Sweden-China Bridge

Collaborative Academic Platform for the
Electrification of Transportation Systems

September 2021

ELECTRIFICATION OF THE TRANSPORTATION SYSTEM IN CHINA

EXPLORING BATTERY SWAPPING FOR HEAVY TRUCKS IN CHINA 1.0

Title: Exploring Battery Swapping for Heavy Trucks in China 1.0

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ABOUT THE SWEDEN-CHINA BRIDGE PROJECT

This project funded by The Swedish Trafikverket (TRV), formally started the 1st of September 2020, and will last until the end of 2022.

Exploratory approach

This project is exploratory in nature and includes a step-by-step approach to knowledge development in the Swedish and the Chinese context. The project spans different areas of knowledge in which we will highlight what technologies and systems are prioritized in China, Sweden and in Europe, what drivers and motives exists for them, what actors are involved in the transition to electrified, intelligent and integrated transport systems, and what conditions and business models look like to achieve this conversion to electrified and integrated transport systems in an intelligent and smart society.

The purposes of the Sweden-China Bridge Project

1. The project aims to establish and develop an academic knowledge-sharing and -transfer platform between Sweden and China for collaboration between universities and research institutes in the two countries, in order to contribute to increased understanding and information and knowledge sharing on the technical and commercial development of electrified vehicle systems, integrated transport system solutions, and energy supply infrastructure as a fully integrated system of intelligent and smart cities.

2. From this perspective, the project will explore the development and implementation of relevant technology for the electrification of vehicles, such as fuel cells, bioenergy, battery storage, combinations of energy systems for hybrid vehicles, energy supply for integrated electrified vehicles, integrated electric road technology, associated charging infrastructure, and static and dynamic technology.

3. We also intend to explore the management of renewable energy supply systems, from the production of renewable electricity to its distribution to consumers of electrified transport systems, which is needed to ensure that electrified vehicles and transport systems.

Expected value creation

1. To create insights into the current and future status of electrification of transportation systems in Sweden and in China from technical, social, societal and economic perspectives.

2. To learn and mutually develop insights into how new knowledge, technology, system-based solutions, logistics and transportation systems can be developed, commercialized and operated according to a lifecycle perspective in both Sweden and China.

3. To create a long-term learning context in which Sweden and China exchange experience for the benefit of both countries and their industries.

4. To develop a deeper understanding of how Sweden and China are managing the large-scale electrification of the road network using different technologies, including electric charging, energy production (fuel cells, hybrid vehicles, battery storage and electric roads): what do the short- and long-term potentials look like? How are they using long-term industry policy instruments to develop technology and implement it in society? How are they outlining business models for the large-scale roll-out of electrified transportation systems?

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Industrial partners in China

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When the The Swedish Transportation Administration (Trafikverket, TRV) presented the results in the Swedish government assignments on the electrification of heavy vehicles in February 2021, TRV presented three main recommendations:

- The lack of infrastructure for stationary charging is considered to be an obstacle to electrification of heavy vehicles and should be expanded in the near future to accelerate electrification of heavy vehicles
- There are several possible solutions for electrification of heavy vehicles that are used over larger areas, have longer driving distances or have a higher energy requirement
- In the next few years, we will continue to work on developing a knowledge base to clarify uncertainties about how heavy trucks can be electrified more efficiently in the future.

The first point refers primarily to trucks in local and regional traffic. Trucks that can drive the majority of all their assignments by only charging at the depot after completing the driving mission. On individual occasions, additional charging may be required.

The Sweden-China Bridge project is a logical part of the overall recommendation to explore and develop deeper understanding of the development of technologies and practices in international settings. Through this knowledge development process we can contribute to better and deeper understanding of the conditions and develop possible solutions to enhance electrification of transportation systems in Sweden, Europe and globally.

It would not have been possible to establish and operate this project without the extensive support of the Swedish Transportation Administration (Trafikverket, TRV), as the funder of the research, and the support of our home universities in Sweden and our academic colleagues in China and their home universities, and finally all the support of businesses and industry in Sweden and in China.

We are particularly grateful to the following key individuals for supporting us: Mr. Jan Pettersson and Dr. Magnus Lindgren from the Swedish Transportation Administration; Mr. Joakim Diamant and Mr. Andreas Jerhammar from Scania Innovation Team in Beijing; representatives for Enneagon and Aulton for sharing their experiences with battery swapping in the Chinese context; Professors Susan Lijiang Sun and Ma Hongwei at Shanghai Dianji University, who helped connect us to all the supportive and helpful Chinese academics and industry for this project.

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As project leader, I am grateful to my research fellows and colleagues in this project: Dr. Jasmine Lihua Liu, Professor Tomas Müllern, Tech. lic. Arne Nåbo, and Dr. Philip Almestrand-Linné.

As co-author of this paper, I am grateful to Dr. Jasmine Lihua Liu for her collaboration, contributions and, commitment.

I thank you all from the bottom of my heart.

Professor Mike Danilovic on the behalf of the entire research team.

ABSTRACT

Electric transportation systems (ETS) are essential for meeting the European Union's (EU) decarbonization and energy security goals. The EU and China are leading the way in transformations involving ETS. Heavy trucks generate the majority of all vehicle pollution. The introduction of electric vehicles has so far emphasized passenger vehicles, but heavy trucks are becoming the focus of EV expansion.

In our first report on battery swapping, Exploring Battery swapping for Electric Vehicles in China 1.0, our focus was on passenger vehicles and the development and establishment of large-scale battery-swapping systems in China. In this report we focus on the use of battery-swapping technology to develop and market Electric Heavy Trucks (EHT) in China.

Heavy trucks have different characteristics compared to passenger vehicles. They are seen as means of production, and thus truck operators are more sensitive to vehicle cost and place high requirement on time efficiency. A heavy truck's lifetime fuel consumption costs three to five times the price of the vehicle itself.

At present, there are several radical paths in EV energy technology evolving simultaneously in the EHT industry. These can be grouped by battery type into fuel cell EVs (FCVs) and traction battery EV (BEVs). They can also be grouped by the means of supplying energy to the EV battery: cable charging, battery swapping, conductive charging, and inductive charging (static and dynamic). Even though FCVs are thought to be fundamental solution for long distance commercial heavy vehicles, their development is progressing slower than expected due to the enormous effort involved in establishing the entire fuel cell value chain for such vehicles. Cable-charged battery EHTs are the main solution currently being developed. However, development is not progressing smoothly due to the high cost and poor time efficiency and load efficiency.

Our research has found that since 2019, Chine has explored and developed battery-swapping technology for EHTs. In 2020, this form of battery charging was situated as a national strategic initiative and receive strong policy support. By the middle of 2021,

- almost all major Chinese heavy truck manufacturers had launched a battery-swapping mode for their EHTs being developed for the market;
- the battery-swapping ecosystem consists of battery-swapping EHTs manufacturers, investors and suppliers for battery-swapping stations, and suppliers of key components and systems;
- support has been developed for a business model based on physical and financial independence of the vehicle and battery;
- customers have placed orders for 15,000 battery-swapping EHTs units in the first half of 2021;
- 23 battery-swapping stations/projects following different scenarios have been put into operation and are performing satisfactorily;
  A nationwide pilot program for of battery-swapping EVs will also be implemented.

These findings indicate that the preliminary technical and economic feasibility of battery-swapping EHTs has been tested and accepted by the Chinese market.

- This fueling mode decreases the purchase price of EHTs by 50%. The "Independence of vehicle and battery" business model means operators need only pay for the vehicle, while the battery is owned and handled by the battery bank for operators to rent.
- It creates economic efficiency by lowering the operating and maintenance costs of EHTs.
- It increases the efficiency of time and resource utilization because it only takes five minutes to swap the battery. It also requires less energy and land resources compared to charging mode.
- It offers safer battery management and higher battery value over its lifecycle. Centralized charging improves the safety of battery usage and extends battery service life by 20%.
- It allows better scheduling of battery charging according to demand on the electrical distribution grid.
- The challenges that battery-swapping EHTs are facing in China include safety issues, the development of battery standards, and utilization scenarios.

Battery swapping in China is seen as complementary solution to EHTs, since traditional cable charging solutions face certain bottlenecks. Battery-swapping offers dual operational modes for charging vehicles—both cable charging and battery swapping, depending on operator needs.

Our analysis compares this development in China to similar ones in the EU. We have found that the EU is relying entirely on cable charging, which is unable to satisfy the large and rapidly growing need for charging infrastructure, especially for EHTs. Battery-swapping technology is not being discussed in the EU context. We also link our analysis of battery swapping to the ongoing debate in Sweden regarding the establishment of electric road systems (ERS).

An ETS is not only a matter of transportation. We are at the early stages of energy transformation from fossil-based fuels to renewables, and of information technology transformation from networking to digitalization and intelligent systems. Electric vehicles (EV) powered by new energy sources are the first major field of application for renewable energy power, and they can also serve as mobile energy storage units when they are smartly connected to the grid system. Thus, EV's role in energy storage can help support global energy balancing. The EV industry is becoming a key industry that combines renewable energy transformation, green and smart upgrades to the grid system, and intelligent transformation of information systems interconnected with smart-cities.

We would like to remind decision-makers that whatever solutions they chose for ETS, ERS, inductive or conductive charging on the ERS, or battery-swapping system, we need to consider:

- How can increasing digitalization, global system development, the transportation electrification systems, and the development of smart cities come together to form integrated system solutions? This means that when we select technology solutions, we need to consider the context and the needs of tomorrow and not yesterday.
- We need to look for technologies that have the potential to grow, that enable new functionalities, that support the development of smart cities, that use a high ratio of renewable energy from intelligent grid systems, and that are flexible and adaptable.
- We need to consider the beauty of the landscape when we develop our infrastructure and electrified transportation system solutions so they are part of coherent, aesthetically appealing systems.
- We need to consider interoperability across Europe rather than considering only the context and conditions of each country and its specific political situation and logic. We need to consider electrification from the people's perspectives: especially citizens and operators.

In September 2021 the Chinese government licensed 23 new energy heavy truck models. The dynamics of major technology routes distribution for new energy heavy trucks in January, August and September 2021 in China is as follows:

- The hydrogen fuel based heavy trucks accounted for 43.5% % of all licensed EHT models and become the dominant portion of licensed EHTs in China. This is an increase from 5.9% in January 2021.
- The battery swapping based heavy trucks accounted for 39.1% of all licensed EHT models. This is an increase from 17.6% in January 2021.
- The fully integrated battery and heavy trucks vehicles only accounted for 13.0% of all licensed EHT models. This is a decrease from 76.5% in January 2021.
- The ICE hybrid based heavy trucks are falling down to only 4.4% of all licensed EHT models. This is a decrease from 6.7% in August 2021.

The main conclusion of this information is that the hydrogen fueled and the battery swapping based EHTs are taking the market lead in China in 2021.

- Our estimation is that in the field of new energy heavy truck, a phase of comprehensive promotion and application of battery swapping EHTs is taking place.
- Our estimation is that battery swapping and hydrogen based heavy trucks might become the dominant technology for electric heavy trucks in China.

Keywords: Transportation electrification, charging infrastructure, battery swapping, battery exchange, electric trucks, electric vehicles.

OUTLINE OF THE PAPER

This paper consists of six main parts:

Part one
New-energy heavy trucks in China

In this introduction we present some background information for the project regarding transportation development electrification in China, overall numbers for transportation development focusing on heavy trucks, and some key figures for electric truck development. We outline the context of heavy trucks to understand the size of the total Chinese heavy truck market.

Part two
Battery swapping for heavy trucks in China

In this part we introduce battery-swapping technology as the key area of our research. We present a historical overview of the development of battery swapping in China and key electric truck manufacturers that are using this technology and discuss the ways in which cable-based charging electric heavy trucks (EHT) do not suit all the needs of potential operators and users.

We also discuss the main barriers to establishing battery swapping and dissemination of the solution, as well as the main contributions of battery swapping and the policies needed to support dissemination of the technology.

Part three
Technological approaches to battery swapping for heavy trucks in China

Here we describe different approaches to establishing battery swapping for trucks and buses, different swapping solutions and technical standards, and offer a basic technical review of battery-swapping solutions.

This section also presents a technological overview of the dominant truck manufacturers using battery swapping and the technical specifications and performance of their vehicles. In addition, we introduce some basic financial aspects and illustrate the new ecosystem design and key actors for EHT battery swapping.

Part four
Chinese approach to developing battery-swapping electric heavy trucks

In this section we describe what we see as the Chinese approach, which is heavily focused on developing massive systems such the electrification of the transportation system. Several cooperating companies have joined forces to focus on specific projects focusing on both the customer's perspective and the business side of the project. Together they are developing solutions, creating a new ecosystem, and exploring new business models. Often, they buy shares from each other to ensure transparency, trust, and long-term strategic partnerships. Their collaborative capabilities are carried from one project to the next.

Different companies are involved in these cooperative partnerships in different regions of China, and the specific companies involved depends on the characteristics of each specific project.

Part five
The battery-swapping business model - separating ownership of battery and EHT

The development of battery swapping must consider two main challenges: the technology itself and the business model needed to make the technology economically feasible.

In this section we elaborate on one specific battery-swapping business model for trucks based on separating ownership of the vehicle and the battery. This approach lowers the vehicle price and reduces the operator's share of the risk and uncertainty of the battery.

This business model is based on a new ecosystem of actors that includes energy suppliers, investors, truck manufacturers, and battery-swapping station operators and developers.

The new business model of separate vehicle and battery ownership opens up new business opportunities in services such as energy storage and energy balancing and enables reuse of batteries in a second and third lifecycle.

Part six
Battery-swapping EHT projects - Empirical illustrations of battery-swapping EHTs

This section briefly reviews six projects that all use battery-swapping trucks. We present both specialized projects and large-scale projects involving hundreds of battery-swapping trucks in China.

This set of cases illustrates a variety of operational logics and system solutions for battery-swapping EHT systems. Each case is market-oriented and has a strong focus on the operators' businesses.

Part Seven
Conclusions and Discussions

In this part we reflect on the development of electric heavy trucks and the operational bottlenecks of short driving ranges and long charging times due to the technological shortcomings of battery energy storage, the large energy consumption of EHTs, and current charging technology, even so-called "fast charging." Today's EHT offerings and charging infrastructure do not meet fully operators' expectations and needs.

In this section we describe and analyze the Chinese approach to developing system solutions through intensive dialog and strategic positioning of the chosen technology. We also stress that technology development and full-scale implementation in demonstration projects is largely driven by commercial considerations based on operator needs.

Part Eight
The role of heavy trucks in Europe

In this section we describe electrification in the EU and the strong focus on establishing charging infrastructure based on cable charging as a singular solution even though demand largely exceeds the charging supply.

We explore three Electric Road System (ERS) projects in Sweden that use conductive technologies—one using conductive technology, and one new permanent ERS project to be implemented. We also explore Volvo's and Scandia's current EHT offerings and their ability to use the ERS system being developed and implemented.

We propose that battery swapping can complement current cable charging of EHTs, particularly as a technology that supports both intercity and intracity operations.

RESEARCH METHODOLOGY

This research is based on primary data gathered during company visits, observations, and interviews, and secondary sources in English and in Chinese. One senior research team member, Dr. Jasmine Lihua Liu, is of Chinese origin and allowed the research team to explore this topic from Chinese perspectives, both in terms of the literature search and in terms of providing an understanding of the Chinese societal, cultural, and contextual environment as it relates to transportation electrification and the development of battery swapping in China. We participated in and observed webinars, conferences, and discussions among experts to deepen our understanding.

Dr. Liu is an experienced researcher of the transformation towards renewable energy in both the Swedish and Chinese contexts. She received her PhD in Innovation Sciences from Halmstad University in 2019 and thus is well oriented to the Swedish context.

Part of the research team travelled to China from October to December 2020, where they visited corporate organizations, leading research institutions, and major academic centers in Beijing, Shanghai, and Shenzhen. They carried out direct observations and personal interviews with researchers in the area of the transportation electrification systems and discussed the status of battery swapping as a means of reliably supplying electricity to battery-based vehicles. During December 2020, in one intensive week, we conducted company visits, discussions, and formal interviews with key players in the electrification of Shenzhen city, in southern China. This working week was a collaborative venture with the Scania China Innovation Team in Beijing. The information collected during this intensive period in China will be published in forthcoming papers on the development of electrification technology and research on the electrification of Shenzhen, which is the only city in the world that has succeeded in achieving 100% electric taxis and buses and nearly all intra-city logistics and working vehicles.

In May 2021 we collaborated with the Scania China Innovation Team in a joint exploration that entailed corporate visits to several Chinese battery-swapping developers and operators to explore the role of battery swapping for heavy vehicles such as trucks. From April through June 2021, we conducted several seminars in Sweden with participants from academia and industry as a way to share our observations and listen to participants' questions about transportation electrification in China in general, and about battery swapping specifically. This dynamics in our research is a way to create awareness and mutual learning based on our ongoing research on transportation electrification in China.

PART ONE
NEW-ENERGY HEAVY TRUCKS IN CHINA

Introduction:
Why should we electrify transportation systems?

Transportation electrification is a process taking place all over the world and has four main motivations:

- Technology push and opportunities created by technological development, digitalization, and the shift from fossil fuels to renewable energy.
- The pull of demands and expectations seeking to increase the quality of life of people everywhere, improve environmental conditions, and reduce climate change.
- Decarbonization as a specific challenge to address climate change caused by pollution and fossil fuel emissions.
- Transformation of old solutions and old technologies and creation of new technologies, new products, and new markets.

We are facing a social and industrial transformation the scale of which we have not seen for very long time—a new industrial revolution, where energy sources are shifting from fossil fuels to renewable energy and from fossil-fuel vehicles to electric solutions that include both battery and hydrogen-based energy storage. This transformation is driven by the need to conquer new markets with new products. Many interrelated development processes are interfering and pushing up against each other. The consequences are dramatic for industry and business, as well as for government decision-makers and private individuals.

Electrification is taking place nearly everywhere in the world, and thus it is important to grasp, explore, and understand why and how this transformation is taking place in China, an understanding that is currently limited due to geographical distance, cultural differences, and distinct historical roots that are shaping this transformation.

The role of transportation: Where do global CO_2 emissions come from?

The transportation industry plays an important role in CO_2 emissions. Transportation accounts for around one-fifth of global CO_2 emissions (24% if we only consider CO_2 emissions from energy). (Source: Ritchie, 2020)

In 2018, the transportation industry was one of the biggest CO_2 emitters, led by passenger vehicles and followed by freight transportation, aviation, and shipping, as **figure 1** shows. Most emissions from passenger vehicles—cars and buses—which contribute 45.1%. The other 29.4% comes from freight trucks.

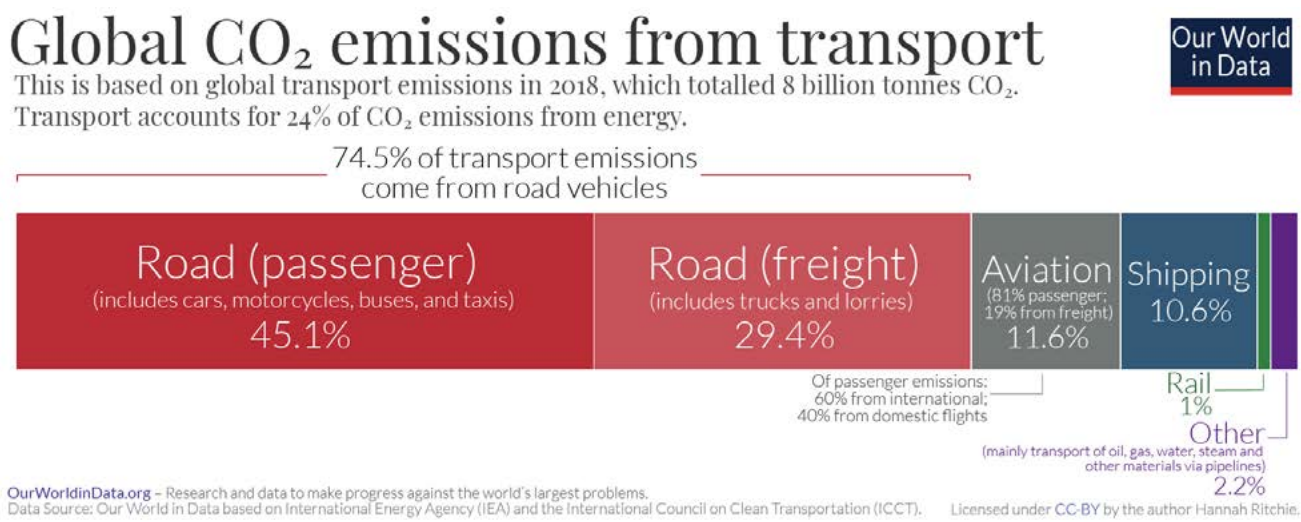


Figure 1: Global CO_2 emissions from transportation in 2018.
Source: Our world in data, 2020.

Towards zero-carbon transportation: How can we expect the sector's CO_2 emissions to change in the future?

Transportation demand is expected to grow globally in the coming decades as populations increase, incomes rise, and more people can afford cars, trains, and air travel. In its Energy Technology Perspectives report, the International Energy Agency (IEA) expects global transportation (measured in passenger-kilometers) to double, car ownership rates to increase by 60%, and demand for passenger and freight aviation to triple by 2070. Combined, these factors would result in a large increase in transportation emissions. Due to historical levels, contemporary levels, and expected future growth, it is crucial and urgent to decrease CO_2 emissions.

Major technological innovations can help offset this rise in demand. As the world shifts towards lower-carbon electricity sources, the rise of electric vehicles offers a viable option to reduce emissions from passenger vehicles.

This is reflected in the IEA's Energy Technology Perspective report, which outlines a "Sustainable Development Scenario" for reaching global net-zero CO_2 emissions by 2070. **Figure 2** shows the pathways for the different elements of the transportation sector in this optimistic scenario.

We see that with electrification and hydrogen technologies, some transportation subsectors could decarbonize within decades. The IEA scenario assumes the phase-out of emissions from motorcycles by 2040, from rail by 2050, and from small trucks by 2060; although emissions from cars and buses are not eliminated until 2070, it expects many regions, including the European Union, the United States, China, and Japan will have phased out conventional vehicles as early as 2040.

Other transportation sectors will be much more difficult to decarbonize, according to the IEA.

Change in transportation CO_2 emissions between 2020 to 2030

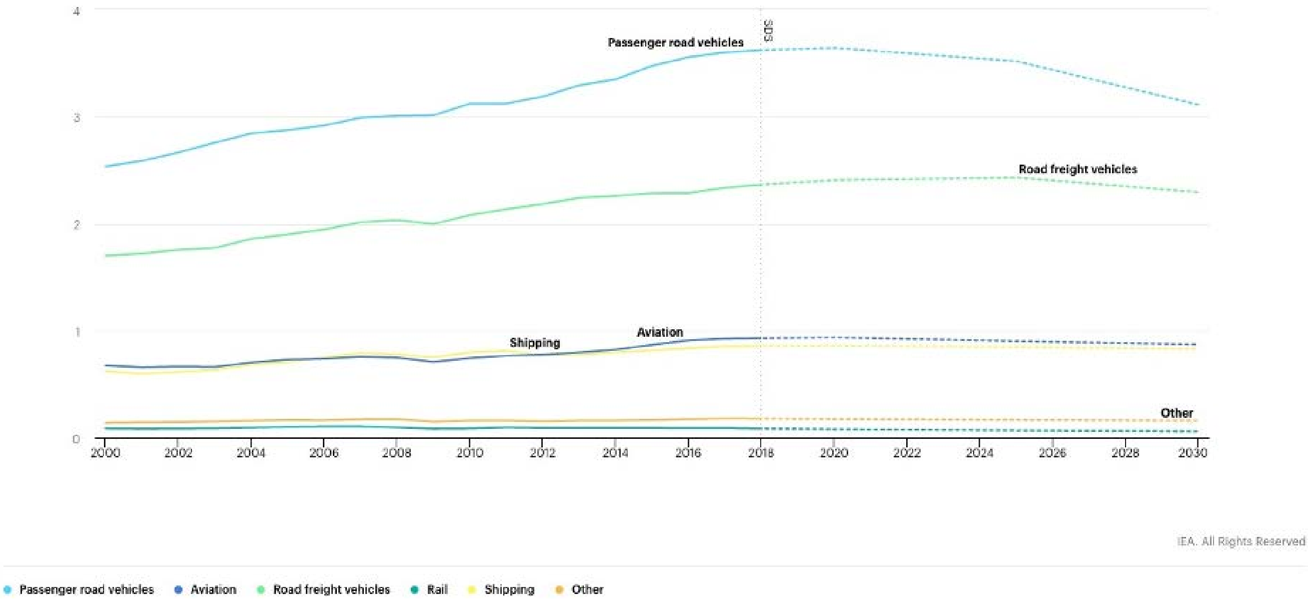


Figure 2: Change in transportation CO_2 emissions between 2020 to 2030.

Source: IEAE, 2021,
https://www.iea.org/data-and-statistics/charts/transportation-sector-co2-emissions-by-mode-in-the-sustainable-development-scenario-2000-2030

Figure 2 shows that peak CO_2 emissions is expected to occur in 2020 for passenger vehicles and 2025 for freight transportation. This shows that global technology transformation is a slow and complicated process.

Achieving this transformation requires grappling with different contexts, conditions, and opportunities in different parts of the world. We can try to develop and implement different solutions globally, or we can learn from each other—both successes and failures.

Background to our research

The Sweden-China Bridge project sought to bring understanding and learning from the Chinese actors, reflecting the specific Chinese context and conditions for transportation electrification. This report focuses on the development of battery swapping for heavy trucks in China.

Our research on transportation electrification in China extends back to 2018, when we made our first exploration into development of this process in China. Our purpose was to explore the status of electric road systems (ERS), but what we found was that China is not developing ERSs in the way Western countries conceptualize them, using conductive technologies such as rails embedded in roads (with vehicles that have a pick-up to receive electricity) or overhead wires (such as trams). Our observations from 2018 indicated that China was pursuing large-scale electrification of the entire transportation system based on modern technologies that enable interconnectivity and using forthcoming electromagnetic technologies such as inductive charging and solar roads (solar panels on the road surface).

We discovered that the Chinese context was quite different than we were used to. In particular, China's massive urban populations create the key differences from the west. The size of the vehicle fleet, the intensity of transportation system usage, and the scale and density of China's cities demand different approaches to electrification not based on electromechanical technologies such as conductive charging infrastructure using overhead wires, embedded electric rails, or cable charging infrastructure. We also needed to understand China's positive attitude towards the opportunities afforded by technological development, and the general social progress that would be enabled by it.

This research encouraged us to establish a new project, which was launched in 2020, with a wider scope focusing on the variety of technologies being developed in China for transportation electrification. The research design was exploratory, in order to identify new findings.

This large-scale electrification and its consequences on societal and industrial development is obvious when looking at Shenzhen city in the southern province of Quandong. Shenzhen started electrifying its transportation infrastructure 15 years ago, and by 2020 Shenzhen had achieved:

- 100% electric buses (about 16,000 units)
- 100% electric taxis (about 22,000 units)
- a majority of electric intercity trucks, with a volume of about 86,000 new-energy logistic vehicles

The entire electric transportation system is charged by hundreds of charging piles, cable charging infrastructure that can be used by all public and private electric vehicle operators and owners in the city.

During our research from October to December 2020 we identified emergent battery-swapping technology in China as something new and interesting that hadn't paid much attention to beforehand in the Western context. Our impression from the Western context was that battery swapping was not seen as something important to transportation electrification. Western countries focused and still are focusing on cable-based vehicle charging. Even the new situation of transportation electrification in Europe under the European Green Deal included no discussions of battery swapping—only battery charging via cable-based fast charging or, in Sweden and Germany, electric road systems (ERS). However, in China, the battery-swapping mode was placed on the national strategic level, and in 2020 was shown to have high national and commercial importance. This is why we focused our research on battery swapping, as an emerging technology that might merit global attention and could have an impact on how we view electrification and solutions to the challenge of charging electric vehicles. How was it possible that China had put such high expectations on battery swapping while nowhere in the West was battery swapping considered as a potential complementary solution to cable charging infrastructure?

Our first extensive report, "Exploring Battery Swapping for Electric Vehicles in China 1.0," published in the spring of 2021, focused on passenger vehicles. This report, in turn, focuses on heavy vehicles—specifically heavy trucks.

Our approach

Our research employed a systems approach in which energy sourcing and energy consumption are viewed as two sides of the same coin. Changing the energy consumption side of the equation to electricity requires that energy sources be in balance with electrification; otherwise, gains made on one side will be lost on the other side. Policymakers and industrial actors both face this dilemma, as the following reflections from two key actors show:

Edmund Araga, president of the Electric Vehicle Association of the Philippines, said:

> *"I would say, yes, right now it is definitely ripe to be scaled up in a more profound way."*

And there's the small matter of all the EV lobbying by the ultimate "tech bro," Tesla CEO Elon Musk, who tweeted in late January 2020:

> *"Battery cell production is the fundamental rate-limiter slowing down a sustainable energy future. Very important problem."*

Musk's statement stands in contrast to the views expressed by another auto industry leader in December 2020. Addressing year-end news conference in his capacity as chairman of the Japan Automobile Manufacturers Association, Toyota President Akio Toyoda blasted politicians for their aggressive push to get rid of vehicles powered by internal combustion engines (ICEs). In a country like Japan that gets most of its electricity from coal or natural gas, EVs don't help the environment, and the Wall Street Journal quoted Toyoda as saying:

> *"The more EVs we build, the worse carbon dioxide gets."* (Jaipragas, 2021)

This discussion reveals the struggle between different technological pathways—battery or hydrogen—as seen in the different paths chosen by Tesla and Toyota.

> *It was the Toyota Prius, released in Japan in 1997, and worldwide in 2000, that became the world's first mass-produced hybrid electric vehicle, combining a combustion engine with a battery-powered electric drive. Toyota started the new-energy vehicle (NEV) revolution, although few really saw it in that way at the time. Toyota foresaw societal challenges, they invented solutions, they developed the markets, and they created the innovation of hybrids. At that time, it was a revolutionary approach.*
>
> (Danilovic & Liu, 2021, p16)

Toyota's focus in vehicle electrification has been towards hydrogen technology, reflecting the Japanese context of energy production and its aim to become a leading supplier of vehicles at the next technology level as ICE and hybrids are abandoned, at least in developed countries. The Toyota Motor Corporation and the BMW Group have been working on joint development of fuel cell drive systems since 2013. Several other companies are also striving to develop hydrogen fuel cell systems, including Volvo, Daimler, Hyundai, and Nikola. The total transformation to NEVs based on electrification and the use of hydrogen as energy storage is on the horizon.

The global development of new-energy vehicles (aside from hybrid technologies) are all based on electric drive systems using electricity as the energy source. This electricity must be either supplied to the vehicle either on the road via conductive or inductive energy distribution systems or carried onboard through batteries (Battery Electric Vehicles, BEVs) or hydrogen fuel cell storage (Fuel Cell Electric Vehicles, FCEVs). Other technologies might be developed in the future. But in 2021, only two pathways are evident: electric batteries or hydrogen fuel cells.

In 2021, battery-based heavy vehicles take a lead globally

Because development works quickly and electric vehicle dissemination still is very slow, we need to be open minded to emerging technologies, which may demonstrate new directions that we do not see today. We also need to be aware of the challenges posed by the need for a system perspective when working on this transformation: the energy supply side needs to balance with the energy consumption side to achieve environmentally friendly and sustainable solutions.

> *On May 14, 2021, a grand ceremony was held in Tangshan, Hebei province, to mark the delivery of 1,000 units SAIC Hongyan electric heavy-duty trucks to their customers. Considering its customer's special needs to transportation the products from Tangshan Steel, SAIC Hongyan is powered by 282 kWh batteries made by CATL. With its motor reaching a rated power of 250 kWh and a peak power of 360 kWh, the electric heavy-duty truck delivers impressive power performances. In addition, it only takes three to five minutes to get its traction batteries replaced … … in April 2021, SAIC Hongyan secured an order of 2,000 units new-energy heavy-duty trucks powered by lithium iron phosphate batteries from Wu'an, Hebei and an order of 1,000 units new-energy heavy-duty trucks recharging battery-powered electric trucks from Jincheng, Shanxi.* (Sara, China Trucks, 2021)

In Sweden, a total of 30 battery-based heavy trucks have been registered. This indicates the speed and the pace of development and dissemination of battery electric trucks in China and Sweden. In the case of Chinese manufacturer SAIC, all its BEVs are designed with swappable battery packs.

So far, the achievements in electrification and the introduction of EVs can be summarized as follows:

Key figures for global electric vehicle use

- The total number of vehicles in the world in 2019 was 1.4 billion.
- The total global stock of electric vehicles was 7.2 million in 2019, of which 47% were in China.
- About 1.5 million electric vehicles were added to the worldwide fleet in 2019.
- Global electric vehicle sales passed 2.1 million vehicles in 2020, up from the 1 million level in 2017 and surpassing the record year 2018.
- Electric cars accounted for 2.6% of global car sales compared to 1.5% in 2017, which is about 1% of the global car stock in 2019, and represents a 40% year-on-year increase.

Figure 3: Key figures for global electric vehicle use.
Source: Global EV Outlook, 2019.

Vehicles that are using batteries for their energy source and energy storage are the current leading solution among electrical vehicles. Thus, “refueling” or charging batteries become one major issue for making electric vehicles feasible in real-life situations. Vehicle batteries can be charged in several ways: static conductive charging via cable, static or dynamic conductive charging via overhead wires or road-embedded rails, static or dynamic inductive charging, or physical exchange of the vehicles’ batteries.

The battery exchange alternative—battery swapping—has garnered great interest in China and many other developing economies in recent years, particularly for two- and three-wheeled vehicles. This battery swapping approach is now tackling the heavy vehicle sector, such as trucks and buses. As a result, this approach to “refueling” electric vehicles is important to explore, and we need to understand the conditions needed for battery swapping to succeed.

Battery charging is a challenge

To achieve successful transportation electrification, we need to understand the role of different vehicle charging solutions. This report focuses on conductive technology that involves the physical exchange of empty batteries with fully charged ones, an approach called battery swapping.

> *The global electric vehicle battery-swapping market was valued at $100.1 million in 2020, and is projected to reach $852.6 million by 2030, registering a CAGR of 24.4%.*
>
> (Allied Market Research, 2021)

Although this market review seems interesting and the business potential is large, it is based on limited exploration of development in the largest electric vehicle market in the world, China.

Only the Chinese passenger vehicle manufacturer NIO is pursuing battery swapping as the standard solution for its entire fleet. In our research we focus on the Chinese context and have identified the main actors—both manufacturers and third-party suppliers of battery-swapping system solutions. We believe that the market potential is much larger than what is indicated by Allied Market Research (2021), based on the information we have indicating that by 2025 there may be approximately 25,000 battery-swapping stations for passenger vehicles installed in China. Chinese vehicle manufacturers are entering the European market, and brands such as NIO, BAIC, AIWAYS, SAIC, and XPeng that are starting to sell BEVs in Europe. All of these brands have battery-swapping technologies. BAIC has established a taxi system in several Chinese cities using its battery-swapping BEV cars. One Chinese supplier of battery-swapping technology for trucks has established operations in Europe, striving to collaborate with European manufacturers in establishing swapping technologies. Thus, we have reason to believe that the time has also come for battery swapping in Europe.

The purpose of our research

This report focuses on the role of battery-swapping heavy trucks as part of the electrification of the Chinese transportation system, with the following aims:

- To explore the status of battery-swapping EHTs in China in order to understand the forces driving the development and large-scale commercialization of this technology.
- To explore the interplay among key actors making this technology possible.
- To understand the business models that make battery-swapping EHTs a smart business choice and a commercially usable technology.
- To understand the conditions needed for battery-swapping EHTs to support society’s transformation to an electrified transportation system.

This research will be presented as one component of the research project our team is undertaking and as a complement to our April 2021 publication focusing on battery swapping for passenger vehicles.

The status of electric heavy vehicles in China

According to international standards and China's national standards, trucks with a total weight of more than 14 tons are classified as heavy trucks. At present, there are a total of more than 281 million vehicles in China. Although heavy trucks only account for about 2.04% of all vehicles in China, they generate 52.4% of particulate matter and 74% of nitrogen oxide pollution from all vehicles in China. To achieve its goal of carbon neutrality by 2060, development of new energy heavy truck is vital, and the charging infrastructure is crucial.

However, between 2018 and 2020, the development of new-energy heavy trucks in China was not progressing smoothly:

- In 2018, fewer than 700 electric heavy trucks (EHT) were sold in China.
- In 2019, the total sales volume of EHTs was more than 5,000 of which about 3,000 relied on a subsidy of CNY 800,000 (~US$123,650) for each truck.

The sales volume in 2020 was greatly affected by the reduction in subsidies, with sales of only about 2,600 vehicles.

Table 1 summarizes electric trucks sales in China for 2018-2020.

Electric trucks sales in China

Year	Sales volume of electric trucks
2018	Less than 700
2019	More than 5,034
2020	2,619

Table 1: Electric heavy truck sales volume in China, 2018-2020.
Source:
www.cvworld.cn, https://www.sohu.com/a/447829002_376032

Feedback from the actual operation of the industry indicates that battery-based electric vehicles (BEV) solutions cannot fully meet the operational needs of truck operators and users. Research shows that light electric commercial vehicles with a total weight of less than 3.5 tons can replace fossil-fuel vehicles at the same price level in terms of cost, freight capacity, driving range, and driving experience. However, BEVs using today's technology have yet to become the best choice for freight vehicles larger than 3.5 tons due to the challenges of energy consumption and vehicle weight.[1]

Compared to lithium battery systems, hydrogen fuel cells offer a longer range, shorter charging time, lower weight, and more potential for performance improvement. The Chinese believe that in the long run, hydrogen fuel cell heavy trucks will come to prevail in long-distance transportation. Ouyang Ming Gao, an influential EV researcher at the Chinese Academy of Sciences, has said publicly:

> *"At least by 2030, pure electric vehicles will be major solution in the field of passenger cars, and fuel cell vehicles will be more suitable in the field of commercial vehicles."*
>
> (Ouyang Ming Gao, 2021)

This assessment was also put forth as part of an industry-wide discussion about selecting the technical pathway for electric vehicle development a few years ago. However, the annual sales volume of HFC heavy trucks has been stagnant since then. By the end of 2020, only 7,352 fuel cell vehicles in total were in operation in China, and only 18 fuel cell heavy trucks were sold in 2020.[2]

Lack of technological maturity, lack of hydrogen filling stations, and the cost of clean hydrogen solutions for heavy trucks across the whole value chain are the major obstacles to the growth of HFCEVs. Fuel cell heavy trucks need more time to develop sustainable technology and system solutions.

According to Chinese industry experts, by 2035 there will be about 5 million light electric commercial vehicles and 600,000 medium and heavy electric trucks in China.

The general expectation for the future is quite certain, but it is not yet clear whether BEVs or HFCEVs will evolve fast and win the competition.

Structure of the Chinese EHT market in 2020

There are many application scenarios for heavy trucks.

- In 2019, the sales volume of logistics heavy trucks accounted for about 72% of all heavy trucks, including tractor semitrailers, tractor trucks, grid-type transportation vehicles, vehicle transportation vehicle, and other vehicle types related to freight transportation.

- The sales volume of construction vehicles in 2019 accounted for about 28% of all heavy trucks, including dump trucks, concrete mixer trucks, truck cranes, and other vehicles used in construction.[3]

In 2020, a total of 2,619 new-energy heavy trucks were sold in China, down 48% from 5,034 in the same period of 2019. This contrasts with China's overall heavy truck market, which grew by 38% in 2020. However, compared with the same period in 2019, the new-energy tractor market segment saw a substantial growth, with an explosive increase of 903% over the same period of 2019.

According to an analysis by CVWORLD (www.cvworld.cn), the dramatic sales volume difference between 2019 and 2020 was mainly caused by the fact that Shenzhen and other regional bulk material handling companies purchased more than 3,000 electric dump trucks in 2019. In 2020, the demand for new-energy dump trucks dropped in comparison, seeing a year-on-year decrease of 87.5% that contributed to the sharp decline in the new-energy heavy truck market as a whole for 2020.

Proportion of new-energy heavy trucks by fuel type in 2020

All new-energy heavy trucks sold in 2019 were BEVs. In 2020, 98.7% were BEVs, while 0.69% were HFCEVs and 0.61% were hybrid vehicles.

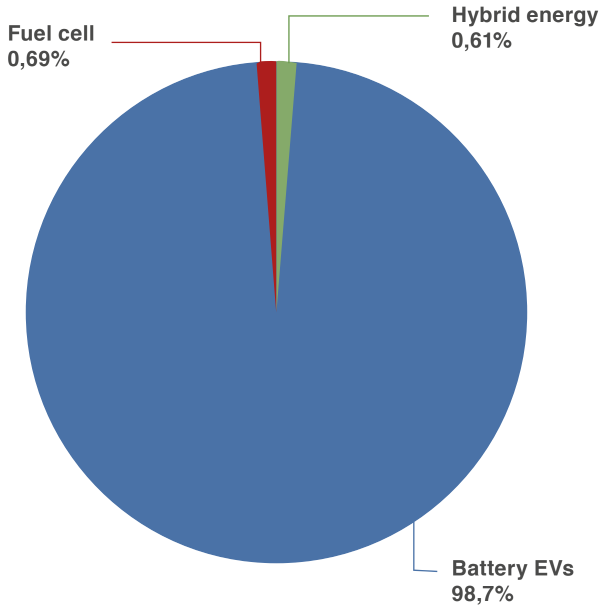


Figure 4: Proportion of new-energy heavy trucks sold in China, by fuel type, 2020.
Source: https://www.sohu.com/a/448565278_526280

Figure 4 shows that the BEVs are taking the market lead with a 98.7% share. The established subsidiaries for hybrid EHTs are being phased out, and in Shanghai subsidies are no longer offered for the hybrid passenger vehicles—only fully electric vehicles. This indicates the direction of policies supporting this technology transformation.

Proportion of new-energy heavy trucks by product type in 2020

Figure 5 shows the new-energy heavy truck market by product type for 2020. In 2020, the sales volume of new-energy special vehicles reached 55.10% of the total new-energy heavy truck market, while tractor trucks and dump trucks accounted for 26.42% and 18.33%, respectively. New-energy freight trucks represented only 0.15%.

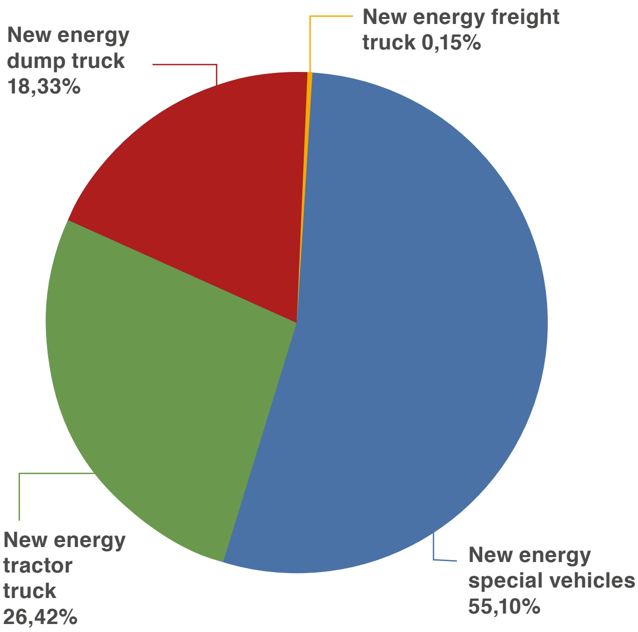


Figure 5: Proportion of new-energy truck sales by product type, China, 2020.
Source: https://www.sohu.com/a/448565278_526280.

Thus, the majority of new-energy heavy trucks currently sold are special urban vehicles such as street sweepers, garbage trucks, sprinkler vehicles, and vacuum trucks. These vehicles operate within a limited urban area along relatively short, fixed operation routes, making them convenient to charge; as such, they are the most suitable application for current new-energy heavy truck technology.

Regional distribution: Guangdong, Henan, and Beijing dominate the market

The main sales areas were Guangdong province (more than 1,000 trucks), Henan province (348 trucks), Beijing (297 trucks), Hebei province (132 trucks), and Shanxi province (123 trucks).

OEM brand distribution

In 2020, among the top ten new-energy heavy truck manufacturers, five are general truck manufacturers:

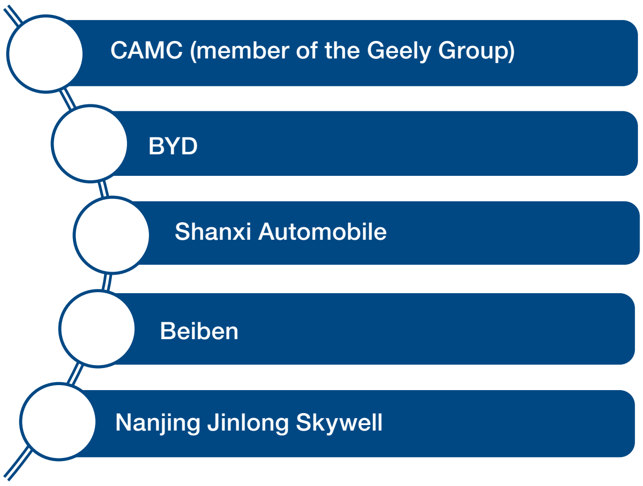


Figure 6: Five key new-energy truck manufacturers in China
Source: Author's summary.

The remaining five manufactures produce special vehicles for specific applications, such as sanitation, and accounting for half of the mainstream enterprises:

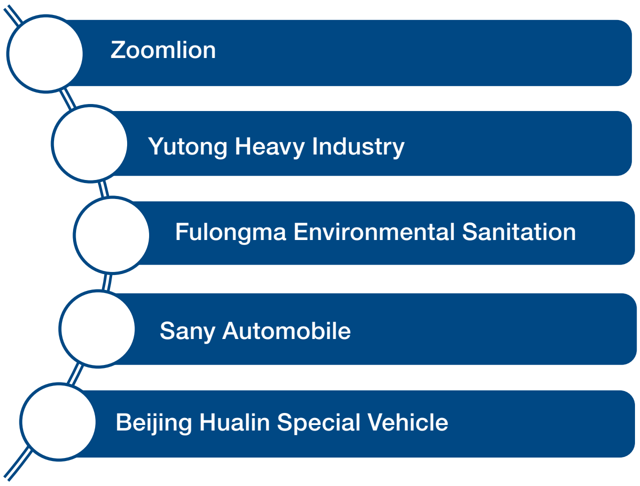


Figure 7: Five main special vehicle manufacturers in China.
Source: Author's summary.

There are some minor truck and special vehicle developers and manufacturers beside those mentioned in the **figure 6** and **figure 7**, but in this report we only focus on the primary manufacturers.

Table 2 lists the top 10 EHT brands in China in 2020, with their sales volumes and market shares for 2019 and 2020.

EHT Brand	Sales volume 2020	Sales volume 2019	Market share 2020	Market share 2019
Total	**2,619**	**5,034**	**100%**	**100%**
Zoomlion	448	394	17.11%	7.83%
Yutong Heavy Industry	336	267	12.83%	5.30%
CAMC	329	69	12.56%	1.37%
Nanjing Jinlong Skywell	309	1,006	11.80%	19.98%
Beiben	249	10	9.51%	0.20%
Fulongma	186	56	7.10%	1.11%
Shanxi Automobile	96	5	3.67%	0.10%
BYD	96	2,853	3.67%	56.67%
Sany Automobile	87	1	3.32%	0.02%
Beijing Hualin Special Vehicle	76	246	2.90%	4.89%
Others	407	127	15.54%	2.52%

Table 2: Top 10 EHT brands in China, 2020
Source: https://www.sohu.com/a/448565278_526280.

Chinese EHT market structure in the first half of 2021

China's new-energy heavy truck market was very hot during the first half of 2021, with orders for more than 15,000 units of new-energy heavy trucks being placed during this period.[4] This creates new historical record for the industry in terms of sales pace and volume, representing 10s of billions of RMB and generating income to support EHT manufacturers' efforts toward improving their EHT solutions. It also means that, based on the current delivery speeds, production capacity for new-energy heavy trucks in the coming few years has already been committed.

Proportion of new-energy heavy trucks by fuel type, first half of 2021

In total, 1,732 new-energy heavy trucks were sold the first half of 2021:

- 1,111 units of BEV EHTs (non-battery swapping), a 64.15% market share.
- 381 battery-swapping EHTs, a 22% market share.
- 240 fuel cell heavy trucks, a 13.85% market share.

Fuel type	Number of units	Percentage in the first half of 2021
BEV EHTs (non-battery swapping)	1,111	64.15%
Battery-swapping EHTs	381	22%
Fuel cell EHTs	240	13.85%

Table 3: Proportion of new-energy heavy trucks sold in China, by fuel type, first half of 2021.
Source: https://new.qq.com/omn/20210728/20210728A04N5300.html.

Sales of fuel cell EHTs grew 13-fold in the first half of 2021 compared to 2020, and battery-swapping EHTs reached their highest market share so far.

Even though the final numbers for battery-swapping EHTs and fuel cell EHTs do not appear to be large, industry exhibitions help illustrate this important industry trend more clearly. At the 2021 China (Nanjing) International New Energy and Intelligent Connected Vehicles Exhibition, held in June 2021:

- 41 total models of new-energy vehicles were exhibited.
- 17 new-energy heavy trucks were exhibited, including:
  - 1 methanol-fueled heavy truck
  - 3 fuel cell EHTs
  - 13 battery EHTs, 11 of which provide both battery-swapping and cable-charging modes.[5]

This indicates that battery-swapping technology is becoming a dominant technology for battery EHTs in China in 2021.

EHT OEM manufacturer figures for the first half of 2021

Table 4 lists the top 10 EHT manufacturers in China in 2019, 2020, and the first half of 2021.

EHT Manufacturer	Sales volume 2019	Sales volume 2020	Sales volume first half 2021	Market share 2019	Market share 2020	Market share first half 2021
All	5,034	2,619	1,732			
CAMC	69	329	382	1.37%	12.56%	22.06%
Beiben	10	249	207	0.20%	9.51%	11.95%
Nanjing Jinlong Skywell	1,006	309	180	19.98%	11.80%	10.39%
Yutong Heavy Industry	267	336	137	5.30%	12.83%	7.91%
Zoomlion	394	448	128	7.83%	17.11%	7.39%
Fulongma	56	186		1.11%	7.10%	
Shanxi Automobile	5	96		0.10%	3.67%	
BYD	2,853	96		56.67%	3.67%	
Sany Automobile	1	87		0.02%	3.32%	
Beijing Hualin Special Vehicle	246	76		4.89%	2.90%	
XCMG			99			5.72%
Dongfeng			91			5.25%
FAW			61			3.52%
Karry			51			2.94%
JMC			49			2.83%
Others	127	407	347	2.52%	15.54%	20.04%

Table 4: Top 10 EHT brands in China in 2019, 2020, and first half of 2021.
Source: https://new.qq.com/omn/20210728/20210728A04N5300.html.

Looking closer in the **table 4**, we can see that the same manufacturers were the top sellers of EHVs for 2020 and 2021: CAMC, Beiben, Nanjing Jinlong, Yutong, and Zoomlion, although their ranking within the top five shifted between the two years. CAMC (Hanma Technology in Chinese), a relatively small general truck producer, is now the leading EHT manufacturer. This company helped pioneer the battery-swapping EHT solution in cooperation with Enneagon (a provider of EHT battery-swapping station solutions) a few years ago. This might contribute to their current market status. XCMG's EHTs garnered new sales from New Zealand, and BYD's EHTs are sold to Budweiser in both China and the United States.

Almost all the major heavy truck manufacturers have now launched a battery-swapping mode for their new-energy trucks, including FAW, Dongfeng, JMC, Shanxi Automobile, and Shanghai Automotive Industry Corporation (SAIC). These major players were slower to join the segment, and that is why they have just start to show up in the sales rankings. However, as traditional major players in the heavy truck market, their strength should not be underestimated. SAIC—one of China's largest truck manufacturers—has taken the lead in new EHT orders for the first half of 2021 and has announced orders of some 6,000 new-energy heavy truck units so far. It has successively realized batch deliveries in Hebei, Shanxi, Hebei, Henan, Guizhou, and other provinces.

SAIC is just one of today's game changers. It is very likely that the list of top-selling Chinese EHT brands might will look different in the coming years.

Battery-swapping heavy trucks enter the scene in 2021

Until now the introduction of electric vehicles in China has focused on passenger vehicles, but heavy trucks are the focus of future EV expansion. Since July 1, 2021, China has implemented its national phase VI emission standard, which enforces more stringent standards for environmental emissions from heavy diesel vehicles. This will further expand the market for EHTs. Starting in the second half of 2021, China will conduct a nationwide pilot program for battery-swapping EVs, with specific initiatives that include pilot applications of battery-swapping EVs for public transportation, taxis, urban logistics and distribution, and port and mine operations. Local governments are also encouraged to introduce policies to support the battery-swapping EVs, and financial and insurance products suitable for the development of battery-swapping EVs are being developed and launched. These efforts will further promote growth in the battery-swapping EHT segment.

It should be noted that while most of new battery EHTs are equipped with both cable-charging and battery-swapping modes, some major EHT suppliers are trying to develop battery EHTs and fuel cell EHTs simultaneously: for instance, Dongfeng and SAIC. Now it is up to users and operators to decide whether they prefer cable-charging or battery-swapping battery solutions or fuel cell trucks.

Nobody knows which technological pathway will be the dominate solution for EHTs in 10 years' time, but several things are clear now. First, EHTs are coming. Second, battery-swapping EHTs are currently getting its opportunity to be used and fine-tuned in the Chinese context. Third, fuel cell EHTs are evolving at the same time but remain a less- mature solution. The practical results and lessons from the Chinese experience will be very interesting to keep our eyes on.

PART TWO
BATTERY SWAPPING FOR HEAVY TRUCKS IN CHINA

Electric heavy trucks go battery swapping

At present, there are in total more than 100,000 battery-swapping electric vehicles in China, accounting for less than 3% of all new-energy vehicles.[6] By the end of 2020, China offered a total of 24 new-energy vehicles models that support battery swapping, of which passenger vehicles were majority, along with a small number of freight vehicles and buses.

There are different strategies for implementing battery swapping:

- NIO (a developer of battery-swapping electric passenger vehicles) represents one approach, focusing entirely on battery-swapping vehicles for the passenger vehicle market. Its entire passenger EV fleet is designed for battery swapping.
- Other Chinese passenger manufacturers are mainly exploring battery swapping as complementary approach to cable charging for BEVs, specifically targeting fixed-site, fixed-route, and high-intensity operating scenarios, such as taxi, ride-sharing vehicles, and time-share rental cars.
- Manufacturers of heavy trucks such as logistics vehicles, dump trucks, and concrete mixers, among others, are also using battery swapping as complementary solution to cable charging of EHVs.

Some manufacturers have established new ecosystems, integrating R&D of battery-swapping technologies, manufacturing of battery-swapping vehicles, operation of battery-swapping stations and mobility services, energy production and energy distribution, new green investors, and more, seeking to expand battery-swapping options from the public market to the private passenger market in the future.

The increasingly clear choice of battery swapping for heavy trucks, including dual cable- charging and battery-swapping modes, opens a new pathway to break through one of the bottlenecks limiting the market for electric heavy trucks. Such dual-mode vehicles means operators are not limited by the usual time/range limitations of battery EHTs and the long recharging times for cable charging. Rapid battery swapping enables trucks to operate over longer distances either by swapping batteries or via cable charging. This gives operators a choice.

China had about ten million heavy trucks on the road in 2020, about one million of them operating in short distance/high frequency operation scenarios. These one million trucks are seen as an ideal market for battery-swapping EHTs. In addition, battery swapping eliminates the barriers for intercity EHT operations.

The short history of battery swapping for heavy trucks in China

Pilot battery-swapping EHT demonstration in China As early as February 2019, Hua Ling Xingma (now CAMC) manufactured 20 electric heavy trucks with battery-swapping capabilities for a demonstration operation in the Yangtze River Delta region, and built the first EHT battery-swapping station. And the development in the last two years has been the rapid establishment and pick-up of battery swapping as solution and ultimately a standard technology offering.

- In June 2020, XCMG launched more than 20 new-energy heavy trucks and construction vehicles and announced strategic cooperation with the Shiqiao Group, China Jinmao Green Building, CALT, and other leading enterprises in the industry to develop the battery-swapping mode.
- In July 2020, CALT and Foton iblue Automobile jointly build a new electric urban ”Road to Rail” transportation system in Beijing that combines battery-swapping EHTs and rail transportation.
- In October 2020, China’s first intelligent battery-swapping system for EHTs was introduced in the Huaneng Yimin Coal Electric open-pit mine in Inner Mongolia, undergoing 100 days of high-intensity trial operation. This is the start of electric energy substitution in heavy construction vehicles in China.

- In November 2020, the first commercialized application scenario for battery-swapping EHTs was officially launched in Miyun, Beijing. Bulk materials start their green, zero-emission journey in the city through a railway + new-energy heavy truck connection.
- In December 2020, the State Grid Jiangsu power company and XCMG jointly launched the first demonstration project for battery-swapping operation of new-energy urban dump trucks in Xuzhou.
- In December 2020, Shanxi Aluminum's charging and battery-swapping station for the State Power Investment Corporation was officially put into operation. The project includes three sub projects, involving EHT + charging/battery-swapping stations, smart logistics, and photovoltaic generation.
- In February 2021, the first EHT charging and battery-swapping station was opened in Henan province, within the Zhengzhou High Tech Zone. This station can charge up to 100 vehicles a day and operates unattended, 24 hours a day.[7]
- In early 2021, a total of 23 EHT battery-swapping stations have been built in China. In addition, 32 stations are under construction, and the plan is to build an additional 400 stations in the remainder of 2021.[8]

However, the entrance of the major truck manufacturers SAIC, FAW, and Dongfeng into the market, with the potential for much larger large numbers of battery-swapping EVs gives reason to believe that the amount of battery swapping infrastructure will be much larger in the years to come.

Scenarios for EHT use in China

Major scenarios for battery-swapping EHTs in China

Battery-swapping technology is not one-size-fits-all solution that meets the needs of all truck operators, but the advantages of battery-swapping EHTs are clear in certain scenarios. **Table 5** shows the major scenarios for EHTs in China and identifies the most promising scenarios for battery-swapping applications. The first three scenarios have already been explored in pilot projects, while the last scenario has not been tested yet.

Scenario	Example	Operation characteristics
Special line transportation	Fixed-route freight transportation lines, such as from coal preparation plants to railway or port transportation	One-way transportation distance of less than 100 km range without need to supply additional electricity en route
Branch line short-distance transportation	From central stations to surrounding cities, such as railway port container transportation.	Suitable for one-way transportation distances within a 150 km range, with no need to supply electricity en route.
Port transportation	Closed route short distance transportation such as freight and container transportation in ports	**Suitable for 24-hour non-stop operation; batteries need to be swapped several times daily.**
Arterial transportation	For cross-city highway/arterial road transportation, such as auto parts, department stores, less-than-truckload goods transportation.	**One-way distances within 350 km, with battery changes once an route.**

Table 5: Major scenarios for battery-swapping EHTs in China.
Source: http://www.360che.com/news/202006/148794.html

Some of these scenarios are suitable for cable-charging EHTs, while others follow a different operational logic and thus need a different charging solution. The intensity of the operation and the route distance are the two main differentiating aspects. In high-intensity operations, trucks operate continuously between two or more points with no time for lengthy stops to charge. Longer-distance scenarios, particularly intercity transportation, exceed current battery ranges, and a cable-charging mode would waste time in the middle of trips for charging.

Other scenarios, in contrast, do have an operational distance and pace that allows free time between runs that can be used for charging—preferably at night. However, from the operators' point of view, there is another aspect of transportation operation that is unforeseeable and requires adaptation. Trucks need to be flexible and be able to be used for operations that are not foreseen and part of their initial designed from the outset. A fully integrated battery/vehicle BEV cannot be retrofitted for battery swapping after the fact. On the other hand, trucks designed to allow battery swapping can also be used in a cable-charging mode of operations depending on the situation and the transportation operator's need.

Several industry insiders pointed out to us that with a matured technology and an appropriate business model, battery swapping is an appealing pathway toward the electrification of the heavy truck market beyond short-distance transportation scenarios.

The dual mode, cable-based charging and battery swapping, can effectively avoid the "unbearable burden of the whole society" caused by a large need to recycle retired batteries under the fully integrated "one vehicle, one battery" operational mode. Other industry actors, however, question the utility of battery-swapping EHTs given that previous discussions in the industry seemed to have settled on a pathway towards electrification involving cable charging for passenger EVs and hydrogen fuel cells for commercial vehicles. Why, they wonder, is the industry now putting a lot of effort in developing battery-swapping EHTs? [9]

We see, therefore, a competition among different experiences, opinions, perspectives, and OEM strategies: whether to invest in a fully integrated vehicle/battery system using only cable charging, or investing in the dual mode combining cable charging and battery-swapping capabilities. What has become evident is that the arguments for battery-swapping emphasize the ability to use batteries through a second and third lifecycle, their potential use for energy storage and energy balancing, and the opening up of business opportunities buying and selling energy. However, not everyone in the industry anticipates all the benefits of battery-swapping technologies and the new business areas that will arise from them. Battery swapping enables new business opportunities and is a threat to old business actors.

Barriers to the growth of electric heavy trucks in the Chinese market

As one practitioner stated in an interview, the EHTs' high price and operational inefficiency due to short range/long recharging times are the two major barriers that EHTs face in increasing their market share.

> *Inconvenient energy supply and high purchase cost are the bottlenecks in the promotion of electric heavy truck.*

First, EHTs are comparatively expensive. In 2021, the average price of an EHT was almost double the price of a traditional diesel truck, at about 1,000,000 yuan (~US$154,559) versus 400,000-500,000 yuan (US$61,823–77,280). Heavy trucks are considered capital goods, and operators are relatively sensitive to the purchase cost of new trucks. The higher price of EHTs cannot be offset by charging higher prices to customers.

This high initial purchase cost is compounded by several operational efficiencies that EHTs in general, and cable-charging EHTs in particular, face compared to diesel trucks:

- **Reduced cargo capacity.** Due to the weight of the vehicle + battery, the total payload of an EHT is 10–20% lower than a diesel truck, which further reduces revenue. Operators can only earn money on their truck's payload.

- **Time cost of charging.** The fastest battery charging technology currently still takes about 2 hours to fully charge an EHT. If drivers need to travel extra distance to a charging piles, charging effectively takes more time away from the route. For vehicles that operate 24 hours a day, spending 2-4 hours a day charging greatly reduces effective operation time, and hence the operator's income.

Finally, in addition to factors that affect operators' revenues, EHTs also have special requirements in terms of infrastructure that also hinder the promotion and growth of this type of EV at a policy level. Their large size means they require larger charging sites, the use of power capacity is significant, with consequences on electricity distribution and a sizable impact on the power grid. In addition, the charging station planning, and construction is difficult and the cost is higher.

Heavy truck electrification and passenger car electrification are different in important ways. Despite the barriers described above, the role of fuel price is a factor that can work in favor of the adoption of EHTs. Lifetime fuel costs for heavy trucks are at least 3 to 5 times the vehicle's purchase price. This means that the price difference between diesel and electricity can form a very good economic incentive for the heavy truck electrification.

Policies supporting battery-swapping EHTs

National level

The Chinese government keeps close track of developments and challenges in key strategic industries and maintains ongoing dialog with leading companies and experts in these fields. The government uses such dialog and communication when exploring policy options and making policy decisions. Sometimes the government explores several possible technological pathways together with industry actors through government-funded research projects or pilot projects and programs.

- Sometimes government representatives visit key companies or pilot projects to understand technical developments in strategic sectors and understand practical experiences and outcomes.
- Sometimes industry actors or academic researchers who are members of the Chinese People's Political Consultative Conference (C.P.P.C.C.) or the National People's Congress (NPC) submit proposals at the two annual national meetings, offering suggestions for industry development to the government.
- Sometimes the government invites a number of actors to participate in cross-industry joint discussions on key development problems or issues, with the support of industry associations.

Using these forms of communication and dialog, the Chinese government develops, implements, and revise policies or measures to promote the development of strategic industries.

Since 2019, the Chinese central government has established the following policies to support the development, establishment, and growth of battery-swapping technology.

- In June 2019, the National Development and Reform Commission of the Ministry of Ecological Environment and the Ministry of Commerce issued the Implementation Plan for promoting the renewal and upgrading of key consumer goods and streamlined resource recycling (2019-2020) to encourage enterprises to develop new-energy vehicle (NEV) products that combine charging and swapping modes.
- In March 2020, charging and battery swapping infrastructure construction was incorporated into the new national infrastructure construction campaign.
- In April 2020, the Ministry of Finance and four other ministries and commissions jointly issued the Notice on Improving the Financial Subsidy Policy for the promotion and application of NEVs, which clearly sought to encourage the development of the new business model of "separate ownership of vehicle and battery" and established a more favorable subsidy policy for NEVs that using battery-exchange technology.
- In May 2020, the Ministry of Industry and Information Technology recognized a battery-swapping mode for electric vehicles as a new vehicle mode for the first time. Battery-swapping vehicles thus received an independent identity for their launch to market.

- In July 2020, the National Energy Administration announced their support for business model innovations within the area of charging and battery-swapping modes.
- In July 2020, the Ministry of Industry and Information Technology emphasized their continued promotion of charging and battery swapping infrastructure construction and the development of battery-swapping EV models for various usage scenarios, and promoted a pilot battery-swapping project in the Beijing region and Hainan province.
- In August 2020, the Ministry of Industry and Information Technology's "Action Plan for Promoting Electric Vehicles in Public Service Areas" took shape. According to the action plan, China will promote the application of new-energy trucks and take the lead in new-energy heavy truck use in specific scenarios, such as short-distance transportation, urban construction and logistics, and mine and port operations. Regions or cities whose conditions are favorable are encouraged to support new-energy heavy truck research and utilization.
- In October 2020, the Ministry of Industry and Information Technology issued a response letter to the proposal for "Electrification of Heavy Trucks and Construction Vehicles" submitted by Yuqun Zeng, the president of CALT (a world-leading battery manufacturer) at the 2020 CPPCC conference. The ministry response supported his suggestions for promoting the electrification of government construction and freight truck vehicle fleets.
- In November 2020, the State Council issued The New-Energy Vehicle Industry Development Plan (2021-2035), which pointed out the need to further pursue the construction of charging and swapping infrastructure and which encouraged the implementation of a battery-swapping mode in future BEVs. This is the most important strategic plan that will guide NEV development in China over the next 15 years.
- On July 1, 2021, the National Phase VI Emission Standard for Heavy Diesel Vehicles took effect; this standard enacts more stringent limits for environmental emissions from diesel vehicles and will help further open up the market for EHTs.
- In the second half of 2021, the Chinese central government will begin to carry out nationwide pilot programs for of battery-swapping BEVs. The specific initiates include encouraging pilot applications of battery-swapping BEVs in areas such as public transportation, taxis, urban logistics and distribution, ports, and mines; encouraging local governments to introduce relevant policies to support battery-swapping BEVs, and developing and launching financial and insurance products to support the development of battery-swapping BEVs. This will further promote the development of battery-swapping EHTs throughout China.

Regional level

National strategic policies and directions have been closely followed by regional governments, who are competing intensely in areas of social and economic development. The region that most quickly implements central government decisions and successfully develops strategic products and services has the chance to be a benchmark or prototype for development throughout the rest of China. Such an achievement is seen as an important accomplishment at the regional and provincial level and showcases a region or province's progressiveness and capabilities.

Shenzhen is the pioneer city in electronic industry and is considered China's Silicon Valley. Shenzhen was also the pioneering city for BEVs development in China. In December 2020, Shenzhen's Municipal Development and Reform Commission, Municipal Transportation Bureau, and Municipal Finance Bureau jointly issued the "Measures for Operating Mileage Assessment and Excess Emission Reduction Award for the First Batch of Electric Dump Trucks (2018-2019)," which is valid for five years.

According to the policy, BEV trucks that were put into operation between November 14, 2018, and December 31, 2019, and meet other relevant conditions can apply for an excess emissions reduction incentive calculated according to operating mileage, with the maximum incentive being 800,000 yuan/vehicle (~US$123,648/vehicle).[10] This award is given after results are demonstrated, and is seen as a way of recognizing and supporting further progress towards transportation electrification.

Other regional governments have launched or are launching policies that support battery-swapping cars and trucks. In March 2021, Hainan province issued a draft version of the ”Hainan Province Guidance Supporting the Construction of Electric Vehicle Battery-Swapping Stations.” This policy especially encourages battery-swapping services that target heavy vehicles, taxis, ride-sharing apps, buses, intercity buses, tourist buses, and so on. Regional governments will subsidize 15% of the developers' costs in building battery-swapping stations that are built between January 1, 2021, and December 31, 2025.[11]

Guangzhou city provides 2,000 yuan/kW (~US$309/kW), and Yunnan province provides 300 yuan/kW (~US$46.4/kW) in subsidies toward battery-swapping station construction costs. Hefei city provides 0.6 yuan/kWh (about 9.3 cents/kWh), Shanghai provides 0.4 yuan/kWh (about 6.2 cents/kWh), and Chengdu city provides 0.2 yuan/kWh (about 3.1 cents/kWh) in subsidies toward the operational costs of battery-swapping stations.

Latest progress after China's 2021 annual CPPCC and NPC meetings: Battery-swapping EHTs might become the new standard

Generally speaking, every year in March, members of the CPPCC and NPC gather together in Beijing to participate in their meetings—the CPPCC first, followed by the NPC. Members come from different regions and provinces, involving different industries and areas. At the CPPCC meeting, members present opinions and suggestions to government officials through research reports, proposals, or other forms, containing ideas and suggestions for development and improvements. An appropriate government agency is assigned to address the proposal, depending on its content. The agency exchanges views with the proposal authors through phone calls, discussions, and investigation, or in-person meetings. After the proposal is processed, the agency drafts a reply to the proposer and related actors. At the NPC, the central government reports on its work over the past year and submits a budget and working plan for the current year for the NPC to evaluate.

In 2021, the NPC government work report once again encourages the construction of battery-swapping stations based on two suggestions from industry. At the CPPCC meeting, Fushu Li, the president of the Chinese automaker Geely, submitted ”Suggestions on Solving the Legal Obstacles to Freight Vehicle Electrification,” suggesting incorporating supplementary provisions on electric freight vehicle weight and length limits into national standards. Hanru Liu, deputy to the NPC and general manager of CAMC (Hanma Group in Chinese, a major new-energy heavy truck manufacturer), put forward proposals offering ”Suggestions on excluding batteries of battery-swapping electric heavy trucks from the overweight range” and ”Suggestions on appropriately adjusting the maximum total weight limits for automobiles, trucks and trailers and A-double trucks.”

The newest policy developments confirm that battery swapping is a strategic goal at the highest level of national politics. In the future, battery-swapping EHTs and associated system solutions may become the main approach to heavy truck electrification in China and will be vigorously promoted.

There are several indicators supporting the statement above:

1. The position of battery-swapping technology on the national list of strategic initiatives and the clear and strong political acceptance of and support for this solution.
2. Multiple major truck manufacturers' embrace of battery-swapping technology in 2021, with most Chinese battery EHT manufacturers now including battery-swapping technology in their solutions.
3. The flexibility of dual cable-charging and battery-swapping capabilities depending on operator needs and business landscapes. Battery-swapping EHTs do not limit operators to a single energy supply mode.
4. The strong commitment from energy producers to engage in technology development and create joint ventures with vehicle manufacturers and other actors to establish battery swapping as national solution.
5. The opportunities that battery swapping presents to achieve national strategic battery energy storage functions, allowing more efficient use of energy due to energy balancing and enabling energy supply businesses to benefit from price differentials in electricity.

6. The ability to recondition batteries for second and third lifecycles and thus extend their lifespans.

National laws and regulations are being adopted to promotion EHT applications in general and are now specifically supportive of swapping solutions. Industry actors are working together with the government to put together the necessary standards and regulations that satisfy demand for EHT development.

On the July 12, 2021, the Ministry of Industry and Information Technology released the "Recommended Models for the Promotion and Application of New-Energy Vehicles," the sixth time it has released its recommendations for new-energy vehicles since the new-energy vehicle subsidy policy was implemented in 2021. This important document shows the direction of the intended transformation towards new-energy vehicles and the subsidy plan that supports it. The July 12, 2021, lists 231 new-energy vehicle models:

- 89 special-purpose models
- 62 new-energy bus models
- 80 new-energy passenger car models

Among the 89 special vehicle models listed, the biggest highlight is the inclusion of 6 battery-swapping EHTs, a 200% increase from the June listing. The growth of swappable systems in the heavy truck segment is gaining momentum.

Some of the arguments for including battery-swapping EHTs on the list as a matter of strategic importance include the following:

1. In China, heavy trucks currently account for the largest share of vehicle emissions. Public data show that heavy-duty diesel trucks account for nearly 60% of total commercial vehicle emissions, the "biggest culprit" for fossil-fuel vehicles. This is especially the case in the Beijing-Tianjin-Hebei region of northern China, where 60% of vehicle pollution comes from heavy trucks.

2. The high efficiency of the battery-swapping mode caters to the needs of heavy truck customers through efficient operation and greater profitability. Currently, the main technological pathway for new-energy heavy trucks is BEVs, with two main forms of charging infrastructure: cable charging and battery swapping.

   Cable charging mode is slow and doesn't meet the productivity needs of heavy truck operators. Battery-swapping mode offers a much greater time efficiency than cable charging, since it normally takes about 5 minutes to swap out a battery —nearly the same amount of time as refueling a diesel truck. This fully caters to heavy truck customers' needs for efficiency and profitability, making swapping-capable trucks a better starting point for electrification of the nation's heavy truck fleet.

3. Battery swapping addresses some of the shortcomings of cable-charging EHTs and eliminates their operational shortcomings. Because EHTs operate over long distances, their range is less than the full route, even when fully charged. Battery-swapping capabilities and swapping station infrastructure resolves this bottleneck of operational range and reduces the difficulty in charging commercial BEVs.

4. National policy now actively encourages the separation of ownership of vehicles and batteries, encouraging the development of heavy trucks with swapping capability.

   Progress from the report from the four national ministries and commissions issued in April 2020 to the recent multiple statements by the Ministry of Industry and Information Technology fully illustrates this point. The Ministry of Industry and Information Technology recently expressed its support for the development of EHTs on various occasions, showing that national-level policy actively encourages separating ownership of vehicles and batteries and the development of battery-swapping capabilities for EHTs.

5. The EHT industry giants receives several large orders for battery-swapping EHTs in the first half of 2021, indicating that more and more end users and operators prefer to use battery-swapping EHTs in specific scenarios, This has also stimulated operators' enthusiasm for adopting to battery-swapping EHTs.

   In the first half of 2021, orders for battery-swapping capable EHTs exceeded 15,000, and industry leaders have received a large volume of orders, indicating that the current battery-swapping EHT market is quite hot.

Our interpretation of the information we have gathered from operators, material presented at conferences, and information from government ministry, leads us to conclude that battery swapping might become the new standard for EHTs in China.

PART THREE
TECHNOLOGICAL APPROACHES TO BATTERY-SWAPPING EHTS IN CHINA

Vehicle batteries can be swapped out in many ways, and batteries can be located in several locations on the vehicle depending on the vehicle design, product architecture, the size, number, and capacity of its battery, and the design of the selected swapping system.

Batteries can be placed anyone on the vehicle and exchanged from any direction; all potential solutions have their own pros and cons and there is no clear best solution yet.

Passenger vehicles

Passenger vehicles present a complex situation due to the large size of the battery with respect to the vehicle and the existing architecture of the vehicle. With fully integrated systems, the battery itself might even be part of the vehicle structure and safety system in the event of a crash. Fully integrated batteries can also be lighter than swappable batteries. However, fully integrated batteries cannot be swapped, upgraded, or downgraded easily. This means the vehicle owner must accept the choice of installed battery for the lifetime of the battery or the vehicle. Due to challenges in connections, software control systems, and interoperability, fully integrated vehicle batteries cannot be easily reconditioned or repurposed after their initial vehicle lifecycle: for example, for energy storage.

When the vehicle is designed for battery swapping, the entire vehicle system must be adapted to the swapping process, including the battery management systems, connections, support frame, docking system, charging system, energy supply, etc. The swapping system must be designed for each specific vehicle, unless a third-party developer adopts solutions that fit several brands, system solutions etc. Such third-party umbrella solutions do exist for passenger vehicles, such as those from one of the largest battery-swapping system providers in China, Aulton.

Passenger vehicles are often swapped from the undercarriage or from the side, although front or rear access are also possible. The most common solution today is undercarriage access, which makes it easier for the battery-swapping components to not interfere with the vehicle's outer design.

Vehicle design is one of the core parameters on which OEMs compete, and thus manufacturers want to have full control over the look and design of each vehicle and branding.

Trucks and buses

From a technology point of view, it is easier to incorporate battery swapping into trucks and buses to passenger vehicles due to their size, in many cases open product architecture, and easily accessible options for battery placement and access. Also, unlike passenger vehicles, trucks branding is dictated by function and not branding. This makes it easier to integrate large batteries suitable for swapping.

Figure 8: Battery-swapping positions on a truck.
Source: Based on Kim et al., 2015.

Figure 8 shows some possible swappable battery positions on EHTs (red boxes). Because trucks are large, they offer possible several positions that can be complementary, allowing several swappable batteries on a single truck to extend their operational range.

The swappable battery can be placed in mainly five positions:

- Behind the cab, the most frequently used swappable battery placement in China.
- On the side, which one new Chinese swappable battery third-party supplier has developed.
- Under the chassis, as is standard in passenger vehicles. This solution has not yet been used on any trucks that we know if.
- In the front of the tractor where the engine was traditionally located, a location one Australian battery-swapping operator has opted for.
- In a special battery trailer, a solution that no manufacturer has put into practice yet.

Figure 9: Battery-swapping positioning on a bus.
Source: Kim et al., 2015.

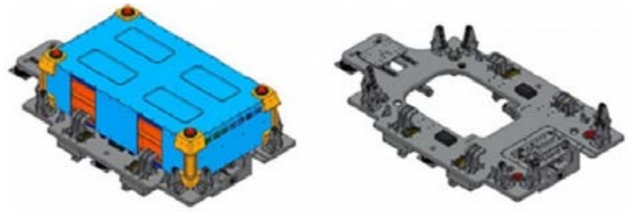


Figure 10: Battery-swapping system, battery, and mounting system.
Source: Kim et al., 2015.

The options for buses

Figure 9 shows that swappable batteries can be stored under the chassis and accessed from the side, at the back and accessed from the side, and in the back or even on the roof and accessed from the side or from the above.

Each solution has its own pro and cons. Different combinations are possible to allow an optimal driving experience and operational range.

Figure 9 shows the battery-swapping system for a bus rooftop position that is accessed from the side.

Figure 10 shows the complex system for a swappable battery installed on the roof of a bus.

Truck design makes it is possible to implement a modular design solution with several swappable positions depending on operator needs, using a variety of swappable batteries.

Evolution of the technological pathway for battery swapping

The earliest application of battery swapping in China was during the period of the 2008 Beijing Olympics, with electric busses that used multiple side-mounted batteries. Two robotic devices worked simultaneously to change the battery packs on each side of the bus. Before 2015, this pathway was the most popular battery-swapping solution in China. However, it required a great deal of space on the vehicle, and so its main fields of application were electric buses, electric sanitation vehicles, and other commercial electric vehicles.

In the past three years, Chinese battery-swapping technology has developed rapidly, allowing for different technological pathways for different types of vehicles and different operational scenarios.

The increased level of technical differentiation and specialization has been obvious. With improvements in the automation, safety, and consistency of battery exchange, the technological pathway of passenger vehicle has developed from multiple battery packs swapped manually to single-package batteries built into the chassis system that can be swapped by automated equipment.

Light logistic EVs mainly use a mid-vehicle mounted battery location. EHTs and buses primarily use top-mounted batteries. As actors roll out battery-swapping EHT models, the dominant technical solution of top-mounted batteries may see competition from other mounting locations/access points.

Battery-swapping standards in China

The promotion and application of battery-swapping EVs depends heavily on technological development, vehicle design, and standardization of battery-swapping solutions. The drafting of battery-swapping standards has lagged behind technological developments in battery swapping, as well as the development of standards for cable charging. Industry practice sometimes moves faster than the process of developing standards.

Battery-swapping standards mainly focus on the quick-swapping battery pack, battery system interface, battery-swapping station, and operations service network and mostly apply to multiple battery pack solutions for swapping. A standard for single battery pack swapping has not emerged, and there are few standards relating to battery mechanical structure, locking mechanisms, high and low voltage electric interface, electric control functions for battery-swapping, and communication protocols.

International standards

In 2016, the IEC 62840 series of standards, convened by Chinese experts, were officially released. The series includes IEC TS 62860-1, ”Battery-swapping system for electric vehicles - Part 1: General principles and guidelines,” and IEC 62840-2, ”Battery-swapping system for electric vehicles - Part 2: Safety requirements.” The IEC 62840 series standards are the world’s first set of IEC standards for EV battery charging and swapping systems and was initiated and released by Chinese experts.

IEC 62840 proposes a battery-swapping system architecture, general requirements, and safety requirements, and sets forth a partitioning of subsystems and permissions, use cases, and suggestions for battery-swapping system design. It also proposes typical designs according to the vehicle’s structure and operational characteristics, for both passenger cars and commercial vehicles. The standards also address the issues of electrical protections, mechanical structure, and communication interfaces through a cross-industry approach.

Chinese domestic standards

The standardization management center of the China Federation of Electric Power Enterprises is taking the lead in formulating a series of standards for EV battery swapping. There are currently 33 special standards for battery-swapping technology, 25 of which have been issued and 8 of which are under development.

The Ministry of Industry and Information Technology also issued the recommended national standards GB / T 34013-2017 ”Specifications and dimensions of traction batteries for electric vehicles” and GB / T 34014-2017 ”Coding rules for automotive traction batteries” in July 2017.[12]

Technological pathway for battery-swapping solutions

Figure 11 shows the principal technical design structure of a battery-swapping system.

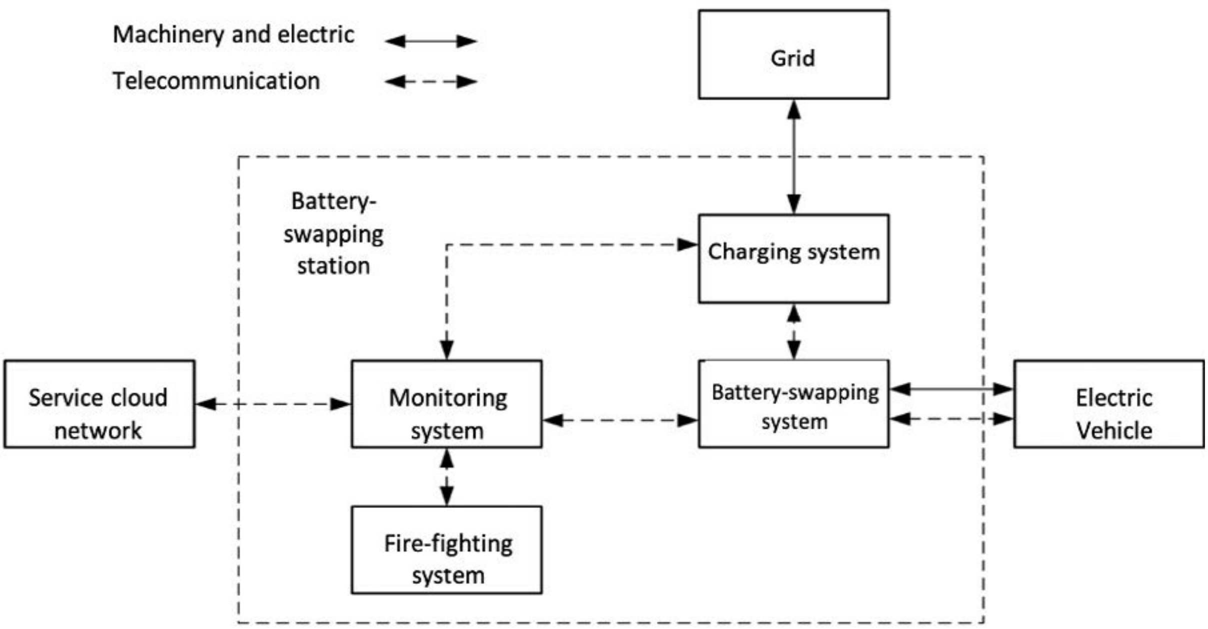


Figure 11: Structure of a battery-swapping system.

Source: 2019 White Paper on the Technology Development of EV Charging Facilities in China, Part 3: Battery-Swap.

Classification of battery-swapping modes

By battery location

Bottom-mounted battery: the battery box is installed on the chassis under the vehicle body, with the battery enclosed in a protective housing. With this alternative, the chassis structure needs to be modified to mount and allow access to the battery. This location is difficult to standardize and only supports an automatic battery-swapping process, which increases cost of the vehicle and the battery-swapping station. On the other hand, because the operation is automated, it is smooth, fast, reliable, and safe.

Side-mounted battery: the battery pack is installed on both sides of the vehicle body. This requires a great deal of space and is mainly used for electric buses, sanitation vehicles, and other commercial vehicles. This mode divides the whole vehicle battery in smaller modularized, standardized components that allow for the use of standardized batteries that are compatible with different various types of vehicles, increasing or decreasing the number of batteries according to the vehicle's needs. Each battery box has a protective housing, which increases the vehicle's weight.[13] This approach enables a modular architectural design that can be shared among vehicle from different manufacturers.

In addition, this mounting location allows for partial swaps that only exchange the batteries that are empty, leaving the fully ones in the vehicle. However, this location also entails a higher cost and longer swap time, which raises the total cost of the vehicle and battery and increasing operating costs for swapping stations.

Rear- or front-mounted battery: the battery box is installed in the front and/or rear compartments of the vehicle body and is swapped out similarly to side-mounted designs.

Top-mounted battery: the battery box is installed at the back of the cab or on the roof of the vehicle. When the battery is mounted behind the cab, it can be accessed from the side or lifted off from the top.

Middle battery-swapping mode: the battery box installed in the middle part of the vehicle body with swapping from the sides.

Following **figures 12—15** shows some typical swappable battery locations: side mount, bottom mount, rear mount and top mount.

Figure 12: Side battery mount

Figure 13: Bottom battery mount

Figure 14: Rear battery mount

Figure 15: Top battery mount

Source: 2019 White Paper on the Technology Development of EV Charging Facilities in China, Part 3: Battery-Swap.

Classified by the number of battery boxes

Single-package swapping: for EVs with a single battery box, the complete battery box is replaced when swapping the battery. The package is large and heavy, requiring machinery-based operations.

Multi-pack swapping: for EVs with battery boxes composed of multiple battery packs. This solution requires a modular design of the vehicle, battery boxes and battery packs and can be carried out manually as well as using power tools. However, this solution is more expensive than the single battery box solution. Due to the large size of the battery and the need to connect the motor to the output power, the drive battery for most battery-swapping passenger EVs is mounted on the chassis.

Table 6 shows different scenario for users and operators and the adaptability to battery swapping.

Scenario	Battery-swapping EV type	Technological pathway
Taxis	EU model of BAIC new-energy vehicle	Single chassis-mounted replaceable battery pack
Private passenger vehicle	NIO ES model EV	Single chassis-mounted replaceable battery pack
Ride-sharing, car sharing	Skio ER30 model EV, Lifan	Multiple replaceable battery packs
Commercial EVs (Mainly utilize top-mounted and side-mounted replaceable batteries)	Shandong Kama light electric truck (2.5 ton)	Middle axle mounted replaceable battery pack
	AUV model of Foton electric bus, AGV container electric truck of Yangshan Port, Shanghai, Dongfeng blue plated light electric truck (lighter than 4.5 ton)	Multiple side-mounted replaceable battery packs
	Electric bus	Multiple replaceable battery packs
	CAMC electric heavy truck	Top-mounted replaceable battery packs

Table 6: Battery-swapping pathways for different types of EVs under different scenarios.
Source: 2019 White Paper on the Technology Development of EV Charging Facilities in China, Part 3: Battery Swap.

As we can see from **table 6**, it is technically possible to adopt battery-swapping technology to many types of vehicles. This is no longer a technical issue or challenge anymore. From practice we see that all these types of vehicles have adopted battery-swapping capabilities.

Technological pathway	Battery concealment	Battery box seal	Battery-swapping equipment cost	Automation of battery-swapping process	Standardization of operation process	Safety risk of connector	Manufacturers
Bottom-mount replaceable batteries	Good	Good	High	Automated	Not easy to achieve	Low	NIO, Aulton
Multi pack replacement	Poor	Poor	Low	Partially automated	Easy to achieve	High	Botann
Side-mounted replaceable batteries	Relatively good	Relatively good	Relatively high	Partially automated	Not easy to achieve	Relatively low	Skio EVs

Table 7: Comparison of characteristics of different battery mounting options.
Source: Research report on building a value-separated vehicle and battery industry ecosystem

Table 7 shows the trade-offs of different battery placement options and suggests that bottom-mounted batteries are the most suitable solution from a technical point of view.

With the continuous development of battery-swapping models, the focus of battery-swapping technologies (from the perspective of vehicle operation) includes speed and safety, reliability and durability of the electrical connection, battery safety and lifespan, battery pack design, adaptability of the locking mechanism, and standardization.

Passenger vehicles, trucks, and buses are architecturally very different and thus require different swapping solutions. Bottom-mounted batteries are the most common solution for passenger vehicles, top-mounted batteries have become the most common solution for trucks, and side/top-mounted batteries have become the most common solution for buses. The product architectural design of a vehicle is the main driver of battery-swapping solutions and the placement of swappable batteries. Safety, driving concerns, transportation capacity and vehicle balance must also be considered in the total system design.

Technology	Performance
Mechanical connection	Mechanical impact: resist 25G impact for commercial vehicles and 50G impact for passenger cars. Lifespan: 1,000-10,000 swaps, with high tolerance for mechanical faults.
Electrical connection	Withstand peak current of 700A/30s, more than 1,000 connect and disconnect cycles, and durability of 2,000-10,000 cycles of swapping operations.
Liquid cooling connection	Most commercial EV batteries and low-power passenger EVs use air cooling, but liquid cooling is gaining popularity. Plugs should withstand 3,000-8,000 connect/disconnect cycles.
Monitoring system	Monitors the position of the battery during the replacement operation the status of the battery locking mechanism to ensure mechanical and electrical safety of the battery.

Table 8: Progress in EV battery-swapping technology development.
Source: 2019 White Paper on the Technology Development of EV Charging Facilities in China, Part 3: Battery Swap.

Table 8 shows some key aspects that need to be considered when choosing battery-swapping solutions. The most important are the mechanical and electrical connections, which must withstand thousands of swaps, along with the cooling system and the swap process monitoring and control system. Battery-swapping solutions must be developed through close collaboration among vehicle manufacturers, battery manufacturers, swapping-system developers and electricity providers. This process requires a high level of integration during development, and solutions must be integrated by the system integrator—i.e., the vehicle manufacturer. Finally, it must be recognized that vehicle manufacturers have ultimate control and responsibility over the vehicle during its entire lifecycle. Thus, safety aspects of vehicle, the battery, and the swapping system fall to the vehicle manufacturer in its role as system designer and guarantor of quality.

To summarize so far, what are the critical aspects in the choice between battery-swapping capable EVs and cable-charged EVs with fully integrated batteries? Vehicle design and branding is one, as is the dual operational option with swapping-capable designs. The cost of the entire system plays a significant role, as does the struggle among actors for power and control of the vehicle architecture and whether the actor seeking to profit from vehicle operation or battery swapping or other services.

It also depends on whether vehicle manufacturers can develop new ecosystems in conjunction with new actors, enabling the creation and distribution of value in a win-win solution. We clearly see a struggle for power and control between vehicle manufacturers and battery manufacturers as the battery is one of the most crucial systems beside the software and control system.

Our research indicates that the two most important barriers to the adoption of swapping systems are:

- The struggle for power and control between different stakeholders when adopting battery-swapping solutions the business model being applied to enable commercialization of battery-swapping systems.
- The business model being applied to enable commercialization of battery-swapping systems.

Technical design parameters for the major battery-swapping EHT models in China

Several commercial vehicle companies, such as CAMC, Foton, Shanghai Automobile Hongyan (SAIC Hongyan), Beiben, XCMG, and BYD, have developed battery-swapping EHTs in recent years or intend to launch new ones in the near future. SAIC is one of the late comers, joining the fray in 2021, which shows the speed of this development in China.

The following table lists the typical technical parameters of several major Chinese battery-swapping EHTs. As we can see, different brands have all adopted similar configurations and performance parameters. All these brands have selected CALT as their battery supplier, and most have selected Top Gear to supply the vehicles' electric motors—both Chinese companies. This means that so far, Chinese EHT manufacturers are relying on domestic suppliers for the most critical components: chassis, battery, electric motors, and software control system.

From the truck operator and user perspective, our research found that the most critical challenges for operators of EHTs are the fear of running out of charge, the long charging times when the vehicle is not earning money, sudden rescheduling of transportation assignments, and loosing recharging capability, the resale and second-hand value of EHTs, the lifecycle of batteries in the integrated EHTs, and the resale value of EHT batteries.

Brand	Battery type	Energy density of battery (Wh/kg)	Battery capacity (kWh)	Motor technology	Peak power (kW)	Rated power (kW)	Speed (km/h)	Battery-swapping time (minutes)	Range (km)
CAMC	lithium ion	Not available	282	Permanent magnet synchronous motor	360	220	85	6	170
Beiben	lithium ion	157	282	Permanent magnet synchronous motor	360	Not available	80	3-5	250
Foton	lithium ion	160	282	Permanent magnet synchronous motor	360	220	89	3-5	150-200
SAIC Hongyan	lithium ion	155	282	Permanent magnet synchronous motor	360	250	70	3-5	200
XCMC	lithium ion	157	Not available	Permanent magnet synchronous motor	260	Not available	80	3-5	170

Table 9: Technical parameters for battery-swapping electric heavy trucks.
Source: Author's summary based on public information.

Table 9 shows some critical parameters in EHT design that determines the operational capabilities of the truck. Please note that there is no ideal vehicle design; rather, each design reflects different buyer/operator demands in terms of payload, range, charging capability, performance, and cost. From this table we can clean certain key aspects of EHT design in China.

- Lithium batteries are the standard solution.
- The standard battery size is about 282 kWh but can be increased or reduced according to the customer's needs, with corresponding impacts on range, charging time, total vehicle weight, payload, and price.
- The nominal range per charge is 150-200 kilometers, depending on payload, driver skill, driving conditions (city vs. highway, terrain, climate, etc.), and batter age.
- The driving range, in hours, can be estimated at 2-3 hours of normal driving.
- Under heavy driving conditions, a 282 kWh battery allows only 1-2 hours of continuous driving before charging.

Up through 2021, the most common battery location is behind the cab, in a swappable box that can be lifted up and moved to the side. Due to the vehicle size and battery pack location, EHV battery-swapping stations need to be taller and larger than passenger vehicle battery-swapping stations.

Figures 16-21 shows some Chinese battery-swapping EHTs.

Figure 16: CAMC electric truck

Figure 17: Beiben electric truck

Figure 18: Foton Iblue electric truck.

Figure 19: XCMC electric truck.

Figure 20: SAIC Hongyan electric truck.

Figure 21: BYD electric truck.

Source: 2019 White Paper on the Technology Development of EV Charging Facilities in China, Part 3: Battery Swap.

Financial solutions for battery-swapping EHTs

Whether talking about traditional diesel heavy trucks or battery-swapping EHTs, the price of the vehicle system as a whole is not low. Therefore, financial actors play an increasingly important role in the design and delivery of products for financing enterprises that require heavy trucks.

At present, both vehicle manufacturers and non-manufacturing actors are involving in the field of heavy truck financing in China. FAW, Dongfeng, SINOTRUK, Foton, and other major vehicle companies have established vehicle financing and financial leasing subsidiaries to offer financial services that suit the needs of both manufacturers and operators.

At present, the main financial product available for battery-swapping EHTs is the innovative business model of purchasing the unpowered vehicle body" (buy or financial lease) and leasing or renting the battery with a subscription for battery charging. The EHT power battery is owned and operated by a battery asset management company, and users only buy the truck body and rent the battery. The asset management company, in turn, buys the battery from the battery supplier at a comparative low price.

When ownership of vehicle and battery is separated, we can more clearly see the importance of the traction battery. Industry experts estimate that if the potential market size for EHTs in China is about one million units, then the potential market size for EHT drive batteries is valued at approximately 400 billion yuan (about US$62 billion). Traction battery asset companies handle lifecycle operational management of the batteries. Through leasing, battery maintenance, data monitoring, and echelon utilization (repurposing of EV batteries for different uses as their storage capacity degrades over time) of traction batteries, it can directly realize the circular economy of the traction battery and indirectly realize the value of battery-swapping EHTs.[14]

Battery asset management companies can form battery networks and data pools by operating battery assets and provide support for other forms of businesses. They can monitor, evaluate, provide early warnings, and collect data on battery status in real time through high-precision battery monitoring technology. They can cooperate with battery manufacturers and swapping station operators to provide traction battery maintenance and other services to establish a professional service network. They can build battery management systems using big data dynamic evaluation models that analyze performance, improve the battery life-cycle performance, safety, and residual value. They can help enhance the battery lifecycle value chain through collaborative echelon utilization scenarios and energy storage applications.

Based on this, one main question is whether traditional truck manufacturers are best positioned to develop these complementary business areas on their own or if they need collaborative partners to develop complementary assets, knowledge, experiences, and to develop the new business ecosystem for battery-swapping systems and for electric vehicles in general.

Major actors in the battery-swapping EHT segment

Starting in 2019 and following two years of development, battery-swapping EHTs have been deployed in bounded closed spaces such as manufacturing plants, industrial parks, docks, and mines. Now they are increasingly being adopted for urban and open road/highway applications, despite their range limitations.

By 2021, Foton Motor, SAIC Hongyan, Dongfeng, FAW, Shanxi Automobile, CAMC, XCMC, Beiben heavy truck, and BYD had all launched their own EHT lines on the Chinese market.

Currently, almost all battery-swapping EHT manufacturers have selected CALT as their battery supplier. However, other battery brands are entering the field as well, including ZENIO, XPT, TEAMGIANT, Pride-Power, and GOTION, all of which have provided batteries for specific battery-swapping EHTs. When it comes to the electric motors, the Shanghai-based brand Top Gear holds a 65% market share for medium and heavy new-energy trucks. In terms of battery-swapping stations for EHTs, Shanghai-based Enneagon Energy has built the greatest number, while State Grid and SPIC (State Power Investment Corporation) are major investors and operators of stations.

Major suppliers of key EHT systems to Chinese manufacturers

Manufacturer	Traction battery	Electric motor	EHT financing products	Battery-swapping station investors and operators	Battery asset management companies	Battery-swapping station developers	Battery-swapping EHT online platform
Major Chinese Truck Manufacturer	CALT and others	Top Gear	SPIC and others	National Grid, Southern Grid, SPIC, Sinopec, Petro China	National Grid, Southern Grid, SPIC, Sinopec, Petro China, Geely, FAW	Enneagon	Zhida

Table 10: Major Chinese actors in the battery-swapping EHT ecosystem.
Source: Author's summary.

We have noted that new companies are entering the battery-swapping EHT market, such as Aulton, a dominant actor in battery-swapping passenger vehicles that is now entering the EHT segment with different solutions that those being provided by Enneagon. It is too soon to know how its entrance into the segment might influence the market situation.

PART FOUR
CHINESE APPROACH TO DEVELOPING BATTERY-SWAPPING EHTs

Pioneer player initiates systematic development of a total system solution

In the development of battery-swapping EHTs, the power company SPIC (State Power Investment Corporation) has played a pioneering role. SPIC is one of the five largest state-owned power companies in China and ranked 316 on the Fortune 500 list in 2020 .[15] The largest renewable and clean energy generation company in the world, SPIC's proportion of clean energy generation has reached 53%, which the highest level among Chinese energy producers. Several years ago, SPIC opted for hydrogen fuel cell, energy storage, and battery-swapping EHTs as strategic business directions. SPIC established a subsidiary, RHET (Rong He Dian Ke in Chinese) to develop new business areas in the new-energy vehicle field. As a power company that is facing challenges in balancing the power supply and the power demand in China, RHET's task is to develop major consumers of clean electricity. EHTs that consumes several hundred kWh electricity each day were identified as one ideal target for new products. Since cable-charging EHTs face many barriers to adoption, battery-swapping EHTs were raised as an option.

However, at that time there was neither battery-swapping EHTs nor battery-swapping stations available on the market. RHET was initially a financial service company established to invest financial resources in future renewable energy businesses. However, its parent company SPIC owned a truck fleet for its mining, port, and power plant operations. Replacing these fleet vehicle with battery-swapping EHTs creates a considerable initial market for RHET and have it confidence to create a battery-swapping EHT solution from scratch in 2018. Gradually, RHET developed the insights, experiences, and solutions needed to be a key actor in the power-swapping EHT segment.

Early key actors in emerging ecosystem for battery-swapping EHTs

RHET called for bids for a battery-swapping station solution provider. They required stringent cost control from the outset, since it was important for the solution to not just be technically feasible but be commercially sustainable. RHET ultimately named Shanghai's Enneagon to supply and jointly develop the battery-swapping station solution. These battery-swapping stations have evolved to their fifth generation and are the only EHT battery-swapping station in operation in China until recently.

RHET then looked to truck manufacturers to design battery-swapping EHTs to its specifications. Their attempts to influence the major manufacturers failed, and finally CAMC—a smaller manufacturer, signed on to become RHET's strategic partner.

> *"For innovative solution development, you have to collaborate with small companies. Don't go for those big companies, for they won't take disruptive action toward themselves."*
>
> (RHET Manager)

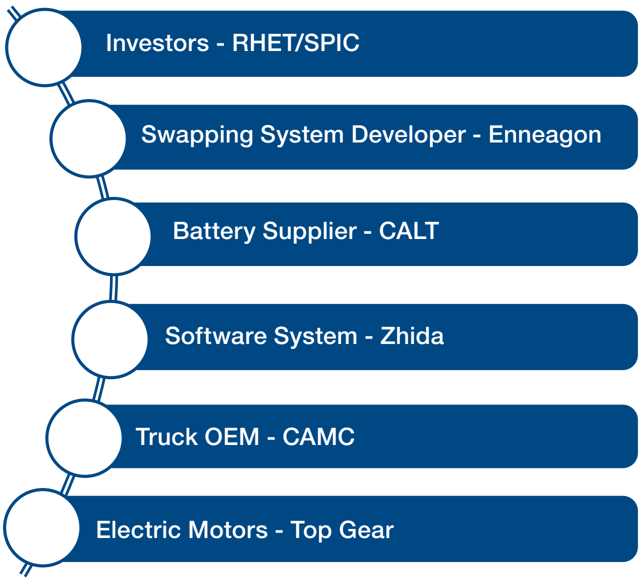


Figure 22:
Key actors in China's initial battery-swapping EHT project.
Source: Author's summary.

They also identified China's most advanced traction battery supplier, CALT, and electric motor supplier Top Gear, to jointly develop key systems for the battery-swapping EHTs. At the beginning the battery supplier had a pessimistic perception of the task:

> *I am absolutely not positive to the attempt. It's impossible. The working environment of heavy trucks is full of dust, it is very easy to bring short circuit and other safety problems.*

However, they did not give up, and their persistency succeeded in the end.

The last step was to develop an online platform for the battery-swapping monitoring and management solution. RHET identified another Shanghai-based company, Zhida, and together they developed the digital platform the battery-swapping EHT ecosystem needed.

New-energy vehicle consortium for joint creation and risk and cost sharing

To achieve a sustainable transition to EHTs, organizations first need to:

- Develop and fine-tune a sustainable original prototype of the product solution.
- Develop the infrastructure for energy supply and services such as charging infrastructure.
- Define the roles of different actors in the value chain.
- Build business-based networks of collaborating and complementary partners.
- Educate the public and build trust in the new solution.

At this point the refined and optimized prototype solution can be rolled out to a broader audience.

With the support of the parent company's truck fleet as its initial market, RHET played the role of industry system integrator for a battery-swapping EHT solution. They built a complete ecosystem for battery-swapping EHTs, holding the core intellectual property. We can see that in the process of creating this ecosystem, equity investment and financing played an important role in shaping a new-energy vehicle consortium that would jointly create the whole solution in the field and share the undertaking's high cost and risk. In the consortium that RHET put together, RHET made investments in Top Gear, Enneagon, and Zhida. CALT made investments in RHET. CAMC, the truck manufacturer, holds five percent of RHET's shares. Working in the form of a consortium, the member entities work closely together and with a higher level of trust as they jointly create and share risks and costs. Joint ownership is one way to develop and sustain trust and long-term strategic collaboration based on partnership. We can think of it as kind of corporate marriage.

CALT
Tractor battery supplier
Top battery supplier in China and worldwide.

Top Gear
Electric motor supplier
Account for more than 60% market share.

Enneagon
Battery-swapping station solution supplier.

Zhida
Online platform solution supplier

Supplier to 65% of EV manufacturers including Tesla, Volvo etc.

Figure 23: RHET's new ecosystem for battery swapping based on equity investment and financing.
Source: Author's summary.

Since the development of new-energy vehicles requires the development of complex systems involving vehicle, battery, swapping stations, energy supply infrastructure, and digital platforms, it entails high costs, high risks, and high demand for collaboration.

It seems that mutual investment among stakeholders is an important mechanism to support technology development and the creation of the invention and ultimately spreads out innovation in practical use in the field so it can become a national standard.

Which came first, the chicken or the egg?

This is a dilemma that every new-energy vehicle technological pathway faces. If new-energy vehicle users and operators cannot find enough energy supply facilities, they feel uncertain in buying the vehicle. However, energy supply facility operators fear that if there are not enough customers to use the facility, they will lose money. This is the chicken and egg dilemma.

Research has found that passenger vehicle battery-swapping stations must have at least 50% utilization of station capacity each day to reach the breakeven point.[16] For innovative solutions to spread successfully in society, key players must come together and take action to jointly create a total system solution that works for customers in a synchronized manner. Thus, the answer to the chicken and egg question is that they both must come at the same time, or else nothing will happen.

Chicken and egg emerge simultaneously and not sequentially—both are needed at the same time!

Creating the initial market volume to allow the new solution to grow

New-energy vehicle solutions involved complex systems the encompass vehicle, battery, energy supply facility, swapping system, and integrating digital platform. Multiple actors are needed to jointly create a total solution for customers, and then this solution needs to be put into practice to generate real-life performance results.

Traditionally, Chinese market actors start by identifying feasible use scenarios for a technical solution, then explore specific customer needs within the chosen scenario, then finally jointly design and jointly create a total system solution that works for the customer both technically and economically. At the end of the day, the developer and manufacturers must also reap economic benefits from the solution.

Currently, battery-swapping EHT projects are being developed case by case in China. For heavy trucks operating in different scenarios and conditions, battery-swapping station providers will work together with customers and suppliers to tailor the battery-swapping solution to each specific project. The entire project is business driven from a customer perspective, and customer oriented, rather than simply being a push from the technology development side or a pull from the customer demand side. Battery size, battery-swapping station size, and the number of the spare batteries in each station will all be calculated and decided on based on the project's needs and the customers' business conditions. Developers will calculate technical and economic feasibility to ensure the commercial success of the project.

The status of battery-swapping EHTs in China in April 2021:

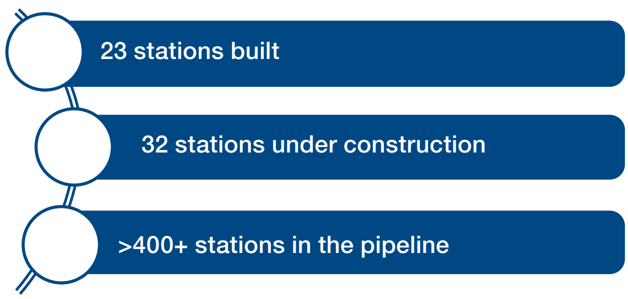


Figure 24: The status of battery-swapping EHTs in China in 2021. *Source: Enneagon company presentation.*

According to Enneagon's information, by the end of April 2021:

- 23 battery-swapping stations for EHTs have been built in China.
- An additional 32 stations are under construction.
- Plans have been made to build more than 400 additional stations in 2021.

Based on information we obtained during our interviews, several manufacturers plan to develop battery-swapping capabilities, and there is strong national support for battery-swapping solutions. Thus, we will see thousands of new swapping stations installed in the coming years in China. This can be compared to the similar development of passenger EVs in China. Considering that battery-swapping EHTs offer even greater benefits to EHT operators, the impact of EHT battery-swapping systems seems it will be much larger that for passenger battery-swapping systems.

Different scenarios of battery-swapping EHTs have been put into operation and generating satisfactory performance results both technically and economically.

These demonstration projects create initial market for the new battery-swapping EHTs and battery-swapping stations.

From one hand, the technical and economic feasibility are proved in real operation. It provides convincing information to educate and persuade the market of the new battery-swapping solution for EHTs. From another hand, battery-swapping solution gets more mature and are polished by absorbing feedbacks from real operation. The battery-swapping station solution for EHT, and for passenger vehicles as well, are both reaching their 4th generation now. Furthermore, the initiate market also provide revenue to solution suppliers, which can support them to survive and grow based on the solution. The initiate market also become base for the innovative solution to roll out later and gradually diffuse to the society.

Thus, identify, explore, and exploit the first batch of niche initiate market plays vital role for the innovative solution to be successful. In the Chinese context and based on Chinese traditions, this is conducted through dialog, collaboration, and cross-company business design.

Challenges of battery-swapping model for heavy trucks

As an innovative solution at early stage of development, battery-swapping model for EHTs is facing a lot of challenges as well.

Safety challenge

Chen Quanshi, director of the Automotive Research Institute of Tsinghua University, emphasized that the most important thing for a battery-swapping station is to ensure safety. EHT batteries store 400 kWh to 500 kWh of electricity and weigh five or six tons. During braking, vibration, and even collision situations, ensuring the safety of the battery is crucial.[17]

First we must ensure the reliability of the circuit interface. EHTs face a working environment with lots of vibration. Their battery pack is a high-voltage, high-current component. In a strong vibration environment, ordinary connectors don't hold up, and the interface can only be secured with bolts. However, high-current terminals can only be made of pure copper or copper alloy, and the service life of bolted terminals is a serious challenge.

Second, the heavy truck chassis is exposed, which increases the potential safety problem of the battery (such as the ease of inducing thermal runaway).

Battery standard challenge

Battery standards—for example, battery layout, size, installation location and interface— are not standardized across different EHT models. Even within the same brand, battery specifications and standards for different products may vary. Although the Ministry of Industry and Information Technology and other departments have issued policies on battery-swapping solutions, it is not clear on how to promote battery standardization in the field yet.

Utilization scenario challenges

Due to the limitations of large battery size, limited driving range, long charging times, and a limited number of battery stations, battery-swapping EHTs currently can only be used in mines, ports, thermal power plants, iron and steel plants, cement plants, slag transportation and construction sites and so on, in limited and closed operational scenarios. Obviously, the application scenarios for battery-swapping EHTs are still too narrow. Even in Inner Mongolia, where electricity prices are cheap and favorable for vehicle and battery value separation, battery-swapping EHTs still cannot be used in most scenarios. It will take quite some time for battery-swapping EHTs to be applied more broadly in China.

The number of battery-stations being build is creating right conditions but still limits the speed of dissemination for this technology. It is not the technology itself, but the infrastructure that battery-swapping requires, that is the lifeblood of battery-swapping and that is needed to enable large scale adoption.

As a production tool, total lifecycle energy consumption costs are more than 3 to 5 times the initial purchase price of the EHT itself. The first batch of battery-swapping EHT projects have shown convincing economic competitiveness. Technically, truck performance at high and low temperatures (minus 40 °C) under different working conditions has been stable and reliable. With the country's explicit policy of supporting truck electrification, the development of battery-swapping EHTs in China is speeding up in 2021. Industry actors shared information with us and explained that a total of about 1,600 battery-swapping EHTs were sold in China in 2020, and through May of 2021 another 2,000 battery-swapping EHTs were sold. Growth is fast.

Several experts in the field expressed optimistic views of battery-swapping EHTs. They believe that as the technology matures and suitable business models are refined, the range of potential applications for battery swapping extends beyond EHTs, with use scenarios for battery-swapping EHTs encompassing more than closed, short distance applications. In their opinion, battery swapping can ensure efficient utilization of traction batteries in our society and can help optimize energy distribution in the new era of growing renewable sources. However, it is worth pointing out that these opinions are based on the current development status of traction battery technology and hydrogen fuel cell technology. If breakthroughs happen in the technical development of either battery or hydrogen technology, the whole technological pathways for new-energy vehicles currently evolving might shift course.

Status of battery swapping in China in September 2021

Since 2018, only new energy vehicle (NEV) models that enter the government monthly published "Catalogue of Recommended Models for the Promotion and Application of New Energy Vehicles" can enjoy subsidies for new energy vehicles.

Analyzing changes of each Catalogue batch explores the dynamics in technology routes of various vehicle manufacturers.

Since the second half of 2020, the heavy trucks' ratio on the Catalogue list increased among new energy vehicles. It shows that heavy truck is becoming the major growth segment among new energy vehicles.

In September 2021 the Chinese government recommended 23 new energy heavy truck models in the Catalogue. **Table 11** (next page) shows the distribution of leading technology routes for new energy vehicles in January, August and September 2021.

- In September 2021, the hydrogen fuel based heavy trucks accounted for 43.5% of all licensed EHT models and become the dominant portion of licensed EHTs in China. This is an increase from 5.9% in January 2021.
- In September 2021, the battery swapping based heavy trucks accounted for 39.1% of all licensed EHT models. This is an increase from 17.6% in January 2021.

	January 2021	August 2021	September 2021
Total licensed new energy heavy trucks	17 models in total	30 models in total	23 models in total
Hydrogen fuel technology	1 model (5.9%)	8 models (26.6%)	10 models (43.5%)
Battery swapping technology	3 models (17.6%)	9 models (30%)	9 models (39.1%)
Battery based heavy truck models	13 models (76.5%)	11 models (36.7%)	3 models (13.0%)
ICE hybrid technology based	/	2 models (6.7%)	1 model (4.4%)

Table 11: EHT technology route structure in 2021 in China
Source: https://baijiahao.baidu.com/s?id=1655859743706983896&wfr=spider&for=pc
https://www.evpartner.com/news/17/detail-57612.html
https://www.evpartner.com/news/138/detail-58120.html

- In September 2021, the fully integrated battery and heavy trucks vehicles only accounted for 13.0% of all licensed EHT models. This is a decrease from 76.5% in January 2021.
- In September 2021, the ICE hybrid based heavy trucks are falling down to only 4.4% of all licensed EHT models. This is a decrease from 6.7% in September 2021.

The dynamic of technical routes' ratio of EHTs in the Catalogue shows that:

- The ratio of battery swapping and hydrogen EHTs are continuing to increase in 2021.
- The battery swapping based EHTs are getting market acceptance and government support.
- The battery swapping EHTs will operate in all market segments. The battery swapping EHT models cover all five major market segments of heavy trucks by September 2021, namely tractor truck, dump truck, sanitation truck, cement mixer and freight heavy truck. However, battery swapping EHT models in 2020 were more focused on specific segment market.
- There is a growth of battery swapping technology acceptance among Chinese heavy truck manufacturers. Now we see large, traditional and well-established suppliers that are adopting battery swapping, not only the new brands that are experimental and early adopters.

The main conclusion of this information is that the hydrogen fueled and the battery swapping based EHTs are taking the market lead in China in 2021.

- Our estimation is that in the field of new energy heavy truck, a phase of comprehensive promotion and application of battery swapping EHTs is taking place.
- Our estimation is that battery swapping and hydrogen based heavy trucks might become the dominant technology for electric heavy trucks in China.

PART FIVE
THE BATTERY-SWAPPING BUSINESS MODEL - SEPARATION OF VEHICLE AND BATTERY

For a review of perspectives and definitions of business model and business model innovation, and a review of the main literature on the business model and business model innovation, please see Liu (2019) and other publications available.

In the process of transportation and vehicle electrification, business model innovation is an important element in promoting the development of new-energy vehicles (NEV). To a great extent, discussions of transportation electrification and the development of electric vehicles have focused on technology, which is obviously an important aspect, as the shift from fossil-fuel transportation to electrical modes requires new technologies. However, research on innovation shows that technology itself does not bring value unless its value is unleashed and commercialized through a suitable business model.

The new business model: Flexible dual-mode cable charging/battery-swapping EHTs

Here we elaborate on the practical side of developing and implementing new business models supporting electrification, particularly business models that support battery-swapping technologies.

The combination of business models of the vehicle and the battery separation from the vehicle utilizing battery-swapping technology plays an important role in solving the dilemma of heavy truck electrification, of short operational range and long charging time via cable. Battery swapping enables the operators to choose which one they prefer or that suits their specific needs. Thus, this business model combines the two worlds into one system solution.

The ”separation of the ownership of vehicle and battery” models directly confronts the core aim of NEV development by improving energy supply efficiency and reducing the threshold for vehicle purchasing.

Since China started developing NEVs, two major forms of vehicle energy supply have come into competition: cable charging and battery swapping. In 2010 and 2011, facing enormous pressure to transform from fossil fuel vehicles to electrical, the development of battery-swapping mode was put on a back burner in China due to high costs, lack of standardization, lack of open vehicle architecture, vehicle manufacturers' protective attitudes towards opening up vehicle infrastructure, and diverging technical and economic interests among old and new stakeholders. However, a few key players continued to explore the model and made progress over time through experimentation.

Although charging piles and charging stations are being installed throughout China on a massive scale, demand for energy supply and energy-based services such as charging piles still exceeds supply. This shortage of energy supply became a major bottleneck hindering NEV sales growth in 2019. At a time when vehicle prices were dropping, the energy supply (from the electricity production and distribution to users), and the charging infrastructure was growing more significantly, and the safety of power distribution and charging process has improved, the industry players began to pay more attention to battery-swapping as alternative to cable-based solutions.

Battery-swapping vehicles can easily offer both cable charging and swapping, reducing some of the limitations of EVs and affording greater flexibility to operators. Increasing the number of charging points and charging piles cannot resolve the operational limitations of short ranges and long charging times for EHTs.

The national debate in the industry over the cable charging vs. swapping options in 2019 led to a consensus to pursue battery swapping as an important complementary EV power supply solution and has become a popular avenue for development since then in China. Chinese government policies reflect a recognition of and support for the battery-swapping alternative. Since 2020, battery swapping has been added to the national list of strategic technologies, and many companies have come to realize its importance. This is also visible in the actions of industry actors in developing battery-swapping products in 2020 and 2021. Plans for the future reflect significant attention to this solution.

Two meanings of ”vehicle and battery separation”

In this report we only cover the business model that is relevant for battery-swapping EHTs, not electric trucks in general.

”Vehicle and battery separation” business model for heavy battery-swapping trucks can be divided into two kinds, as it has been developed so far in China.

Physical separation of vehicle and battery

One kind of separation is called physical separation: that is, the battery can be separated from the vehicle body structure for recharging and quickly being replaced with another fully charged battery. Intelligent battery-swapping stations can solve the problems of operational efficiency, long recharging times, battery monitoring, maintenance, and echelon utilization.

Under this format, the vehicle owner owns the battery as well as the vehicle. The physical battery swapping and the recharging of the empty battery are services that operators must pay for. After swapping, operators receive another battery of the similar capacity and not the same one that was swapped.

The responsibilities for battery functioning, quality, depreciation over time, need to replace the battery—indeed, all technical and economic risks—as well as the resale value of the vehicle and battery are fully in the hands of the vehicle operator and owner. For instance, at the early stage of NIO development, due to government restrictions, customers had to purchase the battery along with the vehicle. The battery could be charged or swapped at NIO battery charging and swapping station.

Vehicle/battery value separation

The other kind of separation is called value separation: that is, separating ownership and use rights to the traction battery from vehicle ownership.

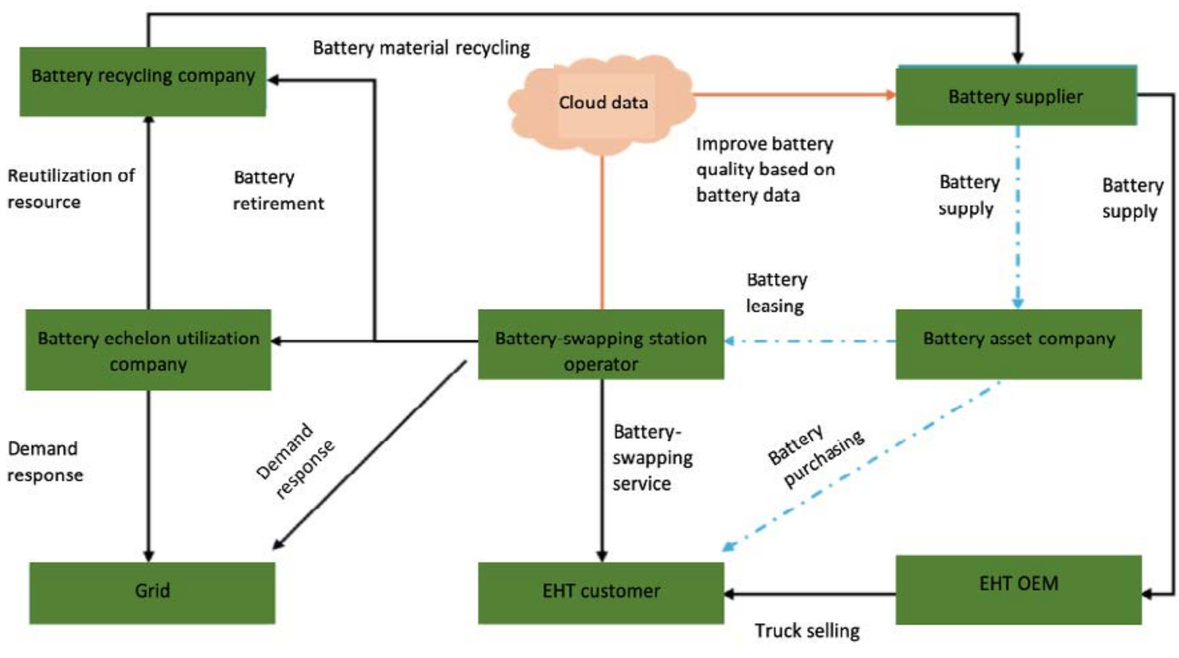


Figure 25: The EV industry ecosystem for battery/vehicle value separated business model.
Source: Research report on building a value-separated vehicle and battery industry ecosystem.

In this situation the traction battery becomes a commodity with liquidity and a value, and the battery asset management company (battery bank or battery investor) invests in purchasing the battery and thus owns the battery—not the vehicle owner, as in the previous case. The vehicle operator and battery user only pays a battery rental fee for the right to use the traction battery for certain period of time (a month or a year for example). The vehicle operator also pays for the swapping and recharging of the battery each time the battery is recharged.

The value separation mode enables the battery leasing company to reduce the cost of vehicle purchase and avoid the problem of low residual resale value for EVs due to battery depreciation. It also enables batteries to be reconditioned/repurposed and used for a second and third lifecycle, for example, for energy storage and energy balancing.

Energy producers and providers take the lead

Currently, the main investors in battery-swapping stations and traction batteries have been the State Grid, the Southern China Grid, and other major power companies in China, for several reasons. Energy companies see the growing future demand for electrical vehicles and as responsible for energy supply and distribution for the transportation electrification and society in general. Thus, they are keen to expand their own business and ensure that the energy supply/demand equation remains balanced. They are also seeking to develop energy storage systems at the national level, enabling the balancing of energy between industrial, household, and transportation needs. Battery swapping is one pathway that energy producers are exploring to optimize production, consumption, and price variation over daily, weekly, and annual cycles. Battery swapping as a form of large-scale energy storage can help buffer national peak energy demands.

Some truck manufacturers—for instance, FAW Jiefang, and Geely—have indicated an interest in establishing battery asset management companies to manage battery fleets for their vehicle models.

Advantages of vehicle/battery value separation for EHTs

Lower purchase price for EHTs

In China, the average price of an EHT in 2020 was about 850,000 yuan (~US$131,375), of which the battery's price accounts for about 50%. That price is based on a current standard battery size of about 282 kWh. The high price of EHTs is daunting to many customers, who are reluctant to invest in expensive EHTs that will drive up operational cost without improving operator revenue. Operators cannot charge higher prices just because they use EHTs. This is particularly true when operators can only drive for 1-2 hours or 200 kilometers and must spend 1-2 hours recharging for every 1-2 of hours of operation. During an eight hour workday, cable-charged EHTs can run for 4 hours and must spend ~4 hours charging, thus effectively reducing the performance capacity of EHTs by 50%, with an equal reduction in revenue. From an operator's perspective, this is not a good business model.

The vehicle/battery value separation model greatly reduces the purchase cost of an EV. The battery is owned and managed by the battery bank, and the user only purchases the vehicle body. In this scenario, the purchase price of an EHT without battery is only about 50,000 yuan (~US$7,728) more than a diesel truck. With a local subsidy of 100,000-200,000 yuan (~US$15,456-30,912), the overall price becomes less than a diesel truck.

Battery-swapping enables new opportunities and flexibility. Vehicle/battery value separation means the vehicle operator can rent the battery capacity they need, when they need it. Operators can increase or reduce the battery capacity if operational demands for their truck change. Battery-swapping stations can store and recharge batteries of different capacities and sizes for different operators. Such flexibility is achievable with the right business model for swapping stations and operators; its operational logic determines the actual final design.

Economic efficiency of battery-swapping EHTs

Lower operational cost

With vehicle/battery value separation, the truck and battery are sold separately. The battery can be rented or purchased. After paying a deposit for the battery, the driver can start to operate the EHT. Each month, the operator pays a battery rental fee, along with a variable fee for battery charging that combines the electricity consumption cost plus a service fee.

China uses a peak and valley electricity pricing system. Battery-swapping stations are categorized as general industry and commerce consumers. Experts estimate that the average electricity cost plus the battery-swapping service fee for an EHT in China is currently about 1.8 yuan/kWh (~US$0.28 per kWh). [18]
Obviously, different types of EHTs (e.g., tractor trailers, dump trucks, cement mixers, street sweeper, garbage trucks, road sprinkler, dust collectors, and other special vehicles) operating on different types of roads and with different loads will vary in total energy consumption.

Both expert estimates and real-world data on average energy consumption for heavy trucks is 0.9 l/km for diesel trucks and 1.4 kWh/km for EHTs. The price of diesel fuel in China is ~US$0.79/l,[19] which means that the energy cost for EHTs is $0.32 less per kilometer than diesel trucks.

Charging batteries at “valley” times will further reduce the cost of energy and thus improve profits for operators using EHTs. Considering that lifetime fuel costs are more than 3 to 5 times the cost of a diesel truck itself, the cost of owning and operating an EHT over its whole lifecycle beats out that of a diesel truck. From the operator’s perspective, at the end of the day, money talks.

Lower repair and maintenance cost of EHTs

EHTs have a simpler architectural design and fewer mechanical components, and thus their maintenance and repair costs are lower. These same factors will make EHT bodies cheaper to manufacturer than diesel trucks. According to our understanding, one model of SAIC Hongyan GENLYON tractor truck, for instance, only requires maintenance to change the conventional power steering fluid and axle fluid. Diesel trucks, in contrast, need motor oil changes, engine cleaning, and many other kinds of oils and fluids. Thus, in contracts, maintenance cost of EHT is almost negligible[20] when considering there is no need for repairs to vehicle components involved in internal combustion engine.

According to the actual EHT operating data, it is estimated that the maintenance cost of an EHT is about 0.6 cents per km, while the maintenance cost of a diesel truck is about 5.4 cents per km—9 times greater.[21]

Table 12 compares the economic performance of diesel heavy trucks and battery-swapping EHTs based on information available in 2021.

Component	Diesel heavy truck (ICE)	Battery-swapping EHT
Purchase cost	$45,113 (300,000 yuan)	$52,632 (350,000 yuan, without battery)
Battery capacity	N/A	141 kWh
Depreciation period (years)	10	10
Annual energy cost	$29,880 (198,700 yuan)	$21,789 (including battery rental fee) (144,900 yuan)
Average daily driving distance	120 km	120 km
Average energy consumption per km	0.9 l/km	1.4 kWh
Unit price of energy	$0.77/L (5.11 yuan)	$0.27/kWh (power price + battery-swapping service fee) (1.8 yuan)
Annual operation days	360	360
Annual energy consumption	38,880 L	60,480 kWh
Monthly battery rental fee	0	$451 (3,000 yuan)
Energy saving	0%	27%
Annual maintenance cost	$1,955 (13,000 yuan)	$752 (5,000 yuan)
Static lifecycle cost	**$363,459 (2,417,000 yuan)**	**$278,045 (1,849,000 yuan)**
Lifecycle cost at 3% discount rate	**$316,691 (2,106,000 yuan)**	**$244,812 (1,628,000 yuan)**

Table 12: Economic comparison of diesel heavy trucks and battery-swapping EHTs.

Source: Research report on building a vehicle/battery value separation industry ecosystem.

U.S. dollar and Chinese CNY (yuan) exchange rate: US$1 = 6.65 CNY.

In general, the economy of battery-swapping EHTs depends on differences in the purchase price between diesel heavy trucks and battery-swapping EHTs (without battery), differences in energy costs, maintenance costs, and the cost of battery rental and swapping and recharging fees.

As we can see from **table 12**, the total lifecycle cost of a battery-swapping EHT is 23.5% lower than that of a diesel heavy truck. We need to keep in mind that these numbers reflects conditions in China for heavy truck operations.

High time and resource utilization efficiency

Battery-swapping trucks need battery-swapping stations to change batteries. The battery-swapping process only takes 3 to 5 minutes, which generates vital time efficiency for EHTs that need to operate for as much of the workday as possible. At the same time, EHT battery-swapping stations occupy limited space—generally less than 300 square meters—and they enjoy a relatively high power distribution capacity coefficient—i.e., the electricity required for battery-swapping mode is only 1/4 of that needed for cable charging the same number of vehicles. Therefore, battery-swapping mode uses land and electric power resources more efficiently.

Table 13 below shows the total cost for a battery-swapping station.

	Details	Number of batteries	Battery unit price	Total price
Traction battery	CATL LFP traction battery, 141 kWh, supporting 4x2 tractor truck units.	70	$21,638	$1,514,683
Spare traction battery	CATL LFP traction battery, 141 kWh, supporting 4x2 tractor truck units.	7	$21,638	$151,468
Battery-swapping station	2,000 kW line, equipped with 7 spare batteries and 1 battery-swapping operation space, serving 70 vehicles.	1	-	$927,357

Table 13: Cost of battery-swapping service solution (battery + battery-swapping station).
Source: Research report on building a vehicle/battery value separation industry ecosystem.

Table 13 indicates that the total cost for one battery-swapping station serving 70 EHTs is about 927,357 USD. Note that this figure is based on the Chinese economic conditions contexts.

Also note that battery-swapping stations are scalable in terms of the number of reserve batteries they can hold, and thus the volume of EHTs they can serve.

Safer battery management and higher battery lifecycle value

Battery-swapping mode recharges batteries at a constant low power under constant temperature and humidity conditions, with continuous monitoring of charging conditions and battery functionality. The automated low charging rate can effectively prevent the negative impact on battery performance from high-power fast charging and power fluctuations during charging. In fact, the optimized management and maintenance of batteries made possible by battery-swapping station operators **can extend the service life of batteries by more than 20%.**

We have received information from industry practitioners who indicate that Chinese traction battery suppliers provide a 500,000 km/800,000 kWh battery warranty when used in a battery-swapping mode, compared to a cable-charged integrated vehicle battery warranty of only 200,000 km. This indicates that battery suppliers have experienced improved battery lifecycles for batteries charged at slow rates in swapping stations compared to fast-charging cable stations, as well as the elimination of issues such as overcharging, overheating and battery fires under the controlled, monitored conditions of a swapping station.

The EV battery fires are very rare, but when they happen it is usually during charging. This is particularly concerning when charging takes placed in enclosed garages. So far, transportation electrification has been more widely implemented in the passenger vehicle segment, with their relatively small batteries. When electrification deploys through the truck and bus segments, with much higher fast-changing energy draws and much larger batteries, this issue may be even more important. Thus the lower powered charging and constant monitoring in battery-swapping stations is an even greater advantage.

Figure 26 shows the effect of charging rate on the lifecycle life of lithium-ion batteries.

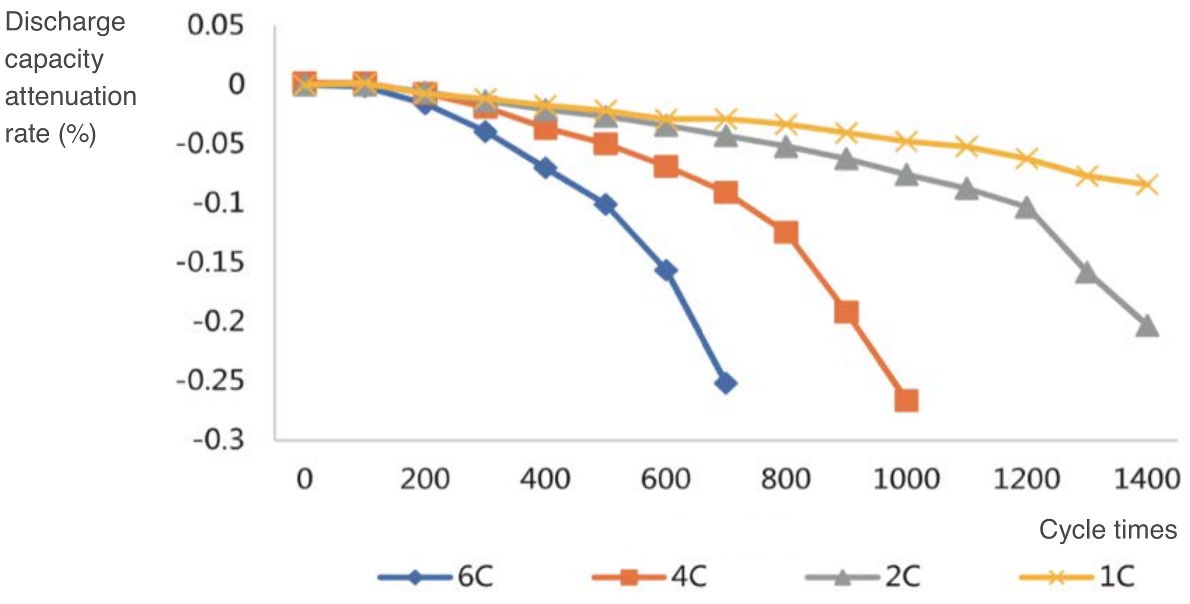


Figure 26: Lifecycle curve of lithium-ion batteries at different charging rates[22]
Source: Research report on building a value-separated vehicle and battery industry ecosystem.

“C” in the figure means charging speed, where 1C is low speed, 2C is 2X speed, etc.

Centralized charging in battery-swapping stations can control the optimal charging environment and curve and improve the safety of the battery charging process. According to experiences in China, the battery is most likely to catch fire within 30 minutes after overcharging or being fully charged. Compared with unattended fast-charging, charging in a battery-swapping station dynamically monitors the charging process, state of charge, temperature, and other indicators of the traction battery, with multiple safety protection measures to ensure comprehensive monitoring and management of the battery by professional and technical staff. It improves battery safety and prevents the most dangerous risk to EV owners.
In 2019, EHT vehicle recalls due to traction battery problems accounted for 18.68% of all recalls. Battery-swapping stations offer centralized management of batteries by conducting real-time data analysis of batteries based on big data, inspecting and replacing batteries on time, providing feedback data for battery manufacturers to improve battery quality, and can decrease major losses to manufacturers caused by battery recalls.

According to the report on China’s automobile value preservation rate in 2019, the rapid iteration of new battery technology and degradation of battery performance over time meant that the residual value of used electric vehicles drops significantly after three to five years of use.[23] Separating ownership of vehicle and battery increases the residual value of the EV body and transfers the risk of battery performance degradation and devaluation to the battery asset management company. In the current business practice on the Chinese market now, the residual value of the truck body and battery can be calculated separately. Through centralized battery management, monitoring data on battery health can provide a basis to evaluate the battery's value and the circulation of batteries in the swapping station, and provide reference information for financial institutions to define the attributes of battery assets and tailor insurance products to the sector.

Battery swapping makes it easier to reuse traction batteries and increases their lifecycle value. Generally, when an EHT's traction battery capacity drops to less than 70% of its initial capacity (80% for passenger vehicles), it will not fully meet the performance demands of the vehicle. However, it can be repurposed for use in other tasks. Traction batteries with 50-80% capacity can be used for forklifts, scenic spot sightseeing car and other non-road vehicles. Traction batteries with 30-50% capacity can be used for household energy storage, commercial energy storage, and battery-swapping station expansion energy storage. At a capacity of less than 30%, the battery can be disassembled for raw material recovery. This shows that batteries can have several lifecycles and thus can be repurposed/reused before they need to be recycled.

Before old and waste batteries can be reused or recycled, they must pass through many procedures, including quality testing, safety assessment, lifecycle testing, etc. Based on their intensive battery lifecycle management, battery asset companies can monitor, evaluate, detect, and collect data on the real-time status of their batteries, build dynamic evaluation models of battery performance, lifetime, safety, and residual value, provide a basis for data analysis that sorts and restructures batteries into echelon utilization stage, and greatly reduce the processing time and cost of retiring batteries.[24]

Battery swapping balances battery management, optimizes charging and discharging, and allows effective evaluation of remaining capacity and remaining life with an eye toward echelon utilization.[25] The model, energy density, use intensity and user scenario of the traction battery used for battery swapping are relatively standard, so retired batteries are more uniform—a question that is again conducive to ensuring the reliability and safety of repurposed batteries, allowing them to realize their maximum value.

Battery-swapping stations are better able to tailor their schedules to optimize EV-to-grid interface

Using a centralized battery-swapping station for orderly charging not only reduces the investments needed to build the overall power grid but contributes to effective demand-side peak shaving and valley filling schemes, offering enormous potential economic and social benefits.

Compared to charging piles, battery-swapping stations can better control their charging times, response rate, and response speed to grid requests, and can obtain a higher rate of return thanks to demand response. Research on Shanghai EV participation in a power demand response pilot project conducted by China EV100, the response rate of the battery-swapping scenario was higher than private charging piles and public charging piles, along with faster response speed—swapping stations were able to participate in demand response within 30 minutes. The kWh compensation price for peak shaving response can be as much as 6 yuan/kWh (~US$0.93 cents/kWh) for battery-swapping stations, much higher than the compensation price achievable by private and public charging piles.

	Response rate	Response speed (hours advance notice)
Private charging piles	5.30%	24h
Public charging piles	75%	24h
Battery-swapping station	81.2%	0.5h

Table 14: Demand response rate and response speed for three types of charging facilities.

Source: Case study of commercial prospects of EV-grid interaction—a pilot case of demand response in Shanghai.[26]

As battery-swapping stations become more commonplace and the number of backup batteries grows, the energy storage function of battery-swapping stations will be notable. It is possible that the two-way interaction between the massive and stable demand from EVs and the power grid will be realized sooner than expected, and additional grid management functions such as peak load regulation and frequency regulation can be provided by battery-swapping stations.[27]

Battery-swapping model might bring benefits to battery manufacturers

It is worth noting that battery-swapping also has many advantages for battery manufacturers. As one industry person stated in an interview:

> *Battery swapping should be good for battery manufacturers. If battery swapping is widely used, it is good for the standardization of batteries. Battery manufacturers will stand in a strong position in the industry value chain, and the manufacturers will be down-graded to vehicle body producers. When there is no separate ownership of vehicle and battery, battery manufacturers can only rely on manufacturers. It is also beneficial for echelon utilization and recycling of batteries. For the battery-swapping mode, the ratio of EHT vehicle and swapping batteries is about 1:1.38, which means that battery business volume can increase by 38%.* [28]

The empirical evidence indicates that battery swapping for EHTs uses 1.38 times more batteries compared to fully integrated systems. However, the total number of batteries is only one comparative aspect. A battery-swapping solution allows lower total battery capacity, improves the total lifecycle of batteries, and allows batteries to be repurposed for second and third lifecycles, along with improving energy efficiency, energy balancing and sales of energy.

However, here we are faced with a dilemma. There is a concurrent collaboration and competition between vehicle manufacturers and battery manufacturers. If battery manufacturers become stronger, vehicle manufacturers might become weaker. Fighting for power and control over the electrified transportation industry requires compromises with reasonable benefit sharing or collaboration across these two types of stakeholders for the long-term benefit of the industry—this is a question that major actors in the industry must find an answer to.

PART SIX
BATTERY-SWAPPING EHT PROJECTS - EMPIRICAL ILLUSTRATIONS OF BATTERY SWAPPING FOR HEAVY TRUCKS

Currently, all battery-swapping EHT projects must create a specific economic feasibility calculation for their scenario that looks at fleet size, battery-swapping station numbers and size, etc., so that parameters can be determined appropriately. A battery-swapping station with 10 battery slots can hold 9 spare batteries and serve a fleet of 70 trucks, while one with 8 battery slots can hold 7 spare batteries and serve a fleet of 50 trucks. Based on the requirements for the specific scenario, trucks will be equipped with battery pack sized from 50 kWh to 400 kWh, with 282 kWh being the most common capacity being used at present.

In May 2021, the research team communicated with Enneagon, the major EHT battery-swapping solution provider in China so far, and they shared the status of their EHT battery-swapping projects in China through April 2021 with us. They have a total of 23 finished projects, 32 projects under construction, and 400 projects in the pipeline. Specifically, they have two long-haul battery-swapping projects planned for implementation in two provinces.

Figure 27 shows the details of these projects.

Network Distribution (Up to 2021-04-23)

Map code	1	2	3	4	5	6	7	8	9	10	11	12
Province	Guizhou	Shanxi	Shandong	Beijing	Tianjin	Shanghai	Hebei	Henan	Jiangsu	Guangxi	Guangdong	Hainan
No. of battery-swapping stations	5	4	3	3	1	1	1	1	1	1	1	1

Figure 27: Distribution of EHT battery-swapping projects in China through April 2021.
Source: Enneagon company presentation, May 20, 2020.

Business-driven battery-swapping projects

In the following section we share information on 6 representative projects to give a brief understanding of each project, the scale of projects, and experiences so far. All the battery-swapping stations for these projects were built by Enneagon.

Project 1
Beijing Miyun Green Chain Battery-swapping station, Beijing municipality.

Project 2
EHT battery-swapping station in Zhengzhou, Henan province.

Project 3
Xuzhou urban new-energy dump truck battery-swapping demonstration project, Jiangsu province.

Project 4
Shanghai Yangshan international port, phase 4 AGV (Automatic Guided Vehicle) battery-swapping solution, Shanghai municipality.

Project 5
Battery-swapping mining truck project in Inner Mongolia province.

Project 6
Battery-swapping EHT long-haul route, Inner Mongolia and Fujian provinces.

Beijing, Shanghai, Tianjin, and Chongqing are the four key cities that are under direct administration of Chinese central government. It means that these four cities have province level status in the Chinese administration system.

Project 1
Beijing Miyun Green Chain Battery-swapping station. Beijing municipality

Project launch: December 2019

Project ownership:

- Truck fleet operator: Beijing Green Chain Multimodal Transportation Co
- Battery-swapping station owner and operator: State Power Investment Group

Number of trucks: 200

Battery capacity: 282 kWh, 360kW motor

Average energy consumption: 1.38 kWh/km

Number of battery-swapping stations: 3

Total number of spare batteries in swapping-stations: 7 spare batteries at each station

Nominal truck range: 200 km with 30 ton load under normal driving conditions

Figure 28: EHT battery-swapping station at Miyun, Beijing.
Source: https://www.sohu.com/a/409710031_683886?_f=index_pagefocus_2&_trans_=000014_sgss_sgnbassy.

Beijing Green Chain Multimodal Transportation Co. operates the EHTs, while the State Power Investment Group owns and operates three battery-swapping stations in Miyun area (a major water resource area for Beijing's water supply system), where diesel trucks are not allowed to circulate due to environmental protection regulations.

This project operates 200 battery-swapping EHTs, all manufactured by CAMC and Foton, using CALT's 2-ton battery and a Top Gear electric motor.

When fully charged, these EHTs can carry 30 tons and travel 200 kilometers under normal driving conditions.

Figure 29: Battery location in this project.
Source: https://www.sohu.com/a/409710031_683886?_f=index_pagefocus_2&_trans_=000014_sgss_sgnbassy.

The three battery-swapping stations were built by Shanghai Enneagon Energy, and the vehicle networking platform was built by Shanghai Zhida. The battery-swapping station is about 30 meters long, with a centrally located open-ended bay used for the battery exchange operation.

Unlike passenger NEVs, where the swappable batter is mounted under the chassis, the EHTs' batteries are mounted behind the cab and lifted off the vehicle by an automated lifter and the moved to the side for exchange. After a Foton iblue battery-swapping 6×4 EHT enters the battery-swapping bay, the lifting boom is manoeuvred to grasp the rectangular battery pack behind truck cab. It is then shifted to the right battery bank, and another fully charged battery is transferred to the truck. The whole process takes about 3 minutes.

By May 2021, the project EHTs had operated safely over more than five million kilometers. Based on a rate of 400 kilometers per truck per day, the 200 EHT fleet is expected to reduce emissions by about 28,000 tons of carbon dioxide and 2,500 tons of pollutants per year. In terms of economic results, the project will save US$6.2 million (40 million yuan) per year in energy costs compare to diesel vehicles.

Project 2
The first fully functional EHT charging and battery-swapping station built by the State Power Investment Group in Henan province

Project launch: February 2021

Project ownership:
State Power Investment Group

Number of trucks: 200
Battery capacity: 282 kWh, 360kW motor

Number of battery-swapping stations: 1

Total number of spare batteries in swapping-stations: Not available

Nominal truck range: 180 km

The EHT battery-swapping station consists of a power distribution system, a charging system, a battery-swapping system, and security and fire prevention system. The station occupies 240 square meters. The station currently has one swapping lane, with room reserved for a second lane in a future phase II expansion.

The vehicle starts the battery swap with code recognition, laser positioning, and a manual confirmation button. After confirmation, the system automatically unlocks the battery, and a robotic crane grabs the battery, lifts it up, and moves it to the side for the exchange with a fully charged one. It takes only 3 minutes to change the battery, and 40 minutes to fully charge the empty battery.

The station can currently serve up to 100 vehicles a day, operating 24 hours a day unattended through fully automated and uninterrupted operation.

In May 2021, 200 SAIC dumper EHTs were delivered to customers in Zhengzhou city. Since this is a very new project, no operational results from the project are available yet.

Figure 30: EHT battery-swapping station in Zhengzhou, Henan province.
Source: https://baijiahao.baidu.com/s?id=1691092706275786429&wfr=spider&for=pc.

Figure 31: A CAMC EHT being served at the battery-swapping station in Zhengzhou, Henan province.
Source: https://baijiahao.baidu.com/s?id=1691092706275786429&wfr=spider&for=pc.

Project 3
Xuzhou urban new-energy dump truck battery-swapping demonstration project, Jiangsu Province

Project launch: December 2020

Project ownership: The State Grid and The State Power Investment Group

Number of trucks: 30 in 2020, 200 anticipated by end of 2021

Battery capacity: 282 kWh, 360 kW motor

Number of battery-swapping stations: 1 completed in 2020, with 3 more planned for completion in 2021

Total number of batteries in swapping station: 8

Nominal truck range: 180 km

China's first urban new-energy dump truck battery-swapping station was officially launched in Xuzhou City, Jiangsu province, in December 2020.

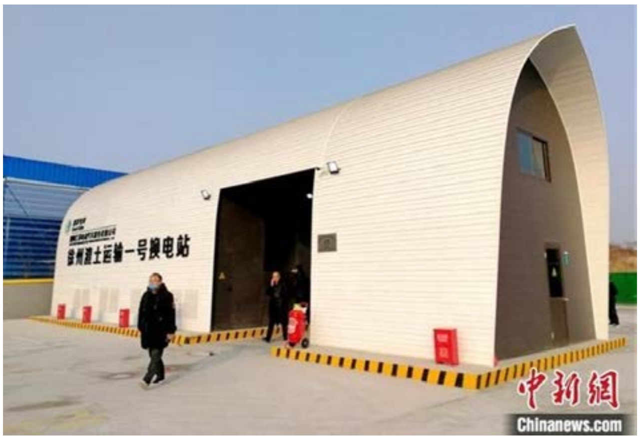


Figure 32: EHT battery-swapping station in Xuzhou city, Jiangsu province.
Source: http://www.bj.xinhuanet.com/bjxxjd/wqxx1/2020-12/09/c_1126841523.htm.

The investors and operators of the Xuzhou stations are The State Grid and The State Power Investment Group.

After the truck stops inside the swapping station, a robotic arm automatically grabs the 3-ton battery from the dump truck and replaces it with a fully charged battery. The whole battery-swapping process for each truck takes only 5 minutes (due to the size of the 3-ton battery). The entire process is fully automated and takes place without human intervention.

This station can serve 150 dump trucks every day, and EHTs using this station can transportation 4.5 million cubic meters of material every year.

The footprint of the battery-swapping station is 25% smaller than a standard cable charging station with a similar charging capacity.

After the successful operation of the first Xuzhou battery-swapping station, State Grid Jiangsu company plans to build three more stations, which are expected to operational by the end of 2021.

The XCMG intelligent battery-swapping dump trucks used for this project mainly transportation earthworks materials for subway construction. Each trip is about 42 km one way, and a round trip takes about 1 hour. The battery is exchanged after two round trips—more than 160 km. After a few months operation, the results show that the battery-swapping EHT fleet has lower maintenance costs and lower energy costs (about 6.2 cents/km) compared to diesel trucks, and fewer range restrictions and higher operating efficiency compared to cable-charged EHTs.[29]

When all 200 new-energy dump trucks are in use, they will save about 8 million liters of diesel fuel and reduce CO_2 emissions by about 25,000 tons per year compared with the same number of diesel vehicles—truly achieving a green urban dump truck scenario. Electric dump trucks require a very large battery that takes at least 40 minutes to charge.

Compared with cable charging, battery swapping will save nearly 1,000 hours per 100,000 km, greatly improving the vehicles' operational time in service, and resolving a major development bottleneck for new-energy heavy trucks.[30]

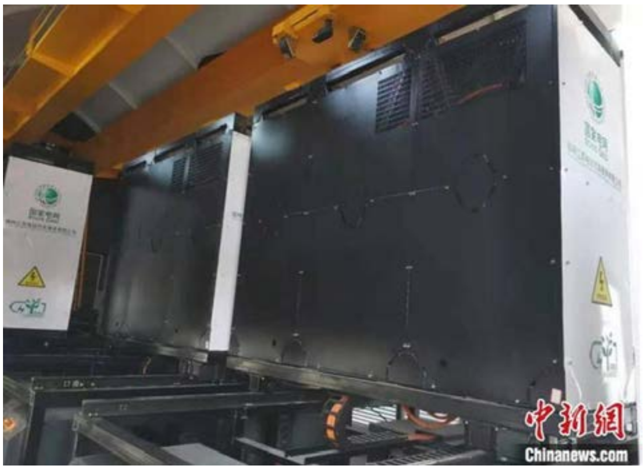


Figure 33: Interior of a fully automated battery-swapping station, with three CALC-manufactured swappable battery units visible.

Source: http://www.bj.xinhuanet.com/bjxxjd/wqxx1/2020-12/09/c_1126841523.htm.

Project 4
Shanghai Yangshan international maritime port - Phase 4 AGV (Automatic Guided Vehicle) battery-swapping solution, Shanghai municipality

Project launch: December 2017

Project ownership: Shanghai Yangshan Port

N**umber of AGVs:** 50 2017

Battery capacity: 338 kWh

Number of stations: 1

Total number of batteries per station: N/A.

Vehicle range: More than 8 hours of continuous operation

Shanghai Enneagon Energy provided an integrated battery-swapping solution for 50 automatic guided container vehicles as part of phase 4 in the development of Shanghai Yangshan international port in 2016. The Yangshan port AGV battery-swapping project is the first project Enneagon has carried out in the field of battery swapping. After starting with this project, Enneagon has explored and created EHT battery-swapping solutions in China together with its partners.

Figure 34: AGV battery-swapping solution at Yangshan Port, Shanghai.
Source: https://www.sohu.com/a/210419828_100086644.

The batteries are mounted on the vehicle chassis and replaced by pulling out the empty battery and pushing in the charged one from the side. The advanced vision system and positioning system automatically identifies changes in tire pressure and vehicle height as part of the battery replacement process, and the battery replacement is completed within 6 minutes.

The battery-swapping station includes 16 overhead chargers, one battery-swapping robot, a horizontal rolling gate, access control system, air conditioning, fire protection system, etc. During each battery-swapping operation, the robot lifts the 5.5-ton battery pack up 3.5 m. In order to ensure that the battery pack can be precisely stowed on the charging rack or AGV body, the positioning of the battery on the lifting fork needs to be controlled within ±3 mm.

A standardized battery pack was designed for the specially designed battery-swapping AGVs. These special vehicles can be tailored to different scenarios depending to the working conditions of each operational location.

Cable-charged AGVs remain idle for two hours to charge, reducing the efficiency of the whole port by 20-30%. The fully automatic AGV battery-swapping solution ensures that AGVs can operate 24 hours a day.

After the container terminal adopts battery-swapping AGVs, container throughput can be increased by nearly 30%.

In the next five years (2021–2026), an additional 2,000-5,000 battery-swapping AGVs and electric construction machinery vehicles will be put into operation in the port area, with no fewer than 30 special EHT battery-swapping facilities planned for construction.

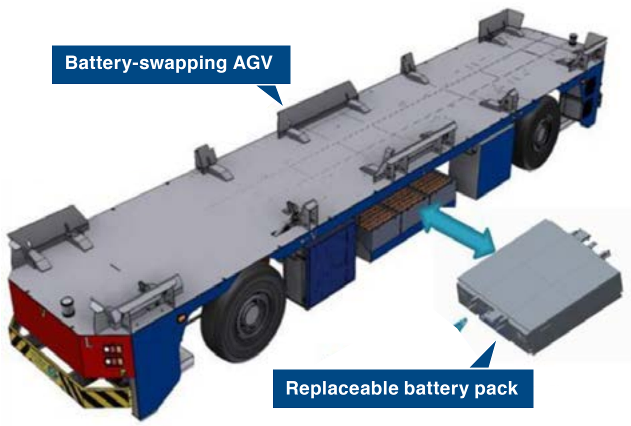


Figure 35: Illustration of battery-swapping AGV.
Source: https://www.sohu.com/a/210419828_100086644.

The total scale of investment is expected to exceed 2 billion yuan (~US$309 million).

Port, storage yard, municipal administration, sanitation, and logistics heavy truck vehicles in the Lingang area will all be fully electrified and connected to the operational networks of truck operators. This will turn Lingang New District into a strategically important demonstration promoting the construction of new-energy vehicle battery-swapping systems. The Lingang area, located on the east side of Shanghai, has been identified as one of the most important strategic development areas for manufacturing, logistics, and deep-water harbor shipping.

Project 5
Battery-swapping mining truck project in Inner Mongolia province

Project launch: December 2020

Project ownership: China Huaneng Group

Number of EHTs: 31

Battery capacity: 260 kWh

Number of battery-swapping stations: 1

Total number of batteries per station: N/A

Truck range: 40 km

A demonstration project has been launched in Inner Mongolia to test and demonstrate the feasibility of battery-swapping mining trucks in harsh environmental conditions; here wintertime temperatures reach –40 °C and summertime temperatures exceed 35 °C.

According to what we know, a single battery of the type used in this project can power a fully loaded heavy mining truck for 35 kilometers, transporting four or five loads of material on a single charge.

The average daily fuel consumption of a diesel mining truck was 800 liters per day, at a cost of 4,000 yuan ($650). The average daily energy consumption of the electric mining truck is 2,240 kWh, with an electricity of less than 2,000 yuan ($325). Just in terms of energy costs, each electric mining truck can save at least 600,000 yuan ($95,000) per year.

In addition, there are savings from reduced maintenance costs. Considering the maintenance and service needed for diesel trucks and the price of electricity price in the mining region, electric mining trucks can achieve a 41% savings in total operational costs.

After three months of intensive operation during the winter period, the trucks have proven they can operate reliably at temperatures of –40 °C.

State Grid plans to replace more than 5,000 traditional diesel mining trucks with battery-swapping EHTs by 2025.[31] To achieve this transformation, large number of swapping stations need to be built to support so many vehicles at different operational locations.

Figure 36: Battery-swapping mining truck project in Inner Mongolia.
Source: Enneagon company presentation, May 20, 2020.

Project 6
Battery-swapping EHT long-haul route, Inner Mongolia and Fujian provinces

Two long-haul highway battery-swapping EHT projects are under construction in China, designed to test and demonstrate battery-swapping operational capabilities along a 180-km stretch of heavily used highway in two different locations: the Baotou to Erdos route in Inner Mongolia, in northern China, and Ningde to Fuqing route in Fujian province, in southern China.

The plan is to build three battery-swapping stations along each 180-km stretch of highway—one each at the end points and one in the middle.

The number of trucks planned for operation along the two highways, along with their technical specifications, battery sizes, and the specifications for the swapping stations, are not publicly available at this time.

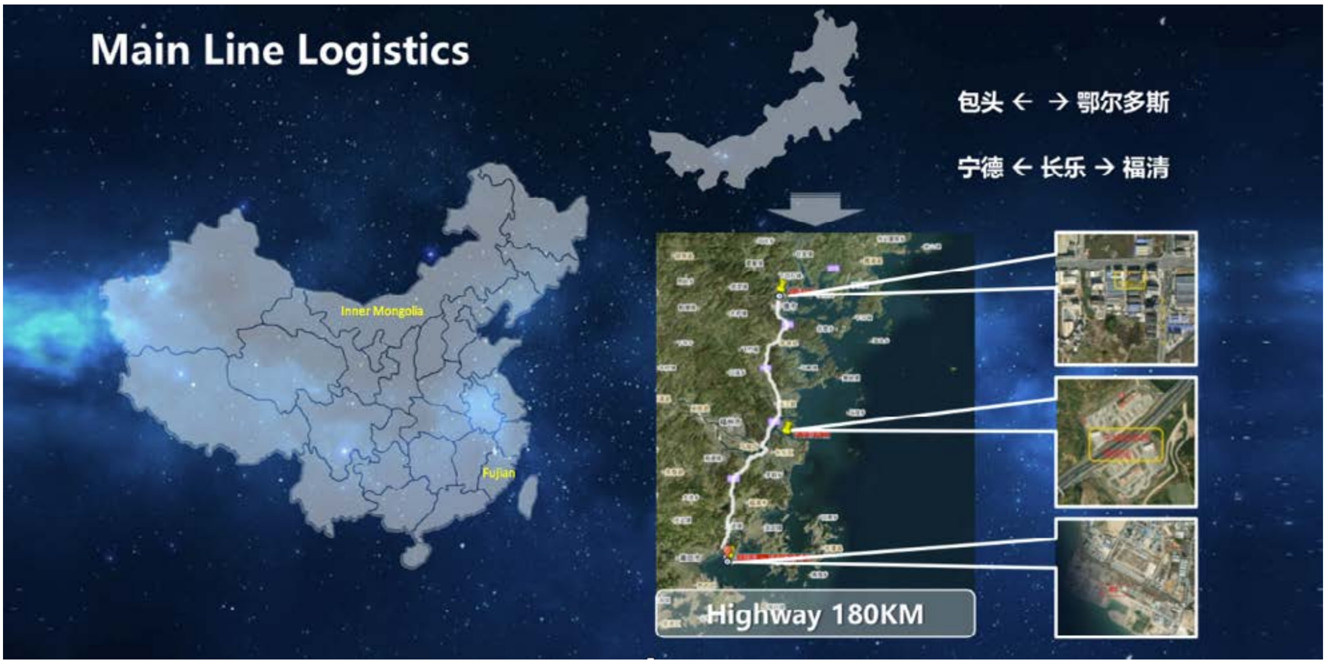


Figure 37: Two highway projects for battery-swapping.
Source: Enneagon company presentation, May 20, 2020

PART SEVEN
CONCLUSIONS AND DISCUSSIONS

As part of the Sweden-China Bridge project's research exploring transportation system electrification, this report focuses on battery-powered electric heavy trucks (battery EHTs) above 14 tons in weight, and specifically on battery-swapping technology.

The electrification of transportation systems, including passenger vehicles, trucks, and buses has rapidly picked up speed in recent years. There are two main pathways to achieving transportation electrification.

- One is by storing electricity in on-board batteries that power the EV; vehicles need large-capacity batteries to enable long driving ranges and large cargo capacities.
- The other is to use hydrogen for energy storage through fuel cells that produce electricity to power the EV.

Regardless which path is chosen, "refueling" is necessary—either recharging batteries or refilling vehicles with hydrogen.

Main barriers to EHTs

Challenges facing battery EHTs

1. Recharging

Battery charging is one of the main challenges for EHTs. To enable EHTs to operate, the onboard battery must be of sufficient size to enable an adequate range, load capacity and competitive pricing. There are several ways to charge EHT batteries, including conductive charging via road-embedded rails, overhead wires, or plug-in cable, inductive charging via magnetic energy dissipation, and exchange of batteries, i.e., battery swapping. The most common way form currently is static conductive cable charging while the truck is standing still. Dynamic conductive technologies that allow charging via in-ground rails or overhead wires have so far been used only for demonstration purposes. No inductive charging technologies are commercially mature at this point in time. The remaining alternative or complement to cable charging is battery swapping.

2. Operational limitations

Typical, EHTs today carry a fixed, fully integrated battery with a 100-500 kWh capacity. EHTs can typically operate at a range of about 200 km or 2-3 hours of driving before needing to recharge, a process that takes 2-4 hours in fast recharging mode and even longer in normal charging mode. Operational performance depends on the driver's experience and skill driving EHTs, as well as driving conditions (summer or winter), geographical location (city or highway, flat or mountainous terrain), cargo load, and battery capacity (both nominal kWh and age).

During a full workday, a cable-charged EHT will be able to cover only 50% of the operational range of a diesel truck. This significantly reduces efficiency for operators. Battery swapping has been introduced to address this challenge, allowing the exchange of empty batteries with fully charged ones in 1–5 minutes. This allows EHTs to achieve almost the same operational capacity, range, and "refueling" time as diesel trucks.

China takes the lead in electrification

China has become the leading country in terms of both EV development and market share (including passenger vehicles, EHTs, and buses) and the development of battery-swapping systems.

Battery-swapping development started around the same time as transportation electrification gained popularity in China between 2000 and 2010. Due to the country's size and the number of vehicles of all kinds, battery swapping was seen as a complementary solution to cable charging. However, it is possible that battery swapping might become the new standard for EHTs due to the efficiency of the overall EHT transportation system, the accessibility to the transportation vehicles, operational system flexibility for both vehicle and charging station operators, and usefulness for both short-haul and long-haul operations.

Our research has identified the following main aspects of battery swapping:

Energy producers and distributors are driving the development of battery-swapping EHTs

- The decarbonization process in China is largely driven by energy producers, who are responsible for ensuring a sufficient electricity supply for the entire transportation system, industry needs, and society in general, and are also responsible for the decarbonization process.
- Energy producers are responsible for ensuring energy production and electricity provision for the national transportation electrification process, and thus they see themselves as clearly responsible for ensuring that the systems being developed fit within the nation's total energy system.
- Energy producers have invested considerable resources in expending their businesses into the new field of battery-swapping EVs from the outset by developing several pilot project collaborations with local partners.
- In China it is energy producers who are the main driving force in the initiation, development, ecosystem construction, and commercialization of battery-swapping systems.

New ecosystem developed

- Energy producers and distributors have established a new ecosystems of investors, EHT manufacturers, swapping-station developers and operators, and software system developers that incorporate new key actors.

From demonstration projects to widespread adoption

- In 2021, battery swapping took a substantial step to becoming a new standard solution, as major truck manufacturers received more than 15,000 orders for battery-swapping EHTs in the first half of the year.
- So far in China, almost all EHTs use the same battery-swapping system developed by Enneagon, with the swappable battery mounted behind the cab. This has become an informal standardized solution.
- Swapping capabilities allow EHTs to use situation adjusted capacity of batteries (smaller as well as larger), increasing their operational efficiency and increase the total payload capacity.

Business-driven system development

- We have detailed six typical battery-swapping projects, and in all these cases the starting point was not a push from technology developers or pull from customers. Rather, they reflect business-driven developments between new ecosystem actors, focusing on the commercial side of the project as seen from the operator's perspective.
- This commercial focus joins new ecosystem actors together and pushes them to make a cohesive effort to succeed. Every successful business-driven project opens the door to future projects.

Current dominant technology solution

- The current dominant swapping solution for trucks has been developed by Enneagon in Shanghai. The system is flexible and scalable and enables battery capacity to be tailored and adjusted to the specific operational need.
- Battery capacity ranges 50 kWh to 500 kWh, and possibly larger. Battery size influences battery price and EHT payload, range and total weight.
- Battery swapping enables operators to rent different capacity batteries at different times, upgrade and downgrade when needed. This allows operators to adapt to different operating conditions and use the same vehicle in different contexts.
- The Enneagon swapping system is flexible compared to fully integrated batteries. With fully integrated solutions, operators cannot change the capacity of the electric truck after purchase.

Battery swapping is not a "one size fits all" solution

- Battery swapping does not fit all business scenarios. It is most suitable for intensive scenarios that require continuous operation where idle time to recharge significantly impacts performance. It is also ideal for long-haul operations of more than 200 km that exceed the range of current battery technology.
- For local scenarios with short trips that do not require 24-hour vehicle performance, cheaper cable recharging options are often more economically feasible.

Battery swapping creates flexibility for operators

- However, battery swapping does give operators two charging options, allowing them to choose the most appropriate solution for their current needs. Operators are not restricted to a single charging solution and means operators can use the same EHT for both local and inter-city tasks.

Battery-swapping business model focuses on operators

- The development of battery swapping has largely focused on the technology. However, the most important aspect to develop is the most suitable business model.
- In China, the favored business models separate the battery and vehicle.
- Battery/vehicle separation can take two different forms:
  - Operators buy the EHT and the battery and finance each system through different financial products.
  - Operators buy only the EHT and rent the battery from a battery bank and pay a fixed rental fee and variable swapping fee.
- This business model enables operators to reduce their investment and feel safer in the shift diesel to EHT vehicles, enjoying a better resale value for the vehicle body and reducing concerns over deterioration of battery quality and resale value over time.
- This enables the battery-bank to use swapping systems to ensure a large supply of uniform batteries for repurposing to a second and third lifecycle, and opens new business opportunities such as energy storage, energy balancing. It also allows them to take advantage of price differences between peak and valley periods when charging.
- To ensure trust, strategic long-term collaboration, financial and business risk sharing, and long-term technology development, ecosystem actors often invest in each other, creating a robust comprehensive business system.

Reflections

There are major differences between the Western and Chinese approaches to transportation electrification

In Europe, fragmented electrification solutions are being developed, not only as demonstration projects but also large-scale commercial implementations. It seems that electrification is being driven by business interests of different stakeholders, with limited coordination from policymakers. Technology is driving the process rather than customer needs.

In China, although different groups of business entities are developing different solutions in different provinces, the major large national energy companies are playing an important role in developing a coherent set of technologies and solutions to meet commercial needs, rather than being pushed by technology developments or pulled by customer demands:

1. China has taken the leading position in transportation electrification. Europe is catching up, while the United States is lagging behind and is trying to catch up with both China and Europe.
2. In 2021, China had more than 100 suppliers of domestically developed and manufactured fully electric passenger vehicles.
3. More and more Chinese companies are developing and manufacturing EHTs.
4. Battery-swapping technology has become a national strategy for transportation electrification, and thus many companies are interested in this EV solution, including passenger vehicles, trucks and buses, and special vehicles.
5. Chinese passenger BEVs are entering the international market, with at least 3 different models now sold in Europe.
6. We have reasons to believe that Chinese EHTs will follow the same path. After establishing a strong domestic position and after demonstrating their capabilities in battery-swapping technology, Chinese actors will expand their operations to Europe as well.

In Europe, electric road systems (ERS) are major focus, promoted by governments and companies in several countries. Sweden and Germany are taking the lead in ERS development. These technologies can trace their roots to the development of the first generation of electric trams in the 1800s. Europe has extensive experience with electric trains and metro systems, which is now being deployed similarly to electrify road transportation systems. However, just because ERS align with tradition does not mean that road electrification should follow the same path, using an older technology in new applications in the context of societal and technological changes.

Technological competition or technological complementation

How can the ongoing process of digitalization, global systems development, transportation electrification, and the development of smart cities work together and integrate into systemic solutions if we use old solutions under new conditions?

Are old technologies actually what we need in today's world? Just because we can do sometimes does not mean that we should do it. We need to consider the current context and the needs of tomorrow, not yesterday.

Just because battery-swapping systems failed as a solution 20 years ago due to Better Place invention and since Tesla developed it in their original Tesla S car, but never commercialized it, should not lead us to see those failures as the final answer. Those early adopters and inventors of battery swapping for passenger vehicles are presented in the report "Battery swapping for electric vehicles in China 1.0" (Danilovic & Liu, 2021). They were only the beginning of a new industry for battery swapping. Earlier explorations of battery-swapping solutions were not mature and the timing was not right. However, times are changing. Our knowledge has evolved and our experiences are more extensive. We need to open our eyes to new technologies, new solutions and new opportunities coming to us being based on original ideas of battery swapping adapted to new contexts, with new actors, in a new shape and new design.

We need to look for technologies that have the potential to grow, that are scalable and flexible, that enable new functionalities, and that support the development of smart cities, that can consume a high ratio of renewable energy from intelligent grids, and that are flexible and adaptable.

We need to consider esthetics and the beauty of the landscape and cities when we develop our transportation infrastructure, and develop transportation electrification solutions into coherent, beautiful, attractive systems. Technology and art are intertwined, as Steve Jobs has demonstrated in Apple product design. Technology and art must be combined to create a beautiful society and not just functionally workable solutions.

We need to consider interoperability across Europe and not only consider the context and conditions of each country and its political situation and political logic. We need to consider electrification from the perspectives of citizens and operators.

Can we trust each country to develop their own transportation electrification solution, forcing operators to buy EHTs designed to handle cable charging, static and dynamic conductive charging via rails or overhead wires, and battery swapping at the same time to ensure operators can use their EHTs through Europe? It seems unlikely!

Research on innovation over the years has shown us that standardization of technologies, solutions, and practices are some of the main ways to improve dissemination of new technologies and therefore encourage innovation. This is true for transportation electrification as well.

Although we are only at the beginning of the electrification journey and many more new technologies and solutions will emerge down the road, we need to consider scalability, flexibility, interoperability, and most of all the feasibility of business models that support users and approach electrification from operator and business perspectives and not only from the technological perspective.

Just because we can doesn't mean we should. We must look toward the future and take a visionary approach to both the finer details and the broader perspective.

From transportation electrification to smart cities and communities

In the first project we conducted with the Swedish Transportation Administration (TRV) on transportation electrification in China in 2018, we noticed that electrification was not an isolated phenomenon or merely an isolated strategy for decarbonization or improving air quality. We realized that China frames technology as something with the capacity to bring value to society as a whole. Decarbonization, improved air quality, and value creation were some of the benefits, but they were not the ultimate target. The ultimate target was building the next generation of smart cities and communities, which needed to be fully integrated with a smart and intelligent transportation system.

Transportation electrification were not pursued by any means available, such as conductive technologies like embedded rails or overhead wires. China's electrification in 2018 was geared toward inductive technologies, along with interest in solar energy cells built into roads.

By 2021, we noted that the development of solar roads was progressing poorly due to technical challenges in material technology, and the sale of inductive vehicle charging technologies and their dissemination were advancing more slowly than expected due to uncertainties about radiation during charging and the lack of international standards for interoperability of systems across different brands. In 2021 we also noticed that several new developers had production-ready inductive charging systems but were waiting for those two barriers to be resolved before launching large scale commercialization.
But perhaps the most important observation at this point in our research was that China had taken large step forward in the development of smart cities and communities.

Technology is developing rapidly, and progress is now visible in this direction all over China. The digital journal WIRED reported on one international contest on smart cities and communities that started in 2017, focusing on artificial intelligence (AI).

In the first years, teams representing American companies or universities took top spots in the competition.

Last year, Chinese companies won three out of four competitions.

Last week, Chinese tech giants Alibaba and Baidu swept the AI City Challenge, beating competitors from nearly 40 nations. Chinese companies or universities took first and second place in all five categories. TikTok creator ByteDance took second place in a competition to identify car accidents or stalled vehicles from freeway videofeeds.

Johnson, WIRED, July 3, 2021

The results of this competition put on display the fruit of years of investment by Chinese government agencies, universities, and industrial actors in developing smart city technologies. Transportation electrification plays an important role in this process. Hundreds of Chinese cities have different pilot programs, with some people arguing that China is home to half of the world's smart city demonstration projects. The development of edge computing, cameras, sensors, and communication technologies using 5G and wireless connections, together with electrification and interconnectivity of electrified transportation systems are expected to accelerate the development of smart cities and communities. Electrification is one cornerstones of this development, and transportation electrification plays a crucial role in this development.

The energy stored in vehicles becomes a very important aspect of energy provision on the national strategic level, and therefore the energy being stored in vehicles needs to be connected to the grid in a way that complements the distribution of electricity from vehicles, and thus become a strategic energy reservoir for energy balancing and the energy distribution bank.

What was just an idea in 2018 is now becoming a reality. The electrification of transportation needs to be seen and understood in terms of greater, aggregated technological development of the society. The electrification of transportation must be integrated into coherent system solutions and implemented in the next generation of cities and communities. Thus, electrification of transportation is not only a limited solution to an eminent electricity supply to electric vehicles but a strategic tool for the development of society as a whole. To achieve this we need a birds-eye view.

> *Stan Caldwell is executive director of Mobility21, a project at Carnegie Mellon University assisting smart-city development in Pittsburgh. Caldwell laments that China invests twice as much as the US in research and development as a share of GDP, which he calls key to staying competitive in areas of emerging technology.* (Ibid)

We need to understand that to develop the leading smart city and community concepts, many different technologies need to be developed, and they must be complementary to and supportive of each other, integrated into functional system solutions, deliver their expected outcomes, and create value. Electrification is thus one key mean to achieve the target of smart cities and community's functionality. Sustainability energy sourcing through renewable energy, emissions-free and de-carbonized energy consumption (zero emissions) are some of the cornerstones of this development.

The smart-city development is based on communication

The development of smart-city concepts are based on three main pillars:

- Interconnectivity of vehicles of all kinds and urban areas, cities across regions and countries.
- Communication between vehicles, headquarters, people,
- Integrated systems based on speed, data flow and sped in the communication.

Autonomous driving, platoon driving and safety all depends on that those three pillows are developed, and fully integrated. 5G technology is important but the next 6G technology will probably bring the game charging capability to automobile and e-mobility industry.

The status of the 6G technology development

The upcoming sixth-generation of mobile communications technology, which is said to be more than 10 times faster than contemporary 5G, expected to be rolled out commercially as soon as 2030, is expected to enable fully autonomous driving, high-definition virtual reality and worldwide internet connections, even in remote deserts. In the 6G era, aerial coverage, such as satellites, as well as ground base stations for broader radio bands, will be needed. Application scenarios include fully automated driving, high-definition virtual reality, etc. 6G will have high impact on next generation of electric vehicle systems.

The status of applied 6G patents

Nikkei Asian Review and Network Innovation and Research has analyzes the approximately 20,000 patents that are being applied for. In the next generation communication standards in the 6G development US, Europe, China, Japan and S Kora are taking a lead.

Applied patents are indicators of the force in this rapid technological development. Following is the indication of applied patents in the 6G technology race by summer 2021:

Rank	Country	Applied 6G patents
1	China	40.3%
2	USA	35.2%
3	Japan	9.9%
4	Europe	8.9%
5	South Korea	4.2%
6	Others	4.2%

Table 15: Global 6G applied patents.
Source: Watanabe, Naoki, Nikkei Asia Review, 16 September 2021. https://asia.nikkei.com/Business/Telecommunication/China-accounts-for-40-of-6G-patent-applications-survey

PART EIGHT: THE ROLE OF HEAVY TRUCKS IN EUROPE

To understand the development of China's electrified transportation system we need to relate this development to conditions and developments in Europe.

The development of vehicles in Europe

For long time, the automotive industry has been important to European society in terms of its technological and economic development, growth and mobility.

The European Automobile Manufacturers' Association (ACEA) publishes a statistical Progress Report that monitors the development of transportation electrification and the availability of charging and refueling infrastructure.

The following table shows the development of different vehicles technologies in Europe between 2014 and 2020.

Here we can see the dynamics of the transformation from diesel fuel to electric vehicles, both BEVs and hydrogen and fuel cell vehicles:

- The BEV has grown from 30,820 units in 2014 to 583,023 units in 2020 (almost 18 times increase).
- The hybrid electric vehicles has grown from 139,280 units in 2014 to 1,182,792 units in 2020 (almost 8,5 times increase).
- The fuel cell vehicles are growing from 32 units in 2014 to 749 in 2020 (almost 23 times increase).

	2014	2015	2016	2017	2018	2019	2020
Petrol	4,174,069	4,752,707	5,481,409	6,205,957	7,055,394	7,514,812	4,713,778
Diesel	5,329,263	5,762,740	5,890,470	5,551,109	4,655,747	4,106,951	2,778,817
Electrically-chargeable	55,356	119,323	118,542	168,901	240,347	387,325	1,045,082
- Battery electric	30,820	49,231	53,215	84,070	131,954	247,371	538,023
- Plug-in hybrids	24,536	70,092	65,327	84,831	108,393	139,954	507,059
Hybrid electric	139,280	174,695	226,940	359,093	503,618	742,084	1,182,792
Fuel cell	32	165	113	218	230	483	749
Natural gas (CNG)	97,214	78,511	57,609	49,553	65,023	68,129	55,028
Other (LPG + E85)	141,452	140,321	118,430	156,710	164,270	186,141	153,344

Table 16: Registered vehicles in Europe, 2014-2020.
Source: ACEA (European Automobile Manufacturers' Association), 2021.

Heavy trucks in Europe are a big business

The European classification defines trucks as “motor vehicles with at least four wheels, used for the carriage of goods” with a weight of more than 3.5 tons. Trucks are classified either as category N2 (weighing more than 3.5 tons) or N3 (weighing more than 16 tons), referred to as heavy trucks.

Below are some key numbers to indicate the main operations and importance of heavy trucks in the European context.

- 6.2 million trucks are in circulation throughout the EU
- 435,976 trucks were manufactured in the EU in 2020
- 247,499 new trucks were sold in the EU in 2020
- 159,233 trucks (over 5 tons) were exported worldwide in 2020, worth €5.7 billion. Trucks generate an annual trade surplus of €4.9 billion for the EU
- 96.5% of all new trucks sold in the EU are powered by diesel, and 0.1% by petrol
- 3.4% new-energy vehicles (battery electric, plug-in hybrid, hybrid, and alternative fuels) represent only 0.7% of all trucks on the road today
- <1% heavy trucks with alternative powertrains represent less than 1% of the current heavy truck fleet

Figure 38: Key figures that indicate the role and importance of heavy trucks in Europe.
Source: Author’s summary.

- 3,415,000 people are employed in the road freight transportation sector. Road freight transportation is the backbone of trade and commerce on the European continent.
- 73.1% of all overland freight transportation in the European Union moves by truck.
- 150 km—In contemporary EU economies, 85% of road freight tonnage is carried over distances of 150 km or less, along routes for which no other form of transportation is realistic.
- Less than 1% is carried over 1,000 km distances.

Trucks are the most flexible, responsive, and economical mode of overland transportation for most goods and freight and are also essential to the functioning of Europe’s broader integrated logistics and transportation system.

(Source: ACEA, 2021)

According to ACEAs statistics:

10,000-15,000 (higher-power) public and destination charging points should be the target, no later than 2025.

40,000-50,000 charging points for no later than 2030.

40,000 lower power (100 kW) public over-night chargers at truck parking areas along the highways should be set for 2030.

Figure 39: ECEA key figures of heavy truck fuels in Europe.
Source: Author's summary.

This indicates that the European market for BE trucks is only barely beginning to be developed, and full exploitation is a question for the future. Due to this, high expectations for achievements in 2035 are viewed as lofty targets.

- From a number of 7.5 million cars registered in 2019, petrol vehicle demand dropped to 4.7 million units in 2020 (just 539,709 units more than in 2014).
- The number of diesel vehicles sold dropped by almost 2.6 million units over the same time period.
- Electrically chargeable vehicles—i.e., BEVs and plug-in hybrids—increased by a total of almost 1 million units (to 1,045,082) over the seven-year period.
- Sales of BEVs more than doubled between 2019 and 2020.

During the same period, sales of plug-in hybrids more than tripled in the EU.

- 1 million more hybrid electric vehicles were sold in 2020 compared to 2014.
- Registrations of fuel cell vehicles increased by 55% between 2019 and 2020, from 483 to 749.

We see that 2020 was a year of transformation from ICE vehicles to BEVs and hybrid vehicles, while deployment of hydrogen technology is still low but growing, as the technology is not ready for full commercialization and the refueling infrastructure is not yet in place.

The European Union is on the way toward changing policies regarding natural gas and other fuels, and this probably will increase the push for electric technology even more than before. When we look at these statistics, we need to consider that the growing numbers mostly reflect passenger vehicles. Heavy vehicles such as trucks and buses have not yet really started to convert to electric technology.

In these numbers we can see the importance of transportation and particularly the role of trucks for the European economy. We also see the low level of new-energy trucks, and particularly the low level of BE trucks. The transformation towards EHTs has just started.

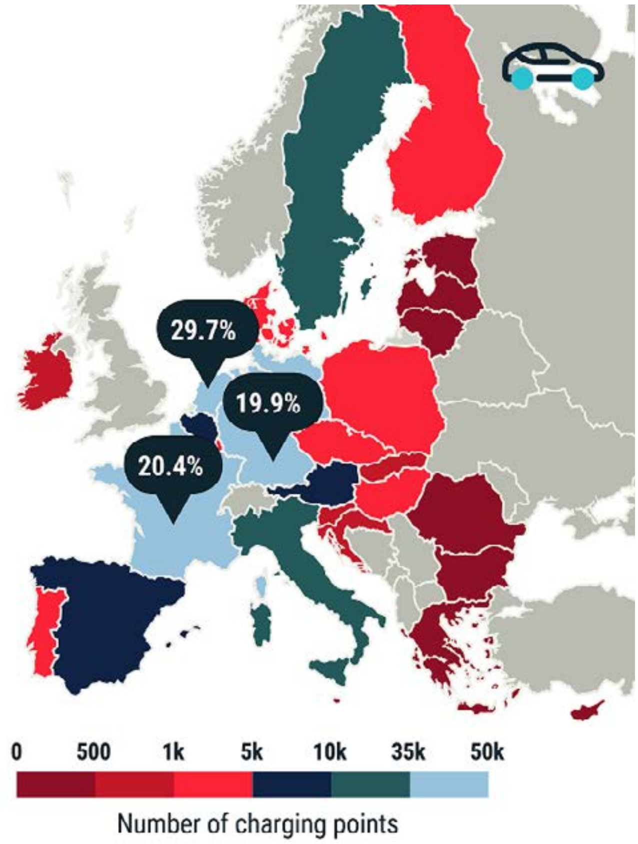
European transportation electrification is so far focusing on BEVs and charging piles

Development of supportive charging infrastructure for passenger vehicles

New data from the ACEA show that there exists a completely unbalanced picture when it comes to the spread of charging points for electric cars across the European Union. (ACEA, 2021).

ACEA finds that about 70% of all EU charging stations are concentrated in just three countries in Western Europe: the Netherlands, with 29.7% (66,665 charging piles), France with 20.4% (45,751 charging piles), and Germany with 19.9%, (44,538 charging piles). Together, these countries make up just 23% of the EU's total area. The other 30% of infrastructure is scattered throughout the remaining 77% of the region.

This imbalanced distribution of charging infrastructure will have impact on the development of different EU countries and European countries outside the EU, as well as on the development of electric vehicles in the future—particularly with regards to EHTs that need to traverse the continent, at times from as far away as Russia or Turkey.



Top 5 countries, no. of installed chargers

1. Netherlands (66,665)
2. France (45,751)
3. Germany (44,538)
4. Italy (13,073)
5. Sweden (10,370)

Bottom 5 countries, no. of installed chargers

1. Cyprus (70)
2. Malta (96)
3. Lithuania (174)
4. Bulgaria (194)
5. Greece (275)

Figure 40: Distribution of charging infrastructure in the EU, Spring 2021.
Source: ACEA, 2021.

The number of installed chargers in different countries should not be seen in nominal numbers only but rather in relation to the area and population of each country.

In the listing of the countries with most installed chargers, the Netherlands ranks first and Sweden ranks 5th.

Rank	Country	Population	No. installed charging piles	Piles per capita	People per pile
1	Nether-lands	17 million	66,665	3,921 per million	255
2	Sweden	10 million	10,370	1,037 per million	964
3	France	67 million	45,751	683 per million	1,460
4	Germany	83 million	44,538	537 per million	1,864
5	Italy	59 million	13,073	222 per million	4,513

Table 17: Comparative ranking of EU countries by charging pile density.
Source: Based on ACEA, 2021.

Considering its population size and number of installed chargers, the Netherlands has four times as many piles per million people as Sweden, even though Sweden's total number of chargers is only 15% of the Netherlands' figure. Even though it ranks only fifth in terms of the total number of charger, it has the second-highest ranking in terms of piles per million people. Meanwhile, the Netherlands ranks first both in terms of total number of piles and piles per million population.

This information on the contemporary allocation and distribution of charging infrastructure indicates the imbalance between wealthier and less wealthy parts of the EU (Netherlands vs. Italy), and that the focus of the transportation electrification so far has been on the passenger vehicles. The electrification of heavy trucks is only in its initial stages.

For heavy vehicles, the situation is even more complicated. Traveling and transportation across European countries in an EHT will be problematic if charging infrastructure is not standardized or evenly distributed—and becomes nearly impossible where no infrastructure exists at all.

In 2021, the European Commission started the review process for the Alternative Fuel Infrastructure Directive. In this process, the ACEA stresses that interest must not only be directed towards charging piles for EVs but also for hydrogen stations for FCEVs, and must consider every EU member state in order to ensure interoperability across the continent.

However, we should be aware of the risks if EU take steps in this development that leave non-EU countries on the continent behind. There is an obvious risk of decoupling well-developed and less well-developed countries in the European context when the transportation electrification is driven at a pace based on what the richest EU countries are capable of, while the rest of the EU and the poorer countries outside EU cannot keep up.

A similar conclusion is valid for progress in EV infrastructure between developed and developing countries. If the EU and other developed countries continue along this path, there is a growing risk of new rift between well-developed and electrified countries and less developed/non-electrified countries that cannot afford to electrify at a fast pace and wind up suffering due to their lack of development capacity. This new EU strategy might become a new international trade barrier against less well-developed countries.

The new EU "Fit for 55" strategy for decarbonization

The European Green Deal, presented by the European Commission on December 11, 2019, sets the goal of making Europe the first climate-neutral continent by 2050. The European Climate Law enshrines the EU's commitment to climate neutrality and the intermediate target of reducing net greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels.

The EU's commitment to reduce greenhouse gas emissions by at least 55% by 2030 were presented in December 2020 as the EU's contribution to meeting the goals of the Paris Agreement.

> *The fossil fuel economy has reached its limits. We want to leave the next generation a healthy planet as well as good jobs and growth that does not hurt our nature. The European Green Deal is our growth strategy that is moving towards a decarbonized economy.*

> *Europe was the first continent to declare to be climate neutral in 2050, and now we are the very first ones to put a concrete roadmap on the table. Europe walks the talk on climate policies through innovation, investment and social compensation.*

(President of the European Commission Ursula von der Leyen)

The "Fit for 55" strategy presented in the summer of 2021 consists of an integrated set of proposals that all drive towards the same goal of ensuring a green transition by 2030 and beyond.

The EU commission stresses:

> *This is why solidarity is a defining principle of the European Green Deal—between generations, Member States, regions, rural and urban areas, and different parts of society …*

The Social Climate Fund will provide €72.2 billion in current prices for the period 2025-2032 in the EU budget from the new Emissions Trading System.

This indicates that the contemporary situation in the EU needs to be balanced, jointly developed and implemented among all member states.

However, Europe is larger than the EU, and the Fit for 55 strategy will have a great impact on European countries outside the EU, as well as global trading partners with the EU, since Fit for 55 includes financial components to force countries outside EU to follow EU standards.

Transportation is vital for the EU: Decarbonizing its energy system to meet the climate goals of Fit for 55

While the energy sector is a major contributor to greenhouse gas (GHG) emissions, so too is road transportation. However, 75% of total GHG emissions in the EU come from the energy sector, while road transportation contributes 20.4%. Road transportation is also a major economic engine for the entire EU and very important industry, from vehicle manufacturing to the transportation of goods and people.

With our three transportation-specific initiatives—ReFuel Aviation, FuelEU Maritime and the Alternative Fuels Infrastructure Regulation—we will support the transportation sector's transition into a future-proof system. We will create a market for sustainable alternative fuels and low-carbon technologies, while putting in place the right infrastructure to ensure the broad uptake of zero-emission vehicles and vessels. This package will take us beyond greening mobility and logistics. It is a chance to make the EU a lead-market for cutting-edge technologies.

(Commissioner for transportation Adina Vălean)

The Fit for 55 targets for transportation

All transportation segments in the EU need to cut emissions by 90% by 2050, according to the Fit for 55 strategy. This is a demanding target, and to achieve such a radical transformation, a new transportation system will be needed to be developed and implemented, requiring a combination of measures to reduce road transportation emissions supplemented by emissions trading. The transition to 55% zero-emission mobility of new cars in 2030 and 100% in 2035 compared to 2021 levels are demanding targets.

To achieve the targets, the entire automotive industry will need to transform its product portfolio from internal combustion engine technology to BEVs or HFCVs. This is the contemporary direction of the entire global automotive industry. Reducing GHG emissions by at least 55% by 2030 requires an integrated system that also includes a greater share of renewable energy and greater energy efficiency. The proposed targets for alternative fuel infrastructure are keys to supporting the penetration of cleaner vehicles and the continued growth of this market, which presents extraordinary opportunities for the EU car industry.

The specific targets for reduction of passenger vehicle CO_2 emissions by years:

- By the year 2025 - Reduction by 15%
- By the year 2030 - Reduction by 55% (-50% for vans)
- By the year 2035 - Reduction by 100%

Figure 41: The specific reduction targets for CO_2 emissions from passenger vehicles, by year emissions.
Source: EU Commission, 2021.

Alternative vehicle technology and fuel infrastructure

As a result, all new cars registered in 2035 must be zero emission. That means that hybrid vehicles will be banned along with ICE vehicles. The remaining question is how this will influence bioenergy and natural gas–fueled vehicles.

To ensure that drivers can recharge or refuel their vehicles at a reliable network across Europe is one main question. Regulations for alternative fuel infrastructure will **require member states to expand recharging capacity in line with zero-emission car sales** and to install charging and fueling points at regular intervals along major highways. According to the Fit for 55 strategy, this should be on average every 60 kilometers for electric charging and every 150 kilometers for hydrogen refueling stations.

Regulation will ensure the necessary deployment of interoperable and user-friendly infrastructure for recharging and refueling green vehicles across the EU, keeping pace with the development of the technology and markets and guaranteeing that rural and remote areas will be covered.

The new charging and refueling infrastructure for Fit for 55

With Fit for 55, the EU is indicating clearly its preferred direction of transportation electrification, based on a combined static conductive cable charging infrastructure with charging piles and hydrogen refueling stations.

Three vehicle types are depicted in the table below, with information on what their charging infrastructure will look like.

Recharging points for passenger vehicles	Hydrogen refueling stations	Recharging points for heavy vehicles
On the TEN-T core network: at least 300 kW power output every 60 km by 2025 and at least 600 kW by 2030.	Available every 150 km by 2030 along the TEN-T core network.	On the TEN-T core network: at least 1,400 kW of recharging points every 60 km by 2025 and at least 3,500 kW by 2030.
On the TEN-T comprehensive network: at least 300 kW power output every 60 km by 2030 and at least 600 kW by 2035.		On the TEN-T comprehensive network: at least 1,400 kW power output every 100 km by 2030 and at least 3,500 kW by 2035.
	In every urban node, serving both light-duty and heavy-duty vehicles by 2030.	In every urban node and at every safe and secure parking area by 2030.
1,400 charging piles along TEN-T corridors.	570 filling stations along the TEN-T corridors.	850 high-capacity chargers along the TEN-T corridors.

Table 18: Fit for 55 charging and refueling infrastructure.
Source: EU Commission, 2021.

Considering that the TEN-T road network totals about 85,000 km across Europe, the number of charging piles might be at least 1,400 for normal charging capacity and 850 high-capacity charging piles, with 570 hydrogen filling stations only along the TEN-T corridors.

These numbers only reflect infrastructure on TEN-T roads and does not include other charging piles and filling stations on other roads and in cities.

Notable observations

We have noticed that EU documents published in summer 2021 regarding Fit for 55 contain no explicit discussion regarding Electric Road Systems (ERS) developed and demonstrated by Sweden and Germany in recent years or regarding battery-swapping technology as complementary strategies and systematic ways to achieve EV recharging at an EU level (EU Commission, 2021).

The entire focus in Fit for 55 is hydrogen fuel cell refilling infrastructure and BEV charging piles.

However, the Fit for 55 strategy documents do open up potential for new technologies and solutions, such as inductive static dynamic charging of vehicles and battery swapping, as indicated in Annex II, paragraphs 1.17 and 1.18, of the documents:

§ 1.6. *Technical specifications for battery swapping for motor vehicles.*

§ 1.17. *If feasible, technical specifications for battery swapping for passenger cars and light- duty vehicles.*

§ 1.18. *If feasible, technical specifications for battery swapping for heavy-duty vehicles.*

(Regulation of the European Parliament and Council, Annex II)

We hope that this report shows that battery swapping has matured beyond the research and demonstration stages and that battery-swapping technology is ready for full-scale commercial operation.

The EU road network—the lifeblood of the European economy

The EU TEN-T (roads) network encompasses approximately 84,700 kilometers, of which 42% are core roads and 58% non-core roads. EU countries are crossed by about 25,800 km of Core Network Corridors (CNCs). Approximately 61% of the TEN-T (road) network is closed-access highway, with the remaining 39% being open-access roads. Most of the TEN-T roadways are situated in a rural areas. However, about 6,850 km (8.9%) runs through urban areas and carries denser traffic than the rural routes.

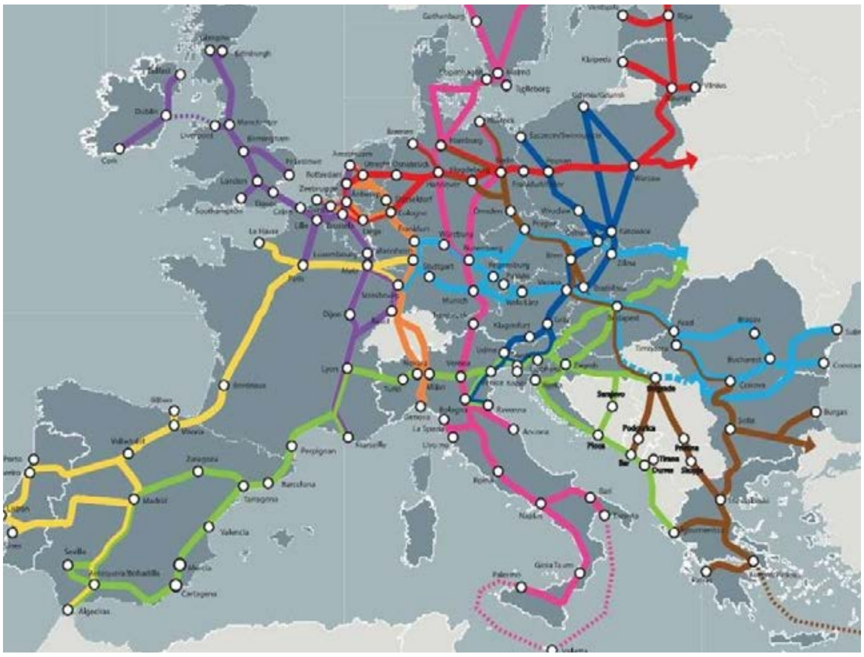


Figure 42: Trans-European Transport Network (TEN-T)
Source: https://ec.europa.eu/transport/themes/infrastructure/ten-t_en

The average annual daily traffic flow (AADT) shows that:

1. 55.5% of the entire TEN-T (Roads) network carries less than 20,000 vehicle per day, while
2. 41% of the network carries more than 20,000 but less than 100,000 vehicles per day.
3. Only 3.4% of the entire network is very heavily trafficked, with more than 100,000 vehicles per day.

Nevertheless, the number of roads in the TEN-T and the total traffic density are necessary to handle EU transportation electrification in an integrated way, so that it can become reality in both large and small, and rich and poor countries, developed and less developed areas, areas of differing traffic densities, and with different structures in terms of vehicle age and quality.

ACEA and industry perspectives on the EU’s Fit for 55 targets

Now that the latest EU policy is on the table, with decisions to achieve zero emissions from the transportation sector by 2035, and an emissions-free environment by 2050 (EUs Fit for 55 targets) stress that:

The European Commission adopted a package of proposals to make the EU’s climate, energy, land use, transportation and taxation policies fit for reducing net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels. Achieving these emission reductions in the next decade is crucial to Europe becoming the world’s first climate-neutral continent by 2050 and making the European Green Deal a reality.

(EU press release, 14 July 2021)

However, the European automotive industry has its own reaction to this wide-ranging and demanding proposal:

The proposed CO_2 reduction target for cars of 55% by 2030 will be very challenging, and certainly requires a corresponding binding target for member states to build up the required charging and refueling infrastructure.

(ACEA, https://www.acea.auto/press-release/fit-for-55-eu-auto-industry-initial-reaction-to-europe-climate-plans/)

We have noted that discussions are focused only on static plug-in charging piles and hydrogen refueling stations. Thus, the focus for vehicle manufacturers’ critique has targeted the charging and hydrogen refueling infrastructure!

Anyone who wants to buy an electric or fuel cell car depends on having reliable charging or refueling infrastructure—whether that is at home, at work and on the road. The time has come for governments across Europe to pick up speed in the race to greener mobility.

(ACEA Director General, Eric-Mark Huitema)

ACEA is arguing, based on European Commission calculations, that a further decrease of CO_2 emissions by 50% in 2030 would require some 6 million publicly available charging points. With less than 225,000 available today, that translates into a staggering 27-fold increase in less than a decade.

That might be challenging to achieve without special arrangements and actions and considering new approaches as complementary to today’s dominant solution of charging piles, or else might require lowering political expectations for the transformation.

As we can see from the ACEA’s analysis, charging infrastructure is becoming a bottleneck for Europe’s transportation electrification.

This is particularly important, as hydrogen fuel cell technology is not mature on a mass scale, and only a few refueling stations have been put into operation.

The focus has so far been on passenger EV infrastructure, with charging infrastructure for heavy vehicles being an afterthought. The operational logic for passenger vehicles and heavy commercial vehicles are different. While passenger vehicles operate mostly in populated urban areas and have a reasonable operational range of 400-600 km per charge, trucks often operate on long-haul routes and have a lower effective range per charge due to their size. Likewise, passenger vehicles and trucks cannot share the same charging infrastructure, and have different needs in terms of charging speed and charging times/locations.

The rapidly growing volumes of EHTs requires the deployment of new charging infrastructure suitable for fast charging of EHTs if these vehicles are expected to fully utilize their capacity to contribute to transportation industry decarbonization and efficiency.

Infrastructure availability in Europe

Although there has been strong growth in the deployment of charging infrastructure since 2014 (+750% increase from a very low starting point), the total number of charging points available across the EU (less than 225,000) still falls far short of what is required. Fewer than 25,000 of those 225,000 points are suitable for fast charging (with a capacity of > 22 kW). Just 1 in 9 charging points in the EU is a fast charger. Based on European Commission calculations, a 50% reduction in vehicle CO_2 emissions by 2030 would require an additional 6 million public infrastructure points.

This translates into a 27-fold increase in less than a decade.

- 70% of all EU charging stations are concentrated to three countries in Western Europe:
    - the Netherlands (66,665)
    - France (45,751)
    - Germany (44,538)
- Together, these countries make up only 23% of the EU's total surface area.
- 124 hydrogen filling stations were available across 10 EU countries in 2020, and 17-EU countries had no hydrogen filling stations at all.
- The EU has some 4,000 natural gas filling stations, up 31.6% since 2015. Two-thirds of these are concentrated in two countries (Italy and Germany). The future of natural gas and biofuel is not clear in terms of Europe's green development.

Oliver Zipse—ACEA President and CEO of BMW Group—stated that:

> *Europe's car makers are open to even higher CO_2 reduction targets for 2030, provided that the European Commission puts the right framework in place. Zipse stresses that the auto industry is fully committed to the ambitious EU Green Deal, but that targets must be mutually binding. In light of the upcoming review of the CO_2 standards for cars and vans, this means that higher reduction targets for industry have to go hand-in-hand with equally ambitious infrastructure commitments from national governments.*
>
> *We urge the European Commission to produce a framework with the revised AFID that will result in binding targets for sufficient infrastructure across all member states. Without these targets, our transformation will lose momentum."*

(https://www.acea.auto/video/car-co2-targets-eu-green-deal-must-be-mutually-binding-member-states-need-to-invest-in-infrastructure-now/)

From his perspective, politics and industry work go hand in hand in the development of EVs and their supporting charging and refueling infrastructure. The President of the European Automobile Manufacturers' Association (ACEA) also points to the societal importance of rolling out a dense infrastructure network that covers the entire EU.

> *An extensive charging network allows manufacturers to keep battery sizes moderate, thus lowering the costs of vehicles. This is crucial for making e-mobility affordable, he argues, as it will allow for the electrification of budget-friendly cars in the €15,000-30,000 price range.*
>
> *The typical EU household does not have the budget for big and expensive batteries. Without charging options, mobility for these customers will effectively be limited….*

(https://www.acea.auto/video/car-co2-targets-eu-green-deal-must-be-mutually-binding-member-states-need-to-invest-in-infrastructure-now/)

EHTs in Europe

The electrification of heavy transportation in Europe has only begun to take place. As indicated in the next section, Volvo and Scania in Sweden announced their first new fully EHTs in 2021.

By 2025, approximately 40,000 battery electric medium-duty and heavy-duty vehicles will be in operation in the EU and UK. European countries outside the EU are not uncounted in this number.

By 2030, this figure will increase to approximately 270,000 trucks.

If this estimate is reasonable, the main concern will be how to ramp up the manufacturing of electric trucks from their current low levels, and particularly how to ramp up the expected demand for battery manufacturing and associated charging and refueling infrastructure.

Charging and refueling capacity is the bottleneck for transportation electrification

The ACEA argues that today, the charging and refueling infrastructure needed for zero-emissions heavy-duty vehicles is almost completely lacking.

For battery electric heavy-duty vehicles, a target of achieving following numbers is set:

ACE targets for charging infrastructure in Europe.

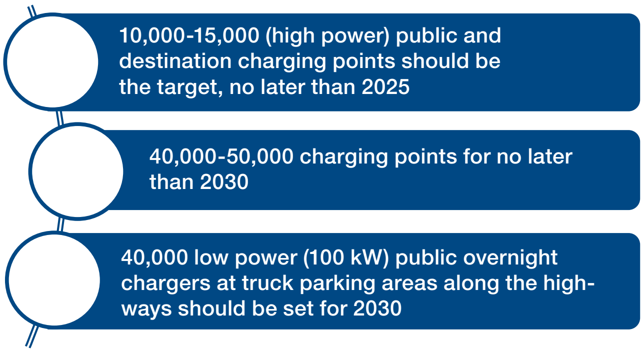


Figure 43: ACE targets for charging infrastructure in Europe.
Source: ACEA, 2021

The ACEA estimates that the total number of charging piles needed is some 100,000 units by 2025, in EU countries only. When including European countries outside the EU, the actual number is very probably much higher.

There are risks that a widespread deployment of EVs will not be possible without a sufficiently dense network of recharging points and hydrogen refueling stations specifically suitable for heavy-duty vehicles, and the scenario is even worse if they are not available at all in certain areas.

In addition, a target of at least 40,000 low power (100 kW) public overnight chargers at truck parking areas along the highways should be set for 2030.

To ensure that the necessary number of charging points are available by 2025 and 2030 in all EU member states, binding targets should be set for each member state according to the proposed methodology. However, attention must also be paid to the economic and political consequences of this rapid transformation on EU and non-EU countries in Europe if the EU moves in this direction at such a rapid pace.

To take in to consideration the substantially higher power demands of heavy-duty vehicles, three power categories should be redefined: below 350 kW, 350-500 kW and above 500 kW.

Public and destination charging points (EU27 + UK)			
	Currently available	**Needed by 2025**	**Needed by 2030**
DC <350kW (CCS)	<10*	1,000 (4,000)**	5,000 (40,000)**
DC 350kW (CCS)* **	0	12,000	15,000
DC >350kW (MCS)	0	2,000	30,000

* As of May 2021

** Required overnight chargers if charging points with 350/>500 kW are not equipped to deliver lower-power at night or overnight parking is not possible.

*** These should allow upgrades to megawatt charging (MCS, >500kW) as soon as standard definition is available.

Table 19: Public charging points needed in EU and UK.
Source: ACEA, 2021.

Table 19 shows the ACEA's estimate for the number of charging piles needed for each of these three charging levels.

The operational logic of trucks in long distance operations, sleeping along the highways etc. places different challenges on truck charging infrastructure. Long-haul battery electric trucks will not always return to home base for overnight charging.

The charging infrastructure needs to **establish low power (100 kW) public overnight chargers at truck parking areas along the highways, with at least 40,000 overnight public chargers in 2030.** In addition, every battery electric truck will require a (lower power) depot charging point (several hours of charging): i.e., 40,000 depot charging points should be installed no later than 2025, and 270,000 charging points no later than 2030.

European industry starts to move

The development of electrification of the heavy-duty transportation segment is illustrated by three of the leading manufacturers of commercial vehicles in Europe: Volvo Trucks, Daimler Trucks, and Traton Group (Volkswagen, Scania, and MAN), who have decided to design, install, and operate, high-capacity public charging pile systems consisting of 1,700 piles across the Europe starting in 2022. These competing manufacturers have identified charging infrastructure as an important area requiring collaboration among them. Well-developed charging infrastructure is needed and beneficial for all. The total investment for this is estimated to be 500 million euros, and the total number of installed piles is expected to increase as other partners joint (perhaps costing 300,000 euros per charging pile for EHTs). Considering the estimated total number of truck charging piles needed, these numbers are still quite low. The anticipated 1,700 piles reflect only 10% of the charging piles currently estimated as needed in Europe.

The chicken and the egg dilemma

The EU is facing a challenge similar to the one China is facing: which comes first, the large-scale adoption of EHTs or the deployment of charging and refueling infrastructure? EHTs need charging or refueling infrastructure for their development and growth, while charging and refueling infrastructure needs buyers and operators. These are the two sides of the coin. This is especially important to consider in the case of EHTs. They are operated by commercial businesses that depend on operational efficiency, optimized driving times, optimal utilization of truck capabilities to transportation paying freight, short idle times for loading and unloading cargo, recharging, or refueling. The must also follow mandated driving/rest intervals for drivers, while EHTs add the additional challenge of recharging time.

We also need to consider that EHT prices are considerable higher than diesel truck prices, and freight customers do not voluntarily pay more for electrified transportation compared to diesel. The cost differences between diesel and EHT operation is and will be an issue for operators and customers.

One important difference between the private passenger vehicle market and the commercial truck market is that private owners might have time for charging but commercial operators don't. This is also true for taxis and other commercial operators of passenger vehicles. For these commercial users, flexibility and time efficiency is crucial.

The development and spread of EHTs is not primary a technical issue; rather, it is a question of business and operational logics. Electrification technology is well known by now. We have developed technologies, and products are already on the market, although in limited volumes. The greatest challenge is whether operators can utilize the capacity of EHTs in a way that satisfies their commercial needs. One of the key issues is the business model needed to increase usage of EVs in general and EHTs in particular. Here charging infrastructure plays an important role, perhaps the most important role. The challenges of deploying charging infrastructure are currently greater than those of developing EHTs. Consequently, a business model for charging and the usage of charging infrastructure is needed.

Charging piles does not resolve the fundamental shortcomings of EHTs

As we have seen Europe, is in urgent need of large numbers of charging piles for both passenger and heavy EVs, but fast charging for heavy trucks requires higher powered chargers at different locations. Also, passenger and commercial EVs do not always cluster along the same transit routes. Trucks fleet require different technologies, numbers, and locations for cable-charging infrastructure.

With hydrogen refueling, in contrast, existing gasoline station infrastructure can largely be used for hydrogen refueling systems as well. Thus, the introduction of hydrogen fuel cell vehicles has a limited effect on the contemporary refueling infrastructure compared to charging piles.

There is a risk in the allowing strategies based on passenger EVs to shape thinking on EHT infrastructural needs: i.e., that cable charging is the best and only solution needed. Here is another example of assuming that existing solutions are adequate for the new demands presented by EHTs.

Passenger EVs have a range of 500-600 km or 4-8 hours, and their recharging time is about 1 hour using fast charging. Battery EHTs have a range of only 150-250 km or 2-3 hours of driving, and recharging takes 2-3 hours with fast charging.

Operational efficiently, driving range, and recharging time depends on the charging capacity and the size of the battery.

Passenger EV drivers can take a break while charging their vehicle. EHT drivers, in contrast, continue to be paid while idling during recharging. Passenger EV owners have space and time to charge their vehicles at night, while professional truck operators don´t. Charging time represents no additional cost for private EV owners, but professional operators must continue to pay for the driver and truck while idling during the charging process.

During a full workday, an EHT driver can spend 4 hours driving but must spend at least 4 hours charging. That translates into a 50% operational efficiency (performance). From a business perspective, this is not acceptable. While is technically possible to use larger batteries for trucks and achieve an EHT truck range of 600 km on a single charge, this increases the vehicle cost and weight while reducing its payload and increasing the time it does take to recharge the battery. The entire EHT design must balance these economic factors, and shortcomings in the product or technology must be offset by other means, such as charging infrastructure.

If we increase the charging speed to a megawatt level, the battery being charged will suffer, the risk of fire will increase, the battery lifecycle will drop, and the likelihood of battery-problems will probably increase. The total price for megawatt recharging will very probably increase as well, compared to normal charging speeds.

Increasing the number of charging piles en route or in cities will not overcome the operational limitations of trucks, which are due to the technical shortcomings of current battery technology. Only the development of some future alternative battery technology with a higher capacity, mounting larger-capacity batteries or reducing gross truck weight can extend the driving range of current EHTs.

Superfast recharging

Superfast battery charging is being developed as one way to shorten charging time. However, superfast charging at very high voltages has negative impact on batteries, such as overheating and risk of fire, faster breakdown of the battery cells that shortens their lifespans, and fast wearing out of batteries with the same result. Battery lifespan determines the total lifespan of integrated-battery EHTs, since batteries account for a large portion of the total vehicle cost. Fully integrated vehicle batteries are also more complicated to replace and reuse for other purposes.

The risk of fire is very low but still present. Considering the growth of EVs and the location of parked vehicles in large garages, ferry transportation, etc. all become riskier when large numbers of EVs are close to each other. One vehicle fire can easily ignite other EVs parked close by, for example. This is particularly important to consider for EHTs with large batteries and fast charging, and soon, with superfast megawatt chargers. Passenger EV batteries are around 50-80 kWh (some up to 150 kWh), while EHT batteries are 250-500 kWh. Because EV batteries account for 40-60% of the total vehicle cost, battery lifecycle is an important parameter in total operational cost. The battery is the most expensive subsystem of any EV. Thus, the economic consequences of shortening batteries lifespans, quality, and capacity are major negatives for operators and owners.

For these reasons, we need to reconsider the contemporary approach to charging infrastructure and think outside the box—outside the established way of looking at the main challenge related to EHT operational shortcomings of driving range and charging cycles.

The EU Fit for 55 needs complementary charging infrastructure

The EU is transitioning the transportation system to electrical technology:

- **By 2025, approximately 40,000 medium-duty and heavy-duty BEVs will be in operation in the EU and UK.**
- **By 2030, this figure will grow to approximately 270,000 BEV trucks.**

To manage the increase in passenger EVs and commercial truck EVs, by 2030 will need a total of around 6 million public charging points, compared to 225,000 charging points available today. Is it possible to manage this increase in installed charging points so quickly, and with this density, in the years to come?

We suggest that the EU commission consider whether battery-swapping technology could be implemented as complementary charging infrastructure, first for EHTs to support long-haul operation and overcome the operational shortcomings of range and long charging times.

Swedish truck manufacturers go electric

Volvo´s Electric Trucks

Sweden is home to two major global truck manufacturers, Scania, and Volvo. Scania is currently owned by the German Volkswagen Group, while Volvo Trucks is owned by AB Volvo. Major shareholders in AB Volvo are Industrivärlden (28%), Geely (16%), investment banks, and pension funds.

Volvo Trucks Corporation is a global truck manufacturer headquartered in Gothenburg, Sweden. In 2016, it was the world's second-largest manufacturer of heavy-duty trucks. Volvo Group was reorganized on January 1, 2012, and Volvo Trucks was incorporated into the Volvo Trucks Group along with two other truck brands: Renault and Mack.

Figure 44: Volvo 2021 electric truck model.
Source: Volvo, 2021

The first Volvo truck rolled off the production line in 1928, and in 2016 Volvo Trucks employed more than 52,000 people around the world. In 2019, Volvo Trucks delivered about 131,000 trucks worldwide. The company has already delivered a total of some 5,000 electrified heavy trucks (hybrid models).

Volvo Trucks announced its first fully electric truck in 2021. This first EHT from Volvo is focusing on garbage handling and local urban distribution and comes in versions with total weights of 16 and 27 tons. The EHTs house an electric motor from 185 to 370 kW and a fully integrated battery system with 100-300 kWh capacity.

The range per charge is 200-300 km depending on battery size, driver skill, and operational conditions such as weather, temperature etc.

The charge time is 1-2 hours with fast charging and 10 hours at regular charging speed.

Volvo's official strategy has been framed as emphasizing BEV trucks for local transportation, and future models of larger hydrogen fuel cell trucks for longer-range operations, being developed in collaboration with Daimler.

Scania´s electric trucks

Scania manufacturing was established in 1891 and since then has manufactured trucks.

Scania became a wholly owned subsidiary of the Volkswagen Group in 2014. In 2015 Volkswagen AG created Volkswagen Truck & Bus GmbH, which grouped Scania, MAN, and Volkswagen Caminhões e Ônibus. In 2018, Volkswagen Truck & Bus became the Traton Group. In 2021, the Traton Group, Daimler, and Volvo Trucks announced a joint venture to implement large-scale fast charging pile infrastructure in Europe.

Figure 45: Scania 2021 electric truck model.
Source: Scania, 2021

In 2019 Scania delivered a total of about 91,700 trucks, 7,800 buses, and 10,200 industrial marine engines.

Scania has been involved in early demonstration projects with developmental ERS in Germany and in Sweden.

In 2021 it started to deliver its first EHTs. Scania's strategy is to offer EHTs that use multiple fully integrated modular batteries instead of one main battery. Scania EHTs have either five batteries providing a total 165 kWh capacity, or nine batteries totaling 300 kWh capacity. The driving range is 200-300 km depending on the number of batteries, truck load, driver skill, and environmental conditions.

Additional batteries can be added to the chassis to extend the range of Scania trucks. Each additional battery adds 200-300 kWh capacity, thus extending driving time to 3-4 hours and charging time to 3-8 hours with fast charging systems. However, because additional batteries increase the total weight of the truck, which cannot exceed a certain figure, payload decreases as batteries are added.

Comments

Both Volvo and Scania represent modern EHT designs. Both have fully integrated batteries with similar capacities, and therefore similar operational performance of 1-2 hours of driving and 1-2 hours of fast cable charging.

Both are designed for urban operations due to the shortcomings of operational performance (range and recharging times). With existing technology, neither Volvo nor Scania EHTs are suitable for intercity transportation without extensive charging times or complementary charging solutions.

Volvo has declared a strategy that views batteries as suitable for urban transportation needs and looks to future HFC trucks, developed in collaboration with Daimler, to address the needs of longer-haul operations that are currently handled by diesel trucks. The Scania solution for urban and long-distance EHTs is not known as this time. What we do know is that Scania has been pioneering conductive technology for overhead wires for static and dynamic charging that has been used in demonstration projects in both Sweden and Germany. It is possible that Scania may also start developing HFC EHTs in the future.

Sweden implements electric road system (ERS) demonstration projects

Sweden was an early actor in the development of transportation electrification and started to develop several Electric Road System (ERS) demonstration projects as early as 2016. At that time, ERS was expected to involve installation of physical systems for electrification of vehicles via technologies for electricity distribution from the road to vehicle, whether passenger vehicles, trucks, or buses.

Two Swedish technical pioneers developed similar solutions using conductive technologies based on embedded rails or placed on the road surface that transferred electricity to the vehicle via physical contact. These solutions could be used by any kind of vehicle that could incorporate an arm under the vehicle that could contact the rail system.

The third solution was a German/Siemens technology using overhead cables that connect to vehicles through a pantograph. This solution could be used for large/tall vehicles such as trucks and buses. Other small vehicles, passenger cars, and vans could not use this solution.

One characteristic of both conductive ERS system solutions was that they could provide high energy levels suitable for large-scale consumption in an intensive traffic scenario, such as on German highways or other intensive transportation networks.

Another inductive charging system is being introduced as a demonstration project by an Israeli company. This project is located in Gotland and will be completed in 2022.

Four Swedish ERS demonstration projects

Sweden has a conducted a total of four test and demonstration ERS projects: three conductive and one inductive.

Table 20 on the next page summarizes some of the characteristics of these four demonstration projects.

	Project 1	Project 2	Project 3	Project 4	Project 5 (under construction)
Key actors/ locations	Collaborative project between Siemens & Scania Sandviken, north of Stockholm	E-Road Arlanda/ Elways Arlanda, north of Stockholm	Smartroad / Electreon/ Gotland island	Evolutionroad/ Elonroad & Lund University, Lund city, south of Sweden	Permanent ERS between Hallsberg and Örebro on the E20, between Stockholm and Gothenburg
Operational	2016—2020	2018—2021	2021 - 2022	2020—2022	Tbd.
Technology	Conductive overhead wires. All vehicles must have rooftop pantographs to connect to the wires and collect electricity Only suitable for large vehicles such as trucks and buses.	Conductive rails embedded in the road. Rails were placed in 15 cm deep trenches. Every vehicle must have an arm that contacts the trail to connect to the electricity supply. Suitable for all kind of vehicles.	Inductive technology using coils positioned 8 cm below the road surface. Suitable for all kinds of vehicles.	Conductive rails embedded in the road or rails on the road surface. Every vehicle must have an arm that contacts the trail to connect to the electricity supply. Suitable for all kind of vehicles.	Tbd.
Energy output	360 kW per vehicle. Dynamic charging.	200 kW per vehicle. Dynamic charging.	25 kW per installed wireless charging receiver. Static and dynamic charging.	300 kW per vehicle. Dynamic charging.	Tbd.
Test road length	2 km demonstration road on E16 outside Sandviken, north of Stockholm.	2 km demonstration road outside Arlanda, north of Stockholm.	1.6 km demonstration road between airport and Gotland Island city.	1 km demonstration road in Lund city, in southern Sweden. 500 m with rails integrated in the road and 500 m with the rails placed on the road surface.	42 km permanent ERS 21 km in each direction.
Financing	77 million SEK: 7 million euros in public funds, 48 million in cooperative funds from regional governments the industry participants.	103 million SEK: 61 million from TRV.	116 million SEK: 91 million from TRV.	96 million SEK: 86 million from TRV.	No information.
Other details	Based on German/ Siemens technology. The world's first electric road system (ERS). During the summer of 2021 this demo site was taken down.	Based on Swedish technology from Elways.	Based on Israeli technology from Electrean Wireless.	Based on Swedish technology.	No information.
Vehicles	Two Scania trucks.		One electric bus and one heavy truck with a supercondensor.	Local bus traffic and one passenger vehicle.	No information.
Main actor	Consortium of Region Gävleborg, Siemens and Scania.	Industrial consortium of Rosersberg Development AB with Elways and NCC as main actors.	Consortium Gotland and Electreon AB.	Consortium Evolutionroad with Elonroad and Lund University.	No information.
Comments on project cost	77 million SEK total cost, or 38 million per km of road.	103 million SEK total cost, or 52 million per km of road.	116 million SEK total cost, or 73 million per km of road.	96 million SEK total cost, or 96 million per km road.	Launched in spring 2021 and operational in 2025. TRV will take bids and select the choice of technology, supplier and operator at a later stage.

Table 20. Summary of four Swedish ERS projects and one permanent ERS project in development.
Source: NyTeknik, 2021.

Reflections on ERS concepts

The Swedish Transportation Administration (TRV) has conducted a special review of conditions for electrification of the Swedish transportation system using ERS solutions proposed a plan for rolling out an ERS system. This plan is based on the assumption that there might be 2,000 km of ERS along the most intensive traffic routes, with the possible option of an additional 1,000 km no later than 2035.

The TRV writes:

> *The results from the analyses show that the freight transportation by road that is estimated to have the greatest benefit from an electric road concept is the so-called long-distance traffic with great energy needs in combination with not having to stop to recharge.*
>
> *The rapid development of batteries has contributed to the vehicle fleet that was previously forecast to use an electric road being judged to be significantly smaller compared with just a few years ago.*
>
> *The assessment is that the proportion of heavy traffic that is expected to use the electric road has gone from between 60-80 percent to around 25 percent by 2040 with an expanded electric road system.* (Natanaelsson, 2021)

These statements indicate that the ERS concept seemed more interesting and feasible some years ago when the concepts were introduced, but that technological development of other technologies for electrification of transportation, such as batteries and hydrogen, has surpassed ERS solutions. With time, it is now predicted that fewer potential operators will find an ERS solution usable. The targeted transportation segments that might benefiting from ERS has dropped from 60-80% to 25% by 2040. There are two potential explanations: increased used of biofuel diesel mixes that reduce emissions towards future targets and the development of BEVs in general and battery EHTs specifically, leaving fewer potential customers for electrification via ERS.

The uncertainty and speed of future technology development is also something that needs to be considered:

> *The amount of traffic that will use the electric road in the future is affected not only by financial incentives but also by the development of alternative solutions (batteries, fuel cells). The technical development for electric roads and other alternative solutions therefore needs to be monitored on an ongoing basis in order to be able to make decisions on each occasion on what any further investments should look like.*
> (Natanaelsson, 2021)

The main conclusions from this TRV review are as follows:

> *The Swedish Transportation Administration's recommendation is to continue to take successive steps in the electrification of heavy transportation as new knowledge is obtained, as the technical development for various systems for an electrification of the transportation sector takes place at a rapid pace.*
>
> *Knowledge of electric roads is still acquired, among other things, via the ongoing demonstration projects and continued planning for the implementation of the electric road pilot. Continued monitoring of the outside world and the acquisition of knowledge also regarding other technical systems need to take place on an ongoing basis.* (Natanaelsson, 2021)

Reflections on the cost of ERS

The costs of ERS entail several dimensions. One is the modifications to the vehicle itself to accommodate technologies for connecting to either embedded rails or overhead wires, or receiver under the vehicle in the case of inductive systems.

TRV is analyzing the cost of vehicle modifications and suggests that the cost is on the level of 354,000 SEK (36,000 USD) per vehicle, which is expected to drop to 127,000 SEK (13,000 USD) by 2065 due to economies of scale. However, as the ERS concepts with rails or overhead wires are based on mechanical designs and construction, the assumption of reduced cost over time might be questioned. That reasoning might be applicable to electronic-based inductive solutions. However, also they need mechanical adaptations in the vehicle that will increase vehicle cost. The other cost of the ERS is the installation cost for the embedded rails or overhead wires, along with additional costs for connections, transformers, monitoring systems, and ancillary equipment and services needed to operate the system.

The TRV review suggests that the costs of ERS might be 11-21 million SEK per kilometer. This estimate is much lower than the real-world cost per kilometer in the demonstration projects and what the suppliers for case B in **table 21** have bid and has been estimated. That can be explained by the extra costs needed to make demonstration projects operational, then to conduct follow up studies and evaluate them, and finally dismantle the demonstration site after the test period.

Beside the estimated cost, one key question is European transportation interoperability and whether international operators will accept Swedish ERS solutions, as well as who will bear the cost for this adaption.

TRV remarked, in this regard, that:

> *There are currently no ready-made European standards for the various electric road technologies, although there are standards for certain sub-components primarily related to the conductive technology with overhead lines. There are proposals that indicate that there could be ready-made standards for the current technologies developed in 2025. At present, there are no permanent electric road facilities built and the assessment is that no technology is preferred internationally over anyone else.*
>
> (Natanaelsson, 2021)

The success of rolling-out the ERS solutions will not be based on only functionality, cost efficiency, usability, or reduction of emissions but more on the economic and business contribution of the selected system and probably even more so on the standardization of the proposed ERS systems. Interoperability will probably be one important aspect in decision-making on the large scale deployment of ERS in Europe.

Sweden makes the move from demonstration projects to the world's first permanent ERS

Tables 20 and 21 show details and demonstrate certain key figures for ERS concepts in Sweden and compares them to a baseline, which is current diesel ICE technology. These figures are drawn from one pilot project that was never completed, and estimate the potential cost of the planned permanent ERS along the E20 between Hallsberg and Örebro.

Estimated cost for an ERS in Sweden

Table 21 shows that the construction cost for the three implemented ERS projects is between 52 and 96 million SEK per kilometer (5–9 million USD). The cost for driving EHTs on those ERS is difficult to estimate at this point.

The comparative contemporary cost for diesel-based ICE truck operating costs is about 3.0 SEK per km of driving. To be competitive, the costly ERS solutions need very large number of vehicles to drive on the ERS.

One Swedish municipality conducted a pilot study of establishing 14 km of ERS in the spring of 2021 and estimated that the cost would be 52 million SEK per kilometer ERS (5 million USD). In this case the price of conductive and inductive technologies was close to each other.

	Case A	Case B	Case C Project 1	Case D Project 2	Case E Project 3	Case G Project 5
Potential technology	ICE/Diesel As the baseline	West Coast Pilot Never completed	Project 1 Sandviken/ Siemens & Scania Completed	Project 2E-Road Arlanda/ Elways Completed	Project 3 Smartroad Gotland /Electreon Completed	Project 4E20 Hallsberg-Örebro To be completed
Technology	ICE (Diesel)	Conductive/ Inductive	Conductive	Conductive	Inductive	Conductive/ Inductive
Price per km in SEK	3.00	18 million	38 million	52 million	73 million	30-70 million
Price per km in US$	0.30	1.8 million	3.8 million	5.2 million	7.3 million	3.0 million

Table 21: Summary of the estimated cost of five Swedish ERS pilot projects.
Source: Author's summary.

Case A

The baseline is the contemporary diesel ICE technology that will be replaced, which is obviously a very cheap solution.

Case B

One Swedish municipality conducted one pilot study of possible ERS concepts based on conductive and inductive technologies in 2021. The total life-cycle cost (based on 40 years of operations) for establishing seven kilometers electric road is estimated to 18 million SEK ($13 million) per kilometer while the direct investment cost is estimated to be 7 million SEK per kilometer ($1 million). This price included ERS materials, installation, connections to the grid system, maintenance and financial cost in a lifecycle perspective. The conductive and inductive systems were on a similar price level.

It should be noted that case B was a pilot project that was initiated in the spring of 2021, with technology suppliers invited to make offers to the municipality, and not a demonstration project funded by the Swedish government for R&D purposes. It was expected to be a business-based project. For this reason, it is interesting to note that both conductive and inductive technology suppliers offered system solutions at a similar pricing level of 7 million SEK per kilometer of ERS for the total cost of installing the system in the road and providing the supporting technologies needed for operation.

However, the price of 7 million SEK per kilometer road does not include the monitoring and surveillance solutions or the payment system needed to make the ERS solution usable in practice. The total price for setting up the ERS would therefore probably be higher.

Case C - F

Four completed Swedish ERS concepts using the conductive ERS technology concept.

Case G

The proposed ERS on E20 between Örebro and Hallsberg which the Swedish government recently decided to implement as a permanent ERS.

All estimated costs are based on official and commercial offers (Case B) or total cost estimates of demonstration projects. Note that the total cost estimates for all the projects are for the total system solution, per kilometer of distance. Based on the empirical cost estimations presented in **table 20** and **table 21,** it is possible to roughly estimate the cost for the permanent ERS on the E20 between Hallsberg and Örebro.

Our estimate is that this permanent ERS might cost at least about 18 million SEK per kilometer.

The 42 km ERS being planned therefore might cost a total of 756 million SEK (80 million USD).

Some key questions need to be asked:

- What is the expected traffic volume for the permanent ERS on E20?
- How many trucks and buses are expected to operate on the ERS per day?
- What will operators be charged for, and how, to drive and charge on the ERS?
- What does the business model look like and how does it conclude that this 756 million SEK of taxpayer's money? The business model needs to be considered on the national, regional, local levels and on the business of operators driving EHTs on the ERS between Hallberg and Örebro.
- What does the business model look like for operators expected to use this ERS of 42 km? (21 km one way).

The Swedish government is interested in taking a lead developing permanent ERS solutions and is ready to invest 756 million SEK to implement 42 km of permanent ERS.

The numbers shown in table 20 and table 21 indicate that the significant cost will be the installation and maintenance of charging infrastructure for these 42 km of the electric road.

It only takes 15 minutes to travel 21 km and energy consumption could be as low as 75 kWh. Thus, the cost for electricity could be around 75-100 SEK per vehicle.

The possible conclusion is that the fixed-asset cost for installing and maintaining the infrastructure far exceeds the variable cost of electricity needed to drive the length of the total 42 km of ERS.

Some key aspects of the E20 ERS project:

In **table 22** we detail some key characteristics of the ERS on the E20. This ERS is planned as one segment of the long-haul route between Stockholm and Gothenburg and not as an isolated track of 21 km. We need to understand the real operational situation for a truck operator driving a fully loaded truck along the entire E20 route between the two cities.

Due to the technology limitations of contemporary battery-based electric trucks, their operational range is limited to 150-250 km, and they need to recharge for 2-3 hours, depending on the charging current.

No.	Activity	Distance/Time
1	Stockholm—Gothenburg	472 km.
2	Driving time for a truck	6 hours one way.
3	Stockholm—Örebro	189 km distance.
4	Örebro—Hallsberg	21 km, ERS charging distance.
5	Charging capacity	300 kW based on assumption of conductive technology.
6	Driving and charging time on the ERS	15 minutes of charging. Every vehicle might use 75 kWh electricity.
7	Charging energy is 75 kWh	If conductive charging is used otherwise depending on the number of receivers on the EHT if inductive charging is used.
8	Gothenburg—Hallsberg	262 km distance.

Table 22: Reflections on EHT usability between Stockholm and Gothenburg.

Source: Author's summary.

The key questions: are who are the target users of this ERS and who will pay for it?

Regardless the chosen technology, conductive charging can supply an EHT with 75 kWh of energy at most using contemporary charging technology.

If inductive charging is used, probably only 6 kWh can be supplied to each receiver under the EHT through dynamic recharging. If several receivers are used, charging capacity improves to 6 kWh times the number of receivers.

From an operator's perspective, the distance between Stockholm and Örebro is at the far end of current EHT's battery range. Operators would probably need to charge before entering the ERS segment, and certainly after leaving the ERS segment in order to continuing driving to and within the Gothenburg region.

Driving along the ERS segment takes only 15 minutes, and thus an EHT could only recharge 20-25% of a full battery charge. This translates into only an additional 15-30 minutes of driving time after leaving the ERS. Otherwise, the operators are in trouble with standing vehicle.

The distance between Hallsberg and Gothenburg is beyond the range of a fully charged current EHT battery. Thus, operators on the E20 would leave the ERS with a limited battery charge that would be insufficient to travel the 262 km to Gothenburg—at least 3 hours of driving. Operators would therefore need to make at least one stop and charge before reaching Gothenburg. They would probably need an additional charging session to continue operating within Gothenburg. Those two charging sessions would add an additional 4 hours to the driving time.

The result is that the operator using normal, 2021 model ETHs would have to recharge 1-2 times along the E20 between Stockholm and Gothenburg, and possibly a third time.

The normal drive time for a diesel truck between Stockholm and Gothenburg is 5 or 6 hours. An EHT, in contrast, would take at least 4 more hours for recharging.

We also need to consider that the maturity of inductive charging technology is not yet ready for full-scale commercial use, as there are yet no international standards, no interoperability standards between different brands, and high uncertainty regarding radiation and safety when using high-capacity inductive charging in a commercial work environment. According to our research, it will probably take 3-5 years before those issues are fully resolved so as to enable commercialization of inductive charging systems.

Technological choices have consequences

Overhead wire conductive technology was used in the German demonstration project and the first German commercial project put into service in northern Germany. As a result, it is possible that Sweden might instead chose this solution as a way to improve interoperability across Swedish and German ERS implementations. However, Germany and Sweden experience different levels of traffic volume.

The Swedish company Scania has experience with this solution and has technology ready to roll it out for their new EHTs or to add on to other brands of EHTs. It should be noted that mounting a pantograph on any EHT requires the permission of the OEM, since it requires modifications to the software and battery management system. It is not a question of a simple add-on part from any third-party supplier.

However, it should also be noted that the other major Swedish truck manufacturer, Volvo, has declared that they do not want to pursue overhead wire charging solutions. They are instead focusing on battery EHTs for short-distance scenarios and hydrogen fuel cell EHTs for long haulage. This means that operators intending to use ERS routes would need to buy Scania EHTs if Sweden opts for overhead wire ERS solutions, or Volvo battery or fuel cell EHTs if they don't intend to depend on ERS routes. This indicates the development of two separate but complementary solutions that force operators to choose one option or another. After choosing, operators are stuck with their choices for the 5-10 year lifecycle of the truck or bus.

So far this pilot project has not presented any business model, that handles the life-cycle cost of this pilot project, focusing on business perspective for operators of heavy duty transportation.

ERS decision-making in Sweden

An electric road system is based on the idea that not only vehicles can be electrified, but that the entire road systems can be electrified, as a way to supply electricity to vehicles, using both static and dynamic charging, in a way to how trains and subways work today. In addition to conductive and inductive technologies, ERS solutions can also tap into technologies such as photovoltaic road surfaces that generate their own electricity that can then be transmitted via conductive or inductive charging. Photovoltaic road surfaces can produce energy for vehicles, for heating roads to melt snow and ice, and for energy storage systems.

Both Germany and Sweden have developed demonstration sites using conductive technologies, and there is now one project that has been implemented using inductive technology. The ERS systems that both Sweden and Germany are exploring offer an alternative to large battery EHTs and serves as a complementary power supply solution to cable-charging infrastructure while awaiting hydrogen fuel cell technology to mature to the point where it is ready for mass adoption. One main issue and challenge with ERS solutions is interoperability across European countries, which requires standardized solutions.

However, the technology options for conductive charging (embedded rails or overhead wires) are not very new, are inflexible once installed, have little capacity for future technological and functional development, and are complicated to connect to smart cities and communities. It is technically complicated to implement conductive charging infrastructure that suits passenger EVs, electric trucks and buses, and special vehicles such as dump trucks. It is not easy to find a one-size-fits-all solution.

The origin of electric road systems

These conductive technologies derive from 20th century technology for electric trains and underground/metro systems. These systems are complicated to alter and upgrade, which means we still have new rapid trains operating using electricity distributed via overhead wires. Even rapid train systems charging via overhead wires due to standardization by practice. Replacing an old system with a new one is complicated once it becomes the standard. At least in Sweden, we have problems with overhead cables that are knocked down by storms, something that paralyzes train operations from time to time.

During the opening session of the international ERS conference in Frankfurt in 2019, one keynote speaker made it clear:

> *We have electrified trains. We have the technology. We know how to do it. Now we will electrify the road transportation systems as we did with trains in the first place.*

What worked a long time ago might still work. However, there might be other, more modern solutions that we need to consider.

Reflections on decision-making

Research on decision-making has developed have two major models or theories to explain it. One is "Rational Decision-Making," which focuses on the problem itself and trying to solve problems by applying logical/analytical thinking and looking for the best workable solution that fits within the context, assumptions, and logic. The outcome is expected to be the optimal solution to the problem.

The other one is what is called the "Garbage Can" model (a metaphorical approach). In this model, the focus is not on the problem itself but rather on the "can," which holds a collection of old solutions of all kinds. Instead of looking at the problem one looks in the garbage can to see what old solutions might be applied to new problems, regardless of whether they might be the optimal or best solution to the new problem at hand. In other words, it's a matter of a solution in search of a suitable problem to solve.

In this case we have a "garbage can" that contains conductive charging technologies that use overhead wires or ground rails, which were obviously successful ways to electrify trains, subways, and trams. The key question becomes finding a problem in today's world that this old, time-tested solution can be applied to. The new solution becomes road transportation electrification, using the old solution applied to electrify trains. Whether this is the best solution to the problem is not the key question, from this perspective. The solution has found the new problem to solve. The problem existed in the real world, and the solution came from the garbage can.

The garbage can approach makes it harder to see the problem in a contemporary light, let alone to address the challenges and demands of tomorrow. It is not visionary and does not enable transformation and innovation to make conditions different from yesterday.

Can battery swapping be an option in the Swedish context?

Based on the cost estimate presented in **table 21**, we see that implementing 21 km of ERS (42 km for both directions) might cost around 756 million SEK. As this mostly involves physical construction, economies of scale are not as obvious as they are with electronic technologies. Very often, this kind of large-scale, costly project experience cost overruns, and thus it is plausible that the project will ultimately wind up costing 20-40% more than originally estimated.

Let's consider if battery swapping might be an option.

As we indicated in **table 13**, the cost of each battery-swapping station is ~US$927,357 USD (18 million SEK), and holds 7 batteries, with a capacity to serve 70 EHTs per day. Battery swapping is a scalable system that can be both increase and decrease the number of batteries in use.

Considering the 483 km distance between Stockholm and Gothenburg and considering that a battery-swapping station might be located every 75-125 km to ensure full charging capacity, including short stops and short driving distances along the road, the route would need at least five battery-swapping stations altogether. Five swapping stops only ads 30 minutes of driving time to the journey.

Suggested swapping station placements:

- One just outside Stockholm at the start of the trip to Gothenburg, three swapping stations in-between Stockholm and Gothenburg and one outside Gothenburg before entering the Gothenburg region.
- The cost of one battery-swapping station in China is 3-5 million RMB for the station along and an additional 3-4 million RMB for batteries at the station.
- The total cost is about 6-9 million RMB per fully operational battery-swapping station (0.9-1.4 million USD/8-12 million SEK).
- The total cost of 5 battery-swapping stations between Stockholm and Gothenburg using the cost for a station in China would be about 10 million SEK per station, or 50 million SEK total. Considering that the price in China is likely lower than the cost to build a station in Sweden, a more reasonable estimate would be double the price in China, or 20 million SEK for each station, yielding a total cost for all five stations of about 100 million SEK.
- Those 5 battery-swapping stations could serve a total of 350 battery-swapping EHTs each day.
- If there are more EHTs operating along this route, the battery-swapping station could be upgraded to house more swappable batteries, or more stations could be installed to increase total capacity and coverage.

Cost of the different alternatives for the E20 EHT electrification

For the estimated cost of 756million SEK for the proposed ERS on E20, it would be possible to build at least 38 battery-swapping stations along Sweden's main roads.

This would not only serve 2,660 EHTs with the charging needed along the roads, but the entire fleet of 38 battery-swapping stations could be used for energy storage: 38 stations * 282 kWh batteries * 7 batteries in each station = 75 MWh stored energy

This alternative would also enable second and third lifecycle reutilization of batteries, supporting societal goals of decarbonization both in the short and long run.

Figure 46 indicate possible locations of five battery-swapping stations along the E20 between Stockholm and Gothenburg. The cost estimate is > 100 million SEK.

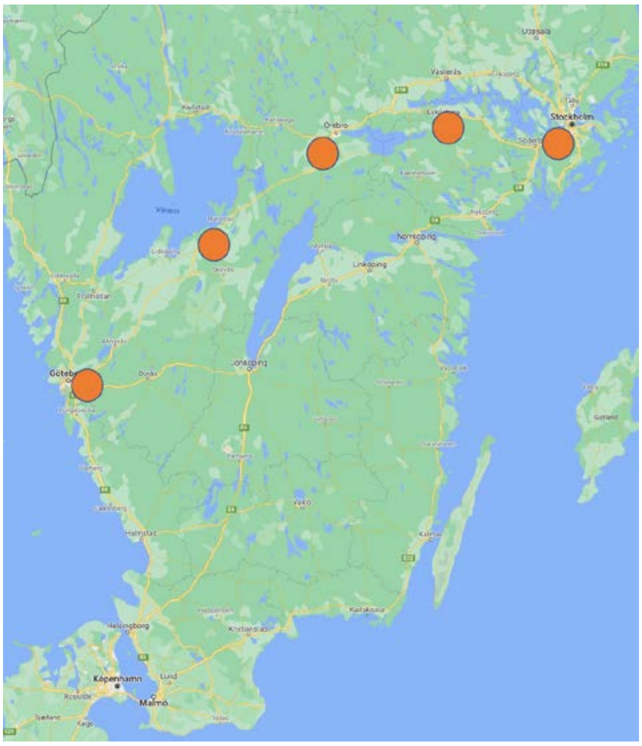


Figure 46: Five battery-swapping stations along the E20 between Stockholm and Gothenburg.

Source: Author's summary.

Figure 47 indicate how 38 EHT battery-swapping stations could be built to cover the southern part of Sweden for the same cost of building 42 km of ERS along the E20 as is planned.

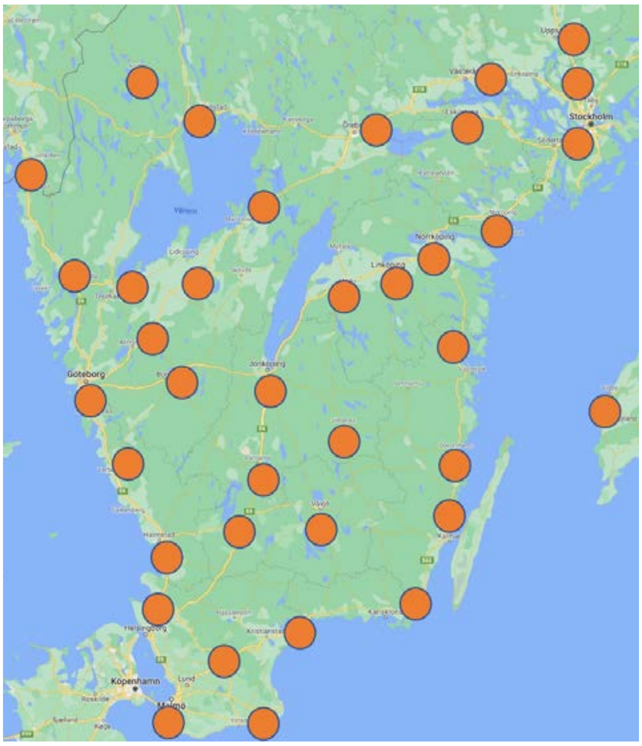


Figure 47: Illustration of how 38 battery-swapping stations could be installed along southern Sweden's main intercity roadways.

Source: Author's summary.

Implementing battery swapping as system solution in Sweden requires that at least one EHT manufacturer to adopt this technology and design EHT models to accommodate it. Also, an ecosystem of collaborating partners is needed, including energy producers, swapping technology providers, EHT operators, and swapping station investors and operators. It also requires strong and clear political support, of course.

It is not a question of technology

Regardless which solution is chosen—ERS, inductive or conductive charging, or battery swapping, the five most important issues are:

- International interoperability to allow European operators to drive trucks between countries and widely within each country.
- Acceptance of the proposed solution by vehicle manufacturers and willingness on their part to develop vehicles for that system.
- Willingness of truck operators to use the chosen system.
- A suitable business model that considers operators, how they will pay for their use of the system, what aspects they will pay for, and who they pay it to.
- To design a business model that appeals to business driven truck operators and owners and that enable them to make reasonable business on electrified transportation as with diesel based truck operations.

We need to understand that the choices we are facing are not technological ones but business, economical, and societal ones. Technology is the easy part. The others are the difficult ones.

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