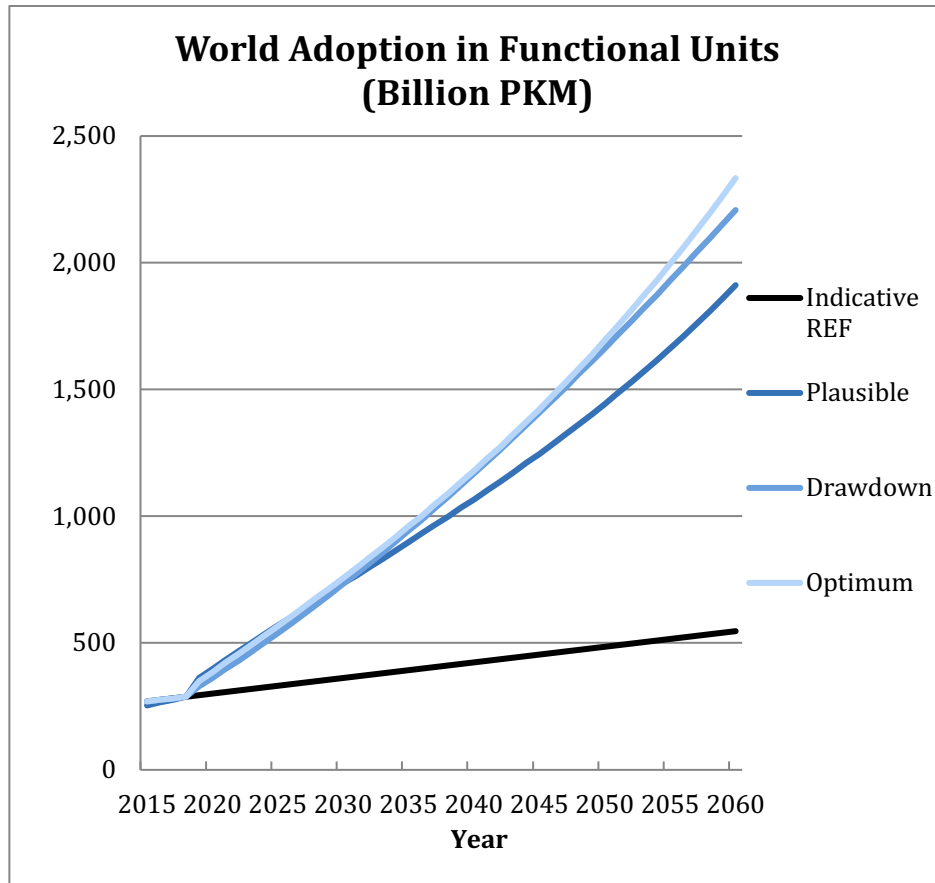


Figure 3-1 World Annual Adoption 2020-2050

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>	0.07	1.14	0.03	0.07
<i>Drawdown</i>	0.10	1.54	0.03	0.10
<i>Optimum</i>	0.15	1.60	0.03	0.10

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
	<i>PPM CO₂-eq (2050)</i>	<i>PPM CO₂-eq change from 2049-2050</i>
Plausible	0.10	0.01
Drawdown	0.13	0.01
Optimum	0.14	0.01

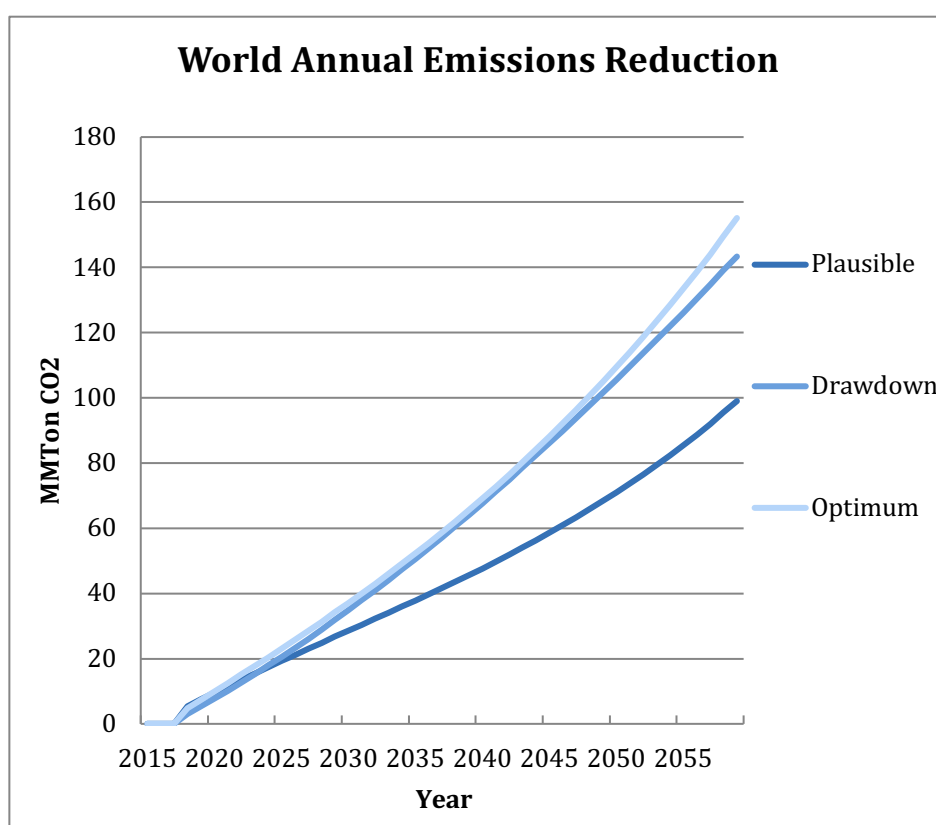


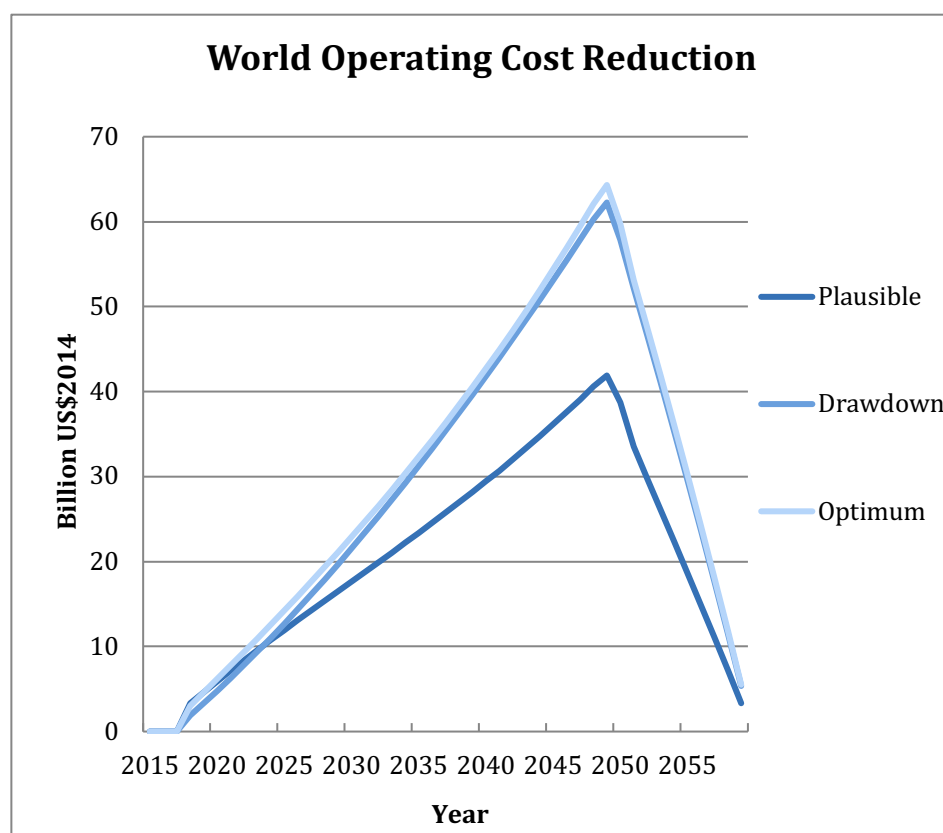
Figure 3.2 World Annual Greenhouse Gas Emissions Reduction

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.

Table 3.4 Financial Impacts

Scenario	Cumulative First Cost	Marginal First Cost	Net Operating Savings	Lifetime Profit Margin	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	150.47	-286.47	696.93	910.50	520.92
Drawdown	162.96	-380.53	944.59	1270.49	691.62
Optimum	166.79	-397.53	983.25	1319.24	725.77



4 DISCUSSION

Shifting passengers to lower emission modes is a huge step towards achieving drawdown. E-bikes is an important solution to help with this shift. Currently it is estimated that 9.5 Gt CO₂ eq was produced due to the transportation sector around the world in 2018 (IEA, 2018). The current estimates show that using e-bikes in place of the composite conventional mode can reduce CO₂ eq per year by 0.07 Gt (on average for 2020-2050 in the Plausible Scenario-PDS1). The cumulative reduction total for 30 years (2020-2050) is 1.14 Gt CO₂ eq. In more aggressive scenarios, bicycling increasingly replaces car trips and the portion of bicycle trips made by e-bikes increases. The decrease in car trips and increase in bicycle trips has the concomitant benefits in congestion, air quality, noise, stress, travel delay and GHG emissions.

The global pandemic that began in 2020 saw a shift towards bicycling and particularly for e-bikes for recreation and for replacing trips that would have been done using public transit. E-bikes and bicycles sold out in many places around the world and several governments began offering incentives to replace old cars with e-bikes. Temporary bicycle lanes popped up all over the world. Policy makers are trying to make this shift permanent

In addition to climate impacts, e-bikes are cheaper, emit less and use less materials (ITF/OECD, 2020) than cars, do not cause congestion, and can be faster in congested traffic than cars (Astegiano et al., 2019). Additional benefits of e-bikes include improvements to health (de Geus et al., 2013) and positive impacts on the local economy as bike users tend to shop in their local community (Arancibia et al., 2019).

The financial results presented in **Error! Reference source not found.** show the NPV of the e-bike solution to be \$521 billion with a net operating savings of \$697 billion from 2020 to 2050. While e-bikes replace a composite of conventional modes (ICE cars, public transit, 2/3 wheelers) like, GHG emission reductions, most of the cost savings comes from the switch away from ICE cars to e-bikes. This hints at the enormous financial cost of car use that many owners often don't realize, focusing instead on fuel prices. Our data, for instance, indicate that vehicle maintenance increases the cost for operating a car by 66% (above that of fuel alone) and doesn't even include fixed costs such as registration and insurance. These are very significant, and almost always higher than more sustainable alternatives like public transport and biking. E-bikes is an easy to implement, cost-effective solution that has significant reductions in emissions.

Cost savings are only accounted for in the period of analysis (2020-2050) hence the sudden drop illustrated in Figure 3.3.

Some improvements in the modeling could be expanding the scenarios to include the results of the achievement of a specified mode share goal (5% or 6%) by 2050. All of the cars in the composite of conventional modes are ICE cars and could include the mix of electric and hybrid vehicles along with any improvements to ICE cars. The costs are modelled based upon the purchase of an e-bike (amortized to an annual cost) and not per trip where a shared bike system ride could be purchased.

4.1 LIMITATIONS

The quantity of e-bikes are significantly larger than other alternative fuel vehicles such as electric cars in the world. E-bikes could provide similar benefits like conventional bikes (e.g., flexibility, low-cost, and environmental benefits) (Fishman & Cherry, 2015). Yet, e-bikes require less human power with the help electricity-drive or electricity-assist motor, which is friendly for hilly environments and extends the cycling life for older people. The implementation of e-bikes will increase the share of cycling, physical activity, and health benefits (Fyhri et al., 2017; Hoj et al., 2018).

However, the fast implementation of e-bikes can also bring problems due to the various types (such as high-speed moped types not accounted for in this analysis), incomplete regulations, and poorly built environment. The higher speeds of e-bikes (compared to traditional bicycles) leads to an elevated risk for road accidents for e-bike users (Haustein & Møller, 2016). Additionally, older people are not able to maintain the balance of e-bikes due to its heavy weight (Van Cauwenberg et al., 2018). These potential safety problem with e-bikes makes their future development unclear (Gu et al., 2020). Local governments in different cities in China have different attitudes to e-bikes and some cities even banned the e-bike on road (Sun, 2020). This will hurt the potential development of e-bikes in the future if following current loose regulations and high road incidents.

The high cost of e-bikes is another limitation to adopting e-bikes across the world. Based on the ITDP report, current e-bike prices range from \$291 in China to \$2,300 in the U.S. (ITDP, 2019). The expensive e-bike price (excluding China) is still challenging for e-bike implementation. People will choose motorcycles rather than e-bikes in countries without enough charging infrastructure and access to electricity. These limitations mentioned above will hinder the growth of e-bikes in the future if keeping current situation.

4.2 BENCHMARKS

As discussed above, adoption data is reported in different forms and requires adjustment for comparison. Therefore it is difficult to find comparable (without adjustment) sources for benchmarking. Only one source

reported adoption data as a percent of urban passenger travel and is benchmarked in Table 4.1 BenchmarksTable 4.1

Table 4.1 Benchmarks

Source and Scenario	Market Share in 2050 (%)
(Astegiano et al., 2019) Baseline Scenario ⁷	2.7%
(Astegiano et al., 2019) Policy Scenario	2.9%
Project Drawdown – Plausible Scenario (PDS1)	2.0%
Project Drawdown – Drawdown Scenario (PDS2)	3.2%
Project Drawdown – Optimum Scenario (PDS3)	3.3%

4.3 SUMMARY

Bicycles have been a popular and environmentally friendly form of transportation throughout the world for more than 100 years. Electric and hydrogen fuel-cell cars receive a lot of attention as exciting new technologies, but many overlook the fact that e-bikes are the most popular and successful form of alternative-fuel transportation in the world. Moreover, e-bikes will benefit from the technological advancements of electric car manufacturing, especially in the realm of Lithium-ion battery technology. As electric cars become more common and reliable, e-bikes will become less expensive and more powerful. This dual benefit bodes well for the worldwide growth of e-bike PKM in the coming decades. Because e-bikes will always be less expensive than electric cars, their potential market will be larger. This market will include people who cannot afford personal automobiles and are not in the physical condition to be able to ride a traditional bicycle. In this way, e-bikes offer the opportunity to make climate-smart transportation choices for people who otherwise would be immobile or dependent on others for their travel needs. E-bikes will reduce global carbon emissions and save people money on transportation in the long run, but perhaps their biggest impact will be felt by people who gain the agency to choose low-carbon travel modes.

⁷ The Baseline scenario considered an already high level of adoption (using the EU 28 as a proxy) therefore the baseline scenario was used as a conservative adoption case.

5 REFERENCES

- AAA. (2019). AAA's Your Driving Costs | AAA Exchange. Retrieved April 5, 2021, from <https://exchange.aaa.com/automotive/driving-costs/#.YGpUgZ37Tid>
- An, K., Xiaochong, C., Feifei, X., Bin, L., & Longyu, W. (2013). Travel Characteristics of E-bike Users: Survey and Analysis in Shanghai. *Procedia - Social and Behavioral Sciences*, 96, 1828–1838.
- Arancibia, D., Farber, S., Savan, B., Verlinden, Y., Lea, N. S., Allen, J., & Vernich, L. (2019). Measuring the Local Economic Impacts of Replacing On-Street Parking With Bike Lanes. *Journal of the American Planning Association*, 85(4), 463–481. <https://doi.org/10.1080/01944363.2019.1638816>
- Astegiano, P., Fermi, F., & Martino, A. (2019). Investigating the impact of e-bikes on modal share and greenhouse emissions: A system dynamic approach. *Transportation Research Procedia*, 37, 163–170. <https://doi.org/10.1016/j.trpro.2018.12.179>
- Bakker, S. (2018). Electric Two-Wheelers, Sustainable Mobility and the City. *Sustainable Cities - Authenticity, Ambition and Dream*. <https://doi.org/10.5772/intechopen.81460>
- Bartlett, J. S. (n.d.). The Cost of Car Ownership Over Time. Retrieved April 5, 2021, from Consumer Reports website: <https://www.consumerreports.org/car-maintenance/the-cost-of-car-ownership/>
- Battery Council International. (2014). Recycling Batteries—How a Lead Battery Is Recycled. Retrieved March 31, 2021, from https://battery council.org/page/battery_recycling
- Bernhard, A. (2020). The great bicycle boom of 2020. Retrieved July 2, 2021, from <https://www.bbc.com/future/bespoke/made-on-earth/the-great-bicycle-boom-of-2020.html>
- Bieker, G. (2020). *European vehicle market statistics: Pocketbook 2019-2020* (p. 56). icct (the International Council on Clean Transportation).
- Bigazzi, A., & Wong, K. (2020). Electric bicycle mode substitution for driving, public transit, conventional cycling, and walking. *Transportation Research Part D: Transport and Environment*, 85, 102412. <https://doi.org/10.1016/j.trd.2020.102412>

- BTS. (2019). Average Cost of Owning and Operating an Automobile | Bureau of Transportation Statistics. Retrieved April 5, 2021, from <https://www.bts.gov/content/average-cost-owning-and-operating-automobilea-assuming-15000-vehicle-miles-year>
- Carnext. (2019). How many kilometers did the break-even point between hybrid and gasoline vehicles run? | Everyone's scrap car information navigation. Retrieved April 5, 2021, from https://carnext.jp/magazine/article/hybrid_break-even_point/
- Carview. (2019). Which is more advantageous, a hybrid car or a gasoline car? I compared by fuel efficiency & price. Retrieved April 5, 2021, from 日本最大級のクルマ総合情報サイト、カービュー! website: <https://carview.yahoo.co.jp/news/detail/c59aa60e0ee1d234a25d071e6392f45e559a978b/>
- Center for Research into Energy Demand Solutions. (n.d.). Decarbonising transport: Growing cycle use – CREDS. Retrieved July 2, 2021, from <https://www.creds.ac.uk/publications/decarbonising-transport-growing-cycle-use/>
- Center for Sustainable Systems University of Michigan. (2020). Personal Transportation Factsheet | Center for Sustainable Systems. Retrieved February 26, 2021, from <http://css.umich.edu/factsheets/personal-transportation-factsheet>
- Cherry, C., & Cervero, R. (2007). Use characteristics and mode choice behavior of electric bike users in China. *Transport Policy*, 14(3), 247–257. <https://doi.org/10.1016/j.tranpol.2007.02.005>
- Cherry, C. R., Yang, H., Jones, L. R., & He, M. (2016). Dynamics of electric bike ownership and use in Kunming, China. *Transport Policy*, 45, 127–135. <https://doi.org/10.1016/j.tranpol.2015.09.007>
- China Urban Public Transport Association. (2013). *Research on the Impact of Electric Bicycles on Urban Traffic in China*. Retrieved from <https://www.efchina.org/Attachments/Report/reports-efchina-20140307/%E7%94%B5%E5%8A%A8%E8%87%AA%E8%A1%8C%E8%BD%A6%E5%AF%B9%E6%88%91%E5%9B%BD%E5%9F%8E%E5%B8%82%E4%BA%A4%E9%80%9A%E7%9A%84%E5%BD%B1%E5%93%8D%E7%A0%94%E7%A9%B6%E4%B8%AD%E6%96%87%E7%AE%80%E6%9C%AC.pdf>

- Coren. (2019). The average electric vehicle is getting cheaper in the US — Quartz. Retrieved April 5, 2021, from <https://qz.com/1695602/the-average-electric-vehicle-is-getting-cheaper-in-the-us/>
- de Geus, B., Kempenaers, F., Lataire, P., & Meeusen, R. (2013). Influence of electrically assisted cycling on physiological parameters in untrained subjects. *European Journal of Sport Science*, 13(3), 290–294. <https://doi.org/10.1080/17461391.2011.606845>
- eBicycles. (2021a). ALL ABOUT ELECTRIC BICYCLES. Retrieved March 1, 2021, from EBicycles website: <https://www.ebicycles.com/>
- eBicycles. (2021b). Facts & Statistics of Electric Bicycles [2021] + Infographic. Retrieved February 19, 2021, from <https://www.ebicycles.com/ebike-facts-statistics/>
- Energide. (2020). How long does the battery of my electric bike last? Retrieved April 4, 2021, from Energide website: <https://www.energide.be/en/questions-answers/how-long-does-the-battery-of-my-electric-bike-last/1782/>
- Environmental and Economic Policy Research Center of the Ministry of Ecology and Environment. (2018). *The green development report of sharing mobility*. Retrieved from <http://www.prcee.org/yjcg/yjbg/201909/W020190905526779202048.pdf>
- Feijter. (2018a). More On The New Buick Excelle sedan For China—CarNewsChina.com. Retrieved April 5, 2021, from <https://carnewschina.com/2018/05/24/more-on-the-new-buick-excelle-sedan-for-china/>
- Feijter, A. T. de. (2018b, April 13). Nissan Sylphy Goes Electric In China. Retrieved April 5, 2021, from CarNewsChina.com website: <https://carnewschina.com/2018/04/13/nissan-sylphy-goes-electric-in-china/>
- Fishman, E., & Cherry, C. (2015). E-bikes in the Mainstream: Reviewing a Decade of Research. *Transport Reviews*, 36. <https://doi.org/10.1080/01441647.2015.1069907>
- Foresight Industrial Research Institute. (2020). Analysis of the market status and development prospects of China's electric bicycle industry in 2020. Retrieved March 29, 2021, from Strong demand for

- lithium battery market in the future website: <https://bg.qianzhan.com/trends/detail/506/201208-7c2481c2.html>
- Fortune Business Insights. (2020). Electric Bike Market Share, Analysis | E-Bike Industry Growth [2027]. Retrieved March 31, 2021, from <https://www.fortunebusinessinsights.com/electric-e-bike-market-102022>
- Fu, A. (2013). *The Role of Electric Two-Wheelers in Sustainable Urban Transport in China: Market analysis, trends, issues, policy options* (p. 17). UN Division of Sustainable Development. Retrieved from UN Division of Sustainable Development website: <https://sustainabledevelopment.un.org/content/documents/3792fu2.pdf>
- Fyhri, A., Heinen, E., Fearnley, N., & Sundfør, H. B. (2017). A push to cycling—Exploring the e-bike's role in overcoming barriers to bicycle use with a survey and an intervention study. *International Journal of Sustainable Transportation*, 11(9), 681–695. <https://doi.org/10.1080/15568318.2017.1302526>
- Gasnier, M. (2019, May 2). Strategy: With its new low-cost brand Jetta, Volkswagen is trying to pull a Dacia in China. Retrieved April 5, 2021, from Best Selling Cars Blog website: <https://bestsellingcarsblog.com/2019/05/strategy-with-its-new-low-cost-brand-jetta-volkswagen-is-trying-to-pull-a-dacia-in-china/>
- Global EV Outlook 2020*. (2020). 276.
- Gu, T., Kim, I., & Currie, G. (2020). The two-wheeled renaissance in China—An empirical review of bicycle, E-bike, and motorbike development. *International Journal of Sustainable Transportation*, 1–20. <https://doi.org/10.1080/15568318.2020.1737277>
- Guidehouse. (2020). Market Data: Electric Bicycles. Retrieved February 11, 2021, from <https://guidehouseinsights.com/reports/market-data-electric-bicycles>
- Hagman, J., Ritzén, S., Stier, J. J., & Susilo, Y. (2016). Total cost of ownership and its potential implications for battery electric vehicle diffusion. *Research in Transportation Business & Management*, 18, 11–17. <https://doi.org/10.1016/j.rtbm.2016.01.003>

- Haustein, S., & Møller, M. (2016). E-bike safety: Individual-level factors and incident characteristics. *Journal of Transport & Health*, 3(3), 386–394. <https://doi.org/10.1016/j.jth.2016.07.001>
- Hawkins, A. J. (2019, December 16). Forget electric cars—E-bikes will be the top selling EV in the next decade. Retrieved March 30, 2021, from The Verge website: <https://www.theverge.com/2019/12/16/21016306/electric-bike-ebike-sales-us-numbers-deloitte-cars>
- Hawkins, T. R., Gausen, O. M., & Strømman, A. H. (2012). Environmental impacts of hybrid and electric vehicles—A review. *The International Journal of Life Cycle Assessment*, 17(8), 997–1014. <https://doi.org/10.1007/s11367-012-0440-9>
- Hoj, T. H., Bramwell, J. J., Lister, C., Grant, E., Crookston, B. T., Hall, C., & West, J. H. (2018). Increasing Active Transportation Through E-Bike Use: Pilot Study Comparing the Health Benefits, Attitudes, and Beliefs Surrounding E-Bikes and Conventional Bikes. *JMIR Public Health and Surveillance*, 4(4), e10461. <https://doi.org/10.2196/10461>
- Hu. (2019a). All-New Toyota Corolla Launched in China Market, Powered by 1.2T & 1.8L Hybrid, Features 12.1in Display—Chinapev.com. Retrieved April 5, 2021, from <https://www.chinapev.com/faw/faw-toyota/all-new-toyota-corolla-launched-in-china-market-powered-by-1-2t-1-8l-hybrid-features-12-1in-display/>
- Hu. (2019b, September 9). Volkswagen's New Brand JETTA Launched First SUV VS5 At 2019 Chengdu Motor Show. Retrieved April 5, 2021, from China Car News, Reviews and More website: <https://www.chinapev.com/faw/jetta/volkswagens-new-brand-jetta-launched-first-suv-vs5-at-2019-chengdu-motor-show/>
- Hu, Y., & Qiu, D. (2019). *Leading suppliers of Electrically Power Assisted Cycles have strong growth across the world*. Hua Chunag Securities. Retrieved from Hua Chunag Securities website: https://pdf.dfcfw.com/pdf/H3_AP201912101371722026_1.pdf?1601214832000.pdf

- IEA. (2016). *Energy Technology Perspectives 2016: Towards Sustainable Urban Energy Systems*. Paris: International Energy Agency. Retrieved from International Energy Agency website: <http://www.iea.org/etp/etp2016/>
- IEA. (2018). *Energy Technology Perspectives 2017* (p. 441).
- IEA. (2019). Global EV Outlook 2019 – Analysis. Retrieved April 5, 2021, from IEA website: <https://www.iea.org/reports/global-ev-outlook-2019>
- IEA, I., & ICCT. (2019). Fuel Economy in Major Car Markets: Technology and Policy Drivers 2005-2017 – Analysis. Retrieved April 5, 2021, from IEA website: <https://www.iea.org/reports/fuel-economy-in-major-car-markets>
- ITDP. (2019). The Electric Assist: Leveraging E-bikes and E-scooters for More Livable Cities. Retrieved March 30, 2021, from Institute for Transportation and Development Policy website: <https://www.itdp.org/publication/electric-assist/>
- ITF/OECD. (2020). *Good to Go? Assessing the Environmental Performance of New Mobility*. 89.
- Jean, K. (2021). Lithium-Ion Battery Recycling Finally Takes Off in North America and Europe—IEEE Spectrum. Retrieved March 31, 2021, from IEEE Spectrum: Technology, Engineering, and Science News website: <https://spectrum.ieee.org/energy/batteries-storage/lithiumion-battery-recycling-finally-takes-off-in-north-america-and-europe>
- Johnson, M., & Rose, G. (2015). Extending life on the bike: Electric bike use by older Australians. *Journal of Transport & Health*, 2(2), 276–283. <https://doi.org/10.1016/j.jth.2015.03.001>
- Koster, H., & Pinchbeck, E. (2018). *How do Households Value the Future? Evidence from Property Taxes*.
- Li, Q., & Pizer, W. (2018). *The Discount Rate for Public Policy over the Distant Future* (No. w25413; p. w25413). Cambridge, MA: National Bureau of Economic Research. <https://doi.org/10.3386/w25413>
- Li, Q., & Pizer, W. A. (2021). Use of the consumption discount rate for public policy over the distant future. *Journal of Environmental Economics and Management*, 107, 102428. <https://doi.org/10.1016/j.jeem.2021.102428>

- Liu, H., Man, H., Cui, H., Wang, Y., Deng, F., Wang, Y., ... He, K. (2017). An updated emission inventory of vehicular VOCs and IVOCs in China. *Atmospheric Chemistry and Physics*, 17(20), 12709–12724. <https://doi.org/10.5194/acp-17-12709-2017>
- Liu, Wei, Chen, L., & Tian, J. (2016). Uncovering the Evolution of Lead In-Use Stocks in Lead-Acid Batteries and the Impact on Future Lead Metabolism in China. *Environmental Science & Technology*, 50(10), 5412–5419. <https://doi.org/10.1021/acs.est.6b00775>
- Liu, Wenqiu, Liu, H., Liu, W., & Cui, Z. (2021). Life cycle assessment of power batteries used in electric bicycles in China. *Renewable and Sustainable Energy Reviews*, 139, 110596. <https://doi.org/10.1016/j.rser.2020.110596>
- Lutney, & Nicholas. (2019). Update on electric vehicle costs in the United States through 2030 | International Council on Clean Transportation. Retrieved April 5, 2021, from <https://theicct.org/publications/update-US-2030-electric-vehicle-cost>
- Markets and Markets. (2020). E-Bike Market Growth, Industry Trends, and Statistics by 2027. Retrieved February 18, 2021, from https://www.marketsandmarkets.com/Market-Reports/electric-bike-market-110827400.html?gclid=Cj0KCQiA962BBhCzARIsAlpWEL15ty3pyKkieDoO0jYRtd6yHvWBpRTsbh4IDV27jzjiwH4rkupRKmoaAmG_EALw_wcB
- Martin, A., Markhvida, M., Hallegatte, S., & Walsh, B. (2020). Socio-Economic Impacts of COVID-19 on Household Consumption and Poverty. *Economics of Disasters and Climate Change*, 4(3), 453–479. <https://doi.org/10.1007/s41885-020-00070-3>
- Masson, S. (2018). Average car costs more than £160 per month to run | The Car Expert. Retrieved April 5, 2021, from <https://www.thecarexpert.co.uk/average-car-costs-more-than-160-per-month-to-run/>
- McQueen, M., MacArthur, J., & Cherry, C. (2020). The E-Bike Potential: Estimating regional e-bike impacts on greenhouse gas emissions. *Transportation Research Part D: Transport and Environment*, 87, 102482. <https://doi.org/10.1016/j.trd.2020.102482>

- Mellino, S., Petrillo, A., Cigolotti, V., Autorino, C., Jannelli, E., & Ulgiati, S. (2017). A Life Cycle Assessment of lithium battery and hydrogen-FC powered electric bicycles: Searching for cleaner solutions to urban mobility. *International Journal of Hydrogen Energy*, 42(3), 1830–1840. <https://doi.org/10.1016/j.ijhydene.2016.10.146>
- Ministry of Industry and Information Technology of the People's Republic of China. (2012). Access conditions for lead-acid battery industry. Retrieved March 29, 2021, from http://www.gov.cn/zwgk/2012-05/31/content_2149860.htm
- Mock. (2018). European vehicle market statistics, 2018/2019 | International Council on Clean Transportation. Retrieved April 5, 2021, from <https://theicct.org/publications/european-vehicle-market-statistics-20182019>
- Navigant Research. (2016, July 13). Global Sales of Electric Bicycles Are Expected to Reach to \$24.3 Billion in Annual Revenue by 2025. Retrieved August 30, 2016, from Navigant Research website: <http://www.navigantresearch.com/newsroom/global-sales-of-electrical-bicycles-are-expected-to-reach-to-24-3-billion-in-annual-revenue-by-2025>
- NHTSA. (2006). *VEHICLE SURVIVABILITY AND TRAVEL MILEAGE SCHEDULES*. Retrieved from <https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/809952>
- Ning, A. W. E. (2018, April 16). First Photos Of The All New Volkswagen Bora For China. Retrieved April 5, 2021, from CarNewsChina.com website: <https://carnewschina.com/2018/04/16/first-photos-of-the-all-new-volkswagen-bora-for-china/>
- Nocerino, R., Colorni, A., Lia, F., & Luè, A. (2016). E-bikes and E-scooters for Smart Logistics: Environmental and Economic Sustainability in Pro-E-bike Italian Pilots. *Transportation Research Procedia*, 14, 2362–2371. <https://doi.org/10.1016/j.trpro.2016.05.267>
- Norman. (2021). Average Car Insurance Costs in 2021—NerdWallet. Retrieved April 5, 2021, from <https://www.nerdwallet.com/blog/insurance/car-insurance-basics/how-much-is-car-insurance/>

- Odyssee-Mure. (2019). Change in distance travelled by car | ODYSSEE-MURE. Retrieved February 27, 2021, from <https://www.odyssee-mure.eu/publications/efficiency-by-sector/transport/distance-travelled-by-car.html>
- OECD/ITF. (2021). *ITF Transport Outlook 2021*.
- Ogden, B. (1895). *United States Patent No. US552271A*. Retrieved from <https://patents.google.com/patent/US552271A/en>
- Ou, S., Yu, R., Lin, Z., Ren, H., He, X., Przesmitzki, S., & Bouchard, J. (2020). Intensity and daily pattern of passenger vehicle use by region and class in China: Estimation and implications for energy use and electrification. *Mitigation and Adaptation Strategies for Global Change*, 25(3), 307–327. <https://doi.org/10.1007/s11027-019-09887-0>
- Rapier, R. (2019). Why China Is Dominating Lithium-Ion Battery Production. Retrieved March 31, 2021, from Forbes website: <https://www.forbes.com/sites/rapier/2019/08/04/why-china-is-dominating-lithium-ion-battery-production/>
- Recycling Today. (2017). Study finds nearly 100 percent recycling rate for lead batteries. Retrieved March 31, 2021, from Recycling Today website: <https://www.recyclingtoday.com/article/battery-council-international-lead-battery-recycling/>
- Schäfer, A. W., & Yeh, S. (2020). A holistic analysis of passenger travel energy and greenhouse gas intensities. *Nature Sustainability*, 1–4. <https://doi.org/10.1038/s41893-020-0514-9>
- Sohu. (2019). Understanding the difference between electric bicycles, electric mopeds, and electric motorcycles in one article. Retrieved March 29, 2021, from www.sohu.com/a/311204451_380539
- Sun, X. (2020). *The new national standard accelerates the lithium-ionization of two-wheel electric bikes*. Tianfeng Securities. Retrieved from Tianfeng Securities website: https://pdf.dfcfw.com/pdf/H3_AP202011241432297727_1.pdf?1606210841000.pdf
- Tate. (2019, June 11). Great Wall Motor Launched 2019 Haval H6 in China Market. Retrieved April 5, 2021, from China Car News, Reviews and More website: <https://www.chinapev.com/gwm/great-wall-motor-launched-2019-haval-h6-in-china-market/>

- The International Council on Clean Transportation. (2012). *ICCT Roadmap Model*. The International Council on Clean Transportation. Retrieved from The International Council on Clean Transportation website: <http://www.theicct.org/global-transportation-roadmap-model>
- UC Davis, Fulton, L., & Mason, J. (2015, November 10). *ITDP-UCD HS Cycling Report Figures*.
- Van Cauwenberg, J., de Geus, B., & Deforche, B. (2018). Cycling for Transport Among Older Adults: Health Benefits, Prevalence, Determinants, Injuries and the Potential of E-bikes. In A. Curl & C. Musselwhite (Eds.), *Geographies of Transport and Ageing* (pp. 133–151). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-76360-6_6
- Wang, A. J. (2018, April 10). This Is The New Volkswagen Lavida Plus For China. Retrieved April 5, 2021, from CarNewsChina.com website: <https://carnewschina.com/2018/04/10/this-is-the-new-volkswagen-lavida-plus-for-china/>
- Weiss, M., Cloos, K. C., & Helmers, E. (2020). Energy efficiency trade-offs in small to large electric vehicles. *Environmental Sciences Europe*, 32(1), 46. <https://doi.org/10.1186/s12302-020-00307-8>
- Weiss, M., Zerfass, A., & Helmers, E. (2019). Fully electric and plug-in hybrid cars—An analysis of learning rates, user costs, and costs for mitigating CO2 and air pollutant emissions. *Journal of Cleaner Production*, 212, 1478–1489. <https://doi.org/10.1016/j.jclepro.2018.12.019>
- Wu, T., Han, X., Zheng, M. M., Ou, X., Sun, H., & Zhang, X. (2019). Impact factors of the real-world fuel consumption rate of light duty vehicles in China. *Energy*, 116388. <https://doi.org/10.1016/j.energy.2019.116388>
- Yang, C.-J. (2010). Launching strategy for electric vehicles: Lessons from China and Taiwan. *Technological Forecasting and Social Change*, 77(5), 831–834. <https://doi.org/10.1016/j.techfore.2010.01.010>
- Yong, P., & Guan, Z. (2020). *Two-wheel bicycle industry report*. CAITONG SECURITIES. Retrieved from CAITONG SECURITIES website: <http://qccdata.qichacha.com/ReportData/PDF/9fe2c8a1a165a42d328d903de193449c.pdf>

Zheng, J., Zhou, Y., Yu, R., Zhao, D., Lu, Z., & Zhang, P. (2019). Survival rate of China passenger vehicles: A data-driven approach. *Energy Policy*, 129, 587–597. <https://doi.org/10.1016/j.enpol.2019.02.037>

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. We take global weighted averages for this input. This is used to estimate the **Replacement Time**.

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 experienced 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.

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