Technological Forecasting & Social Change 183 (2022) 121914

Contents lists available at ScienceDirect

Technological Forecasting & Social Change

journal homepage: www.elsevier.com/locate/techfore

China's leapfrogging in electromobility. A story of green transformation driving catch-up and competitive advantage

Tilman Altenburg [a,*], Nicoletta Corrocher [b], Franco Malerba [b]

[a] German Institute of Development and Sustainability (IDOS), Tulpenfeld 6, 53113 Bonn, Germany
[b] ICRIOS, Bocconi University, Via G. Roentgen, 1, 20136 Milano

ARTICLE INFO

Keywords:
Catching-up
Leapfrogging
Electric vehicle
Technological development
Competitiveness
China

ABSTRACT

For several decades, China tried to catch up in the automotive industry, yet until recently with little success. Now, the paradigm shift from internal combustion to electric driving has opened a window of opportunity to catch up with global competitors. The Chinese government provided a strong policy push to become a lead market, allowing firms to accumulate technological capabilities and increasingly turn into lead manufacturers. This paper combines patent data and qualitative analyses of subsector trends to assess the technological capabilities and the international competitiveness of the Chinese industry in electromobility. We find that the country is indeed leapfrogging ahead in some domains (electric buses, lithium batteries) and rapidly catching up in others, including passenger vehicles. Ambitious green transformation policies can thus spur catch-up and competitiveness.

1. Introduction

Globally, environmental policies are becoming more stringent and better enforced (OECD, 2018). Thereby, production and consumption are gradually geared towards greener technologies. While this change is lagging behind the level of ambition required to avoid major environmental catastrophes (Burck et al., 2019), some economic activities are already undergoing a remarkable “green transformation”, including power generation and the automotive industry. Innovation research suggests that such deep transformations create a more level playing field for latecomers. As existing technological and institutional settings are challenged, certain advantages that incumbents accumulated over time – in terms of specific fixed assets and capabilities, economies of scale and network externalities – become obsolete. New opportunities thus arise for newcomers who are not locked into old business models, technologies and networks.

This paper explores China's attempt to take advantage of the global trend towards electrification of end-use sectors to become a technological leader in the newly emerging electric vehicle and related industries. In doing so, it aims at answering the following research question: To what extent are Chinese firms closing the technological gap vis-à-vis, or even leapfrogging ahead of, the world's leading corporations in key industries related to electric vehicle manufacturing? The topic bears enormous relevance from an energy policy perspective, since transport accounts for 24 % of direct CO_2 emissions from fuel combustion globally (IEA, 2020a). China's leapfrogging experiment holds important policy lessons for the world. Also, there is a heated debate internationally if and when restructuring of existing industries towards greener technologies strengthens or erodes the competitiveness of domestic firms. If we can show that China's automotive industry, after decades of failed attempts, now succeeds in catching up or even leapfrogging ahead by accelerating the shift to cleaner technologies, this would represent an important piece of evidence supporting the business case of green transformations.

The following Section 1 briefly reviews the existing literature on green transformation, catching up and leapfrogging, and argues that the electromobility paradigm in the automotive industry creates favourable conditions for leapfrogging. Section 2 summarises China's objectives and policies to leapfrog in electromobility. In the following two sections, we undertake an effort to assess the technological capabilities and competitive performance of the Chinese automotive industry. Section 3 provides a patent analysis, whereas Section 4 provides qualitative evidence of competitive performance in the market segments of passenger electric vehicles (EV), electric buses and batteries. Section 5 concludes.

---

* Corresponding author.

E-mail addresses: Tilman.Altenburg@idos-research.de (T. Altenburg), nicoletta.corrocher@unibocconi.it (N. Corrocher), franco.malerba@unibocconi.it (F. Malerba).

https://doi.org/10.1016/j.techfore.2022.121914
Received 3 February 2022; Received in revised form 21 July 2022; Accepted 23 July 2022

2. The dynamics of catching up and leapfrogging in green technologies, and the case of electromobility

Evolutionary research has proposed that latecomer economies find it easier to catch up with previous industrial leaders when deep techno-economic and socio-institutional changes alter the rules of the game (Malerba and Lee, 2021). Major changes in knowledge and technology combined with changes in public policy and in demand may open windows of catch-up for latecomers. It is the combination of the opening of a window and the responses of firms and other components of the sectoral system of the latecomer country that lead to catch-up and to a change in industrial leadership (Lee and Malerba, 2017; Lema et al., 2020).

As several authors claim, the shift to greener economies has all the characteristics of such a deep paradigm change (Freeman, 1992; Perez, 2013; Pegels and Altenburg, 2020). The shift from fossil-based to renewables-based energy systems is a case in point. The demand for renewable energy gave rise to a range of new energy technologies – solar photovoltaics, concentrated solar power, wind turbines, geothermal – which allowed the emergence of big new companies, whereas some of the traditional energy utilities accumulated losses and in some cases went bankrupt. The renewable energy technologies furthermore triggered second-round innovations in related technologies, including energy storage and smart grids, as well as new business models, from village-level energy cooperatives to green finance innovations.

Altenburg and Rodrik (2017) argue that the green transformation may be *even more* conducive to leapfrogging than many previous system-wide paradigm shifts. This is because the green transformation is mainly policy-driven. Previous episodes of disruptive technological change had mainly been driven by technological inventions – the steam engine, the automobile, the computer – and unfolded through a market-driven process of innovation, entry of new firms, competition and exit of less efficient firms. The currently ongoing change towards greener production and consumption is driven by scientists identifying alarming sustainability risks and political actors enacting regulation to hedge against these risks (Leggewie and Messner, 2012). Technological solutions are then triggered by new policies: Pigouvian taxes steering investments to greener technologies, green standards, targeted R&D and deployment subsidies for green alternatives, and many others. Hence, policymakers have exceptional leeway for influencing the speed of the green transformation in their home economies, and they can combine environmental and technology policies strategically to catch up with technological leaders in strategic industries.

While these arguments support in general the likelihood of catching up and leapfrogging in a green paradigm change, empirical evidence is still weak. Most examples of early mover advantages in green technologies have been documented for advanced countries (Ambec, 2017) rather than for latecomers.[1]

Within green sectors, China's electric vehicle industry is a particularly interesting case. New green technologies have opened a window of opportunity in which Chinese firms were able to move in forcefully and accumulate advanced technological capabilities in a series of technological domains. This process of learning and capability building has been associated with a response of public policy and a support for domestic demand. The strong complementarity between learning and capabilities by domestic firms and the response by the sectoral system in terms of public policy and demand has triggered a process of catch-up and an increase in the competitive advantages of Chinese firms.

In particular, in the Chinese electric vehicle industry, stringent environmental regulations and an ambitious package of regulations and subsidies have been applied to a latecomer industry with the explicit aim of leapfrogging beyond the traditionally more advanced automobile-producing countries. Globally, electric vehicles are still a niche market, accounting for <1 % of the global overall passenger vehicle fleet in 2019 (IEA, 2020b, 40), but market analyst Bloomberg NEF estimates that 57 % of all passenger vehicle sales will be electric by 2040 (Bloomberg NEF, 2019). At COP26 in Glasgow, 38 governments and an number of leading car manufacturers including Ford, GM, Mercedes-Bent, Volvo and BYD, signed an agreement to "work towards all sales of new cars and vans being zero emission globally by 2040, and by no later than 2035 in leading markets."[2] All major economies have taken action to phase out internal combustion engines (ICE) and subsidise EV. In parallel, performance and cost competitiveness vis-à-vis conventional cars are increasing. By 2020, most new models can drive >300 km with a battery load. The cost of batteries has decreased dramatically – from 1160 real 2018 US$ per volume-weighted average lithium-ion pack in 2010 to 137 in 2020 (Bloomberg NEF, 2019, 2020). As a result, Total Cost of Ownership, which considers both purchase and operating expenses, is expected to be lower for EV than for ICEs from the mid-2020s (Bloomberg NEF, 2019).

This trend devalues many of the incumbent carmaker's competitive advantages in terms of capabilities and network effects (Altenburg, 2014, 14ff.):

- The carmakers' core competence no longer lies in powertrains but in batteries and the abilities to align their performance with the specific requirements of different cars;
- EVs require a range of other components, such as electric engines, charging devices, new thermo management systems and innovative lightweight materials, whereas pistons and crank shafts, alternators, exhaust systems and fuel tanks are no longer needed. Electric powertrains have far fewer parts than conventional powertrains, making the specialised competencies of many established supplier firms obsolete;
- EVs are therefore easier to build, lowering entry barriers for newcomers. This has encouraged industry newcomers to challenge incumbents, including Tesla in the US, BYD and Zotye in China, and many start-ups. Turkey has entered the automotive industry for the first time setting up a company that is expected to roll out electric SUVs in 2022[3];
- Energy supply for cars requires a very different infrastructure, with electric charging stations replacing fuel-filling stations. This devalues assets of oil corporations and creates new investments for utilities and other newcomers.

Moreover, the change of the propulsion technology is only the beginning of further deep changes towards *connected*, *autonomous*, *shared*, and *electric* driving (Teece, 2018; Schloblach and Retzer, 2018). New alliances of firms are investing in big data for mobility services, driverless fleets, sharing and new ownership models. Thus it is not exaggerated to classify this as a techno-economic and socio-institutional paradigm shift. It triggered enormous investments in R&D which is reflected in an increase of world patents and utility models[4] in EV technologies from 5000/year at the turn of the century to 47,500 in 2015 (Fig. 1).[5]

---

[1] Exceptions include Pegels and Altenburg (2020) and Lema et al. (2020).

[2] COP26 declaration on accelerating the transition to 100 % zero emission cars and vans, published 10 November 2021. https://www.gov.uk/government/publications/cop26-declaration-zero-emission-cars-and-vans/cop26-declaration-on-accelerating-the-transition-to-100-zero-emission-cars-and-vans.

[3] https://www.dw.com/en/togg-turkey-auto-industry-erdogan-bursa-electric-vehicles/a-54307384, retrieved 22 December 2020.

[4] Utility models are "fast IP rights" that have lesser requirements than full patents.

[5] For a detailed description of the methodology considered in the analysis, see Section 4. If we consider patent *families*, the total number increased from 2483 at the beginning of the century to almost 24,000 in 2014.

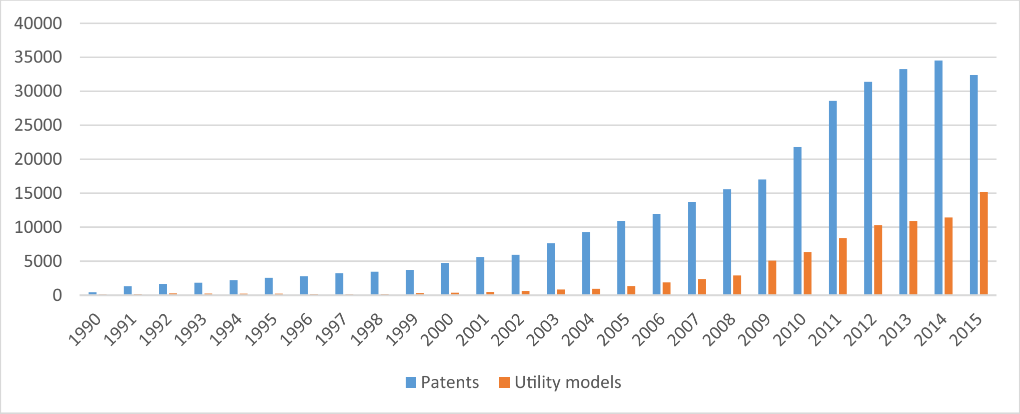

Fig. 1. Total number of world patents and utility models in EV by year.
Source: own calculations based on PATSTAT.

3. China's attempt to leapfrog in electromobility: public policy and firm strategy

Over the last decade, China has promoted electromobility more decidedly than any other car-producing country, both in terms of level of subsidies and comprehensiveness of the policy packages (IEA, 2020b, 99ff.; Altenburg et al., 2016). In doing so, the government pursued two main objectives. First, it aimed at curbing urban air pollution. All large cities in China are surpassing the World Health Organization's recommended limit for particular matter (10 μg/m^3 of PM2.5, annual average), despite considerable recent improvements due to the shutdown of power plants and factories in polluted cities (Leung, 2019). In most Chinese cities, road transport is the second largest source of PM2.5 concentrations (Kao, 2018).

Second, the Chinese government recognised the emerging electromobility paradigm as an opportunity to leapfrog ahead of the established international automotive industry (Altenburg et al., 2017, 188f.). China has promoted automotive production since the 1950s and recognised it as a strategic “pillar industry” in its ‘Automotive Industry Policy’, enacted in 1994 (Holweg et al., 2005, 13f.). Yet, several decades of government support had not been sufficient to achieve international competitiveness. The shift to electromobility is now playing into the hands of China's industry. The most critical component in terms of value added and technological complexity is now the battery. In it, China has two advantages: Control over large shares of global reserves of rare earth elements and other strategic minerals (Fernández, 2017); and technological expertise developed in the manufacture of lithium batteries for the computer and consumer electronics industry.

Around 2009, the central government determinedly shifted gear towards electromobility. Later, the ‘Made in China 2025’ plan defined “New Energy Vehicles” (NEV)[6] one of seven “strategic emerging industries” and set the targets of reaching 80 % EV share in total Chinese car sales and 20 % share in the total vehicle stock by 2025. Over time, a comprehensive policy package was developed to promote electromobility (Goncalves Muniz et al., 2019; IEA, 2020b, 99f.; Zhang and Qin, 2018):

- ICE restriction policies, which control the number of new ICE vehicle registrations and limit the usage of the existing fleet. Many regional governments provide EV license plates for free, whereas residents have to go through a lottery or an auction to register a new ICE. Moreover, there are restrictions for investing in new ICE vehicle manufacturing plants;
- Fuel economy standards, setting a target of a 4 l/100 km as the average that each manufacturer has to achieve for its new fleet by 2025;
- Starting in 2009, both the central and many local governments offered purchase subsidies for locally produced models. In 2016, subsidies were as high as US$ 8000 per purchase of a battery electric vehicle, and between 2009 and 2015, EV purchase subsidies amounted to 4.5 billion EUR (Retzer et al., 2018). In addition, tax incentives were provided, such as the removal of the 10 % purchase tax for the period 2014–2017;
- In 2018, mandatory EV percentage targets for car manufacturers were introduced, based on a complicated system of “credits” depending on performance and type of technology;
- In 2008, 13 city-wide demonstration projects started to test car fleets, roll out charging infrastructure and familiarise citizens with electromobility. Later, another 12 cities were added;
- Public procurement ensured early deployment of electric vehicles, particularly public bus and taxi fleets;
- Government-funded research programs were targeted to the development of battery technology and later on to induce consolidation among battery manufacturers.

In addition, private companies employed a range of activities for tapping into the knowledge base of leading manufacturers. This included traditional technology licensing, dozens of strategic co-investments with leading international manufacturers (e.g. BYD with Daimler, CATL with BMW), cooperation agreements among big Chinese corporations with complementary capabilities (e.g. BAIC Motor with Didi Chuxing for mobility services and CATL for battery know-how) as well as many of the measures that Lema and Lema (2012: 23) classify as “new, unconventional technology transfer mechanisms”. The latter include the systemic hiring of senior executives and chief engineers from established firms. BYD established a “global design center” run by leading designers hired from Audi, Ferrari and Mercedes Benz. Similarly, start-ups like Xpeng and Byton, many of which have financially powerful Chinese technology companies (Alibaba, Didi, Tencent and Baidu) as shareholders, invested heavily in recruiting top managers and developers from leading international carmakers. Other important channels of technology appropriation consist in the acquisition of foreign technology companies (such as the acquisition of Volvo by Geely) and R&D partnerships (e.g. between Shanshan and BASF to develop new battery materials).

This combination of a comprehensive policy package and firm-level technology strategies led to an enormous boom in EV deployment. Between 2015 and 2020, the stock of electric passenger vehicles increased

---

[6] These include battery electric and plug-in hybrid vehicles, thus excluding “mild hybrids” where the main engine still is an ICE. The NEV definition comprises conventional passenger vehicles only, thereby excluding low-speed electric vehicles (LSEVs, see below) from public support.

from 0.3 to 4.5 million. In 2020, 44 % of the world's electric car fleet circulated in China (IEA, 2021).

Overall, the electromobility policy has been characterised by experimentation and repeated evidence-based revisions. As a particularly notable policy adaptation, EV purchase subsidies have gradually been reduced from 2016 onwards and replaced with regulatory targets and indirect subsidies, in an attempt to promote competitive discipline. Subsidies were increasingly made conditional upon technological performance. The explicit aim was not only to decrease the fiscal burden, but also to weed out inefficient manufacturers, leaving only the most competitive ten companies in the market (Retzer et al., 2018, 11). For the same reason, foreign companies are no longer limited to ownership shares below 50 %. In November 2020, China's State Council corroborated this orientation towards international openness, market-led development and greater emphasis on innovation and competitiveness in its "New Energy Vehicle Industry Development Plan (2021–2035)". Foreign carmakers had been reluctant to use cutting-edge technologies in Joint Ventures with Chinese partners, fearing leakage of core competencies. With 100 % ownership, they are now willing to use China as an export platform for the newest designs and technologies.

Have China's ambitious and costly electromobility policies paid off in terms of catching up in automobile manufacturing and related industries? The fact that China is the world's "lead market" (Beise and Rennings, 2003, 6f.) for EVs does not suffice to prove this. First, demand for electric vehicles has largely been driven by government incentives. China's incentive packages have been among the most generous worldwide. Manufacturers in China therefore had a much stronger incentive to sell locally than to export. At the same time, imported electric vehicles pay high import duties and do not benefit from China's EV subsidies. As a result, China is a captive market. GIZ (2019) estimates that only about 2500 EV were exported from China, and 24,000 imported. Given these distortions, trade-based indicators of competitiveness, such as "revealed comparative advantage" (Balassa, 1965), are no useful proxies. In fact, the market expansion ended in 2018/19 when purchase subsidies were cut by 50 %, leading to stagnant sales (IEA, 2021). Second, the entire industry is still in an "era of ferment" (Anderson and Tushman, 1990, 604), typical of technological paradigm changes, where a wide range of technologies are being tested. It is difficult to predict which ones may become the dominant design and which companies may emerge as technological leaders.

With these difficulties to assess competitive performance in mind, we undertook a two stage-analysis to assess China's position relative to technological leaders. First, we analysed patenting trends in the relevant industries with a special focus on assessing their quality. Patents reflect technological capabilities even before they materialise in economic success or failure. Second, we reviewed the specialised 'grey' literature to capture industry statistics and specific information on technological and business model innovation, market shares, export deals, Chinese outward FDI and the like. In our analysis, we distinguish three segments of the EV industry: passenger cars, buses and battery manufacturing (Section 4).

4. China's technological catch-up and innovation performance: a patent-based analysis

We will now focus on the Chinese technological catch-up and innovation performance by examining patent registrations in the PATSTAT dataset. We distinguish technological classes based on the Cooperative Patent Classification (CPC), an effort to harmonise the classification systems of the United States Patent and Trademark Office (USPTO) and the European Patent Office (EPO). The CPC is better suited for our purpose than the International Patent Classification because it adds a new "Y section" for new technologies.

We include in our analysis four classes from the category Y02T ("Climate change mitigation technologies related to transportation") as well as the class Y10S 903/00, which refers to "Hybrid Electric Vehicles". Furthermore, we select a wide range of technological classes not belonging to the Y category, which are nonetheless relevant to investigate the evolution of electric vehicles technologies. We consider all the classes selected by Pilkington et al. (2002) and Yang et al. (2013) and examine the content of the classes to check for consistency with the topic of analysis. Additionally, we ran a search on Espacenet, a public online service offering access to patent documents from all over the world, using the keywords "electric vehicles", "hybrid electric vehicles" and "plug-in hybrid electric vehicles". This helped us to refine further the selection of technological classes (see Appendix A for the complete list of all the classes used). We then collect data on patent and utility model applications in the four most important patent offices - USPTO, EPO, the China National Intellectual Property Administration (SIPO) and the World Intellectual Property Organization (WIPO) - for the period 1990–2015. We use the patent data up to 2015, since more recent data are less reliable. However, looking at the evolution of the innovative activity in the field and at the timing of the implementation of different green policies in China, the selected time span is the most appropriate one to study China's catching up in electric vehicle technologies (see also Corrocher et al., 2021).

Compared to previous studies (Pilkington et al., 2002; Pilkington and Dyerson, 2006; Yang et al., 2013; Faria and Andersen, 2017), we make two novel contributions. First, our analysis covers a more complete set of technological classes, notably including the relevant classes belonging to the new Y category. This includes, for example, "energy storage for electromobility", "technologies related to electric vehicle charging, including electric charging stations" and "information or communication technologies improving the operation of electric vehicles". Second, while the previous studies covered only USTPO and EPO (and also the World Intellectual Property Organization WIPO in the case of Faria and Andersen, 2017), we cover all relevant patent offices including the Chinese SIPO.

China's EV patent and utility model applications have expanded very fast, rising from slightly above 2000 filed in 2005 to almost 16,000 ten years later (Fig. 2).

This growth has been far more rapid than the growth in EV patenting globally. In the same time span the total number of patent and utility model applications at the global level has increased from 12,263 to 47,542. As a result, the Chinese share in global EV patents rose from 2.4 % in the decade 1991–2000 to 15.5 % in the 2000–2016 period (from 13.3 % to 28.0 %. if we include utility models). If we consider the patent *families*, which is a more precise indicator of innovative activity, the Chinese share of patents (excluding utility models) rose from an average of 4.4 % in the decade 1991–2000 to an average of 33.3 % between 2011 and 2014 (including utility models: from 18.9 % to 47.2 %; Fig. 3).

Some of the corporate innovators soon moved into the group of globally leading EV patents applicants. Not one single Chinese firm ranked among the global top 20 patent applicants until 2006, when BYD joined the top EV developers. Ten years later, half of the top 20 applicants were from China (PATSTAT database).

Not all patent applications reflect the same level of innovativeness and have the same commercial value. We therefore analyze the quality of Chinese patenting using four indicators:

a. **Share of patent applications in total IP applications**. Applicants have the choice to apply for patents or utility models. The latter are intellectual property rights that are easier, faster and cheaper to obtain than patents and typically have a shorter term. They can be understood as second-order patents with lower degree of protection and less commercial value. In the early nineties, only 20 % of applications aimed to obtain a full patent, yet this share increased steadily since 2000 and surpassed 60 % in 2014 – a clear sign of increasing quality (Fig. 4).

b. **Number of patents per patent family**. Patent applicants can file their application in only one or in various patent offices. Applying to

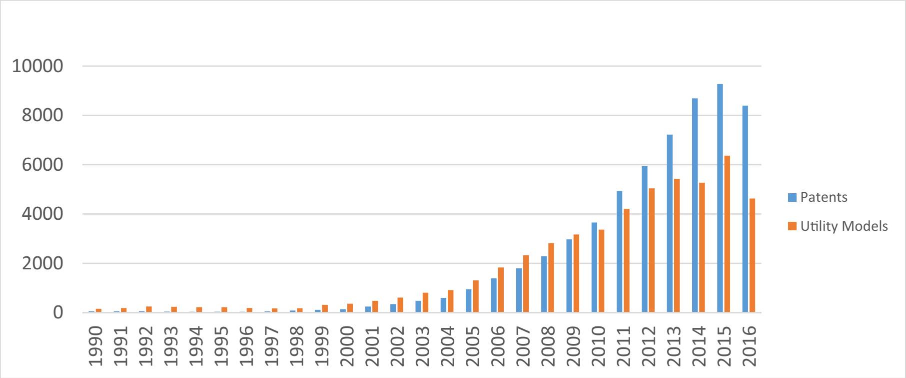

Fig. 2. Patent and utility model applications by Chinese applicants in EV by year.

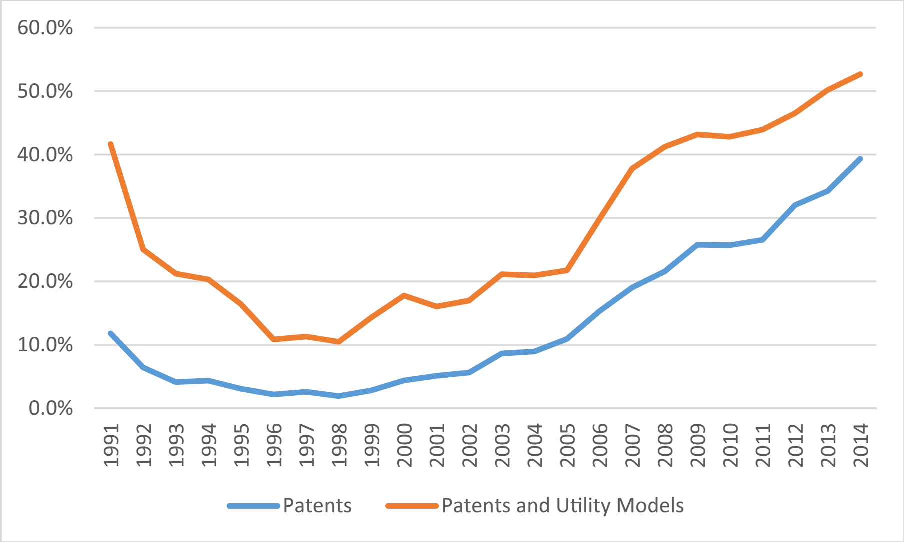

Fig. 3. Share of patent and utility model applications by Chinese applicants.

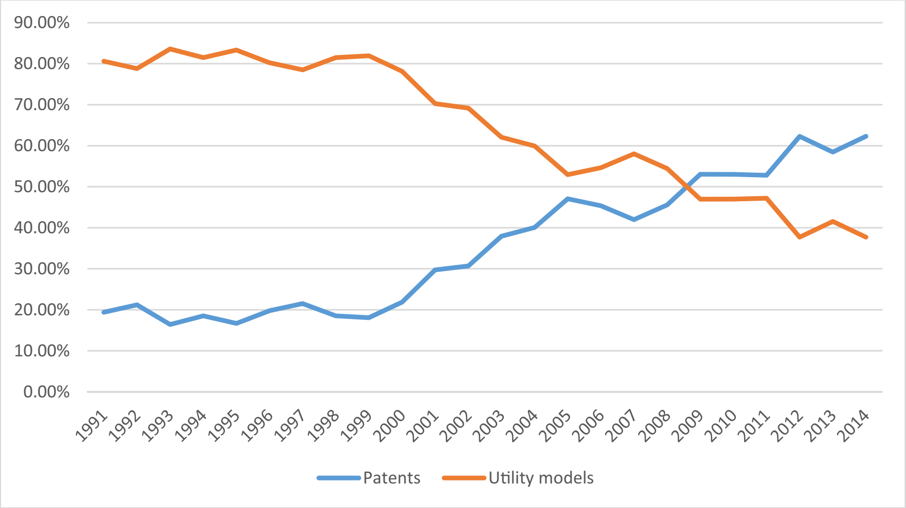

Fig. 4. Share of utility models and patents in total Chinese EV IP applications.

one office only suggests that the respective innovation is not considered to be used elsewhere; conversely, patents filed in multiple jurisdictions van be considered globally valuable patents. Patent *families*, that is, the set of patents taken in multiple jurisdictions to protect the same invention, are a useful indicator. First, a large family size indicates worldwide application of a patent; second, counting patent families avoids double counting of essentially identical patents. Our final sample includes 435,166 patents and 175,046 patent families. Table 1 shows that for Chinese applicants it is quite common to have only one patent per family, whereas the global average is almost three. This suggests that Chinese inventors do not see their inventions as promising for international markets. In the same vein, Chinese patents represent 76.1 % of total applications at SIPO, compared to only 2.2 % at EPO and 3.0 % at USPTO. If we look at trends, however, we see an increase in family size and a steep rise of Chines applications outside of China.

c. **Forward citations** refer to other patents that cite a specific patent, hence, in our case, many forward citations of a given Chinese patent imply knowledge spillovers from that patent to subsequent inventions. On average, Chinese patents have received fewer citations than German, Japanese and US patents. Over time, however, Chinese patents are improving in quality, as newer patents receive more citations than older one (see Table A1 in the Appendix). We have regressed through a linear regression model the number of forward citations by patents over a series of (selected) country dummy variables and over a series of indicators of country-time. These indicators are obtained by multiplying the earliest publication year by a dummy variable that assumes value 1 if the applicant belongs to the country of observation and 0 otherwise (controlling for the earliest publication date). Model 1 includes only the variable on the time from grant, Model 2 includes the dummy for China, Model 3 adds the interaction between China and time from grant and Model 4 includes all the country-dummy and their interactions with time. Results show that even though Chinese patents receive fewer citations than non-Chinese patents overall, the relationship between the number of forward citations and the age of the patent is negative: this means that older patents receive less citations, while newer patents receive more. This can be interpreted as Chinese patents improving in quality over time. Table A2 in the Appendix shows the results of the regressions for the forward citations.

d. **Backward citations** refer to previous patents cited by a new patent. A high number of backward citations suggest that the respective new application draws knowledge from a variety of other inventions, especially when patents from different technological fields are cited. We have regressed through a linear regression model the number of backward citations by patents over a series of (selected) country dummy variables and over a series of indicators of country-time. These indicators are obtained by multiplying the earliest publication year by a dummy variable that assumes value 1 if the applicant belongs to the country of observation and 0 otherwise (controlling for the earliest publication date). Model 1 includes only the variable on the time from grant, Model 2 includes the dummy for China, Model 3 adds the interaction between China and time from grant and Model 4 includes all the country-dummy and their interactions with time. Also for this indicator, empirical findings show its positive correlation with patent value (Harhoff et al., 2003). Looking at backward citations for the period 1991–2016 reveals that Chinese patents on average cite other countries' patents less than patents from other countries (see Table A3 in the Appendix). However, from 2011 onwards, there was a steep increase in the number of citations by Chinese patents towards other patents. In comparison, the trend of this indicator for the benchmark countries was rather stable in the time-window. This is also due to the fact that China is a latecomer country, which does not have much accumulated knowledge and thus has to rely on other incumbent countries as sources of knowledge. It is reasonable to argue that Chinese patents' backward citations are still more directed towards foreign patents, since the increase in the average of forward citations is slower than the increase in the average of backward citations (which doubles since 2010). Table A4 in the Appendix shows the results of the regressions for the backward citations.

Table 1
Average number of patents per patent family in selected countries.

	1991–2000	2001–2014
China	1,0	1,3
US	1,8	3,3
Germany	2,4	3,4
Japan	1,9	3,8
World	2,0	3,1

Overall, the quality of Chinese patents is still low compared to the leading automobile-producing countries, but all four indicators reveal a clear tendencies to catch-up with global leaders.

5. Competitive performance in specific technologies

Patent data capture technological effort, but not competitiveness. Moreover, they are only available with a time lag, which further limits their predictive value, especially in the midst of a technological paradigm change. We therefore complement our analysis with other, more recent sources of information. Many of the conventional measures of competitive performance are not applicable to the case of China's electromobility industries, for the reasons outlined at the end of Section 2. We therefore draw on a combination of, mostly qualitative, data from industry specialist reports,[7] automotive companies' annual reports, specialised sources of statistical data[8] and a web search (company reports and specialised newspapers) for firm-level innovations. Also, some in-depth interviews with experts from Chinese and foreign invested firms were conducted. These served two purposes. Firstly, to triangulate sources of information, and secondly, to explore causalities for which no aggregate information was available, for example how firms responded to policy signals.

We distinguish technological developments in the following three technology domains: electric passenger vehicles; buses; and lithium traction batteries.

5.1. Electric passenger vehicles

China is the world's largest electric car market, accounting for 44 % the worldwide stock % of global EV sales in 2020 (IEA, 2021). Four Chinese manufacturers are now among the global top ten in the EV segment: BYD with 10.0 % of the global market share, BJEV with 7.1 %, SAIC and Geely with 3.4 % each – in stark contrast to the overall list of (traditional) car manufacturers, where the top ten are all non-Chinese (McKinsey&Company, 2020, 11). China ranks first in McKinsey's EV industry supplies index for 2020, which assesses “the share of a country's OEMs in the production of EVs and EV components, such as e-motors and batteries, looking at both current and projected numbers” (ibid., 3). Also, automotive industry managers of Western OEMs' Chinese subsidiaries interviewed for the project recognised a shrinking technological gap between major Chinese brands, such as Nio and BYD, and leading Western brands. A particular strength of Chinese EV manufacturers, including some start-ups with participation of powerful IT companies like Alibaba and Tencent, is seen in the integration of car manufacturing and software.

Growth in a protected market however does not prove international competitiveness. The enormous volume of sales is to a considerable extent due to the very high purchase subsidies. When these subsidies

---

[7] Such as Bloomberg NEF (2019); IEA (2020b), McKinsey&Company (2020) Electric Vehicle Index, www.sustainabletransport.org/ and https://insideevs.com/news.

[8] https://www.statista.com/statistics/976376/china-electric-vehicles-sales-by-oem/.

were gradually reduced, EV sales slowed down radically. Sales in 2020 (1.16 million EV) were only slightly higher than in 2018 (1.08 million), although the EV share in overall car sales kept growing (from 4.5 to 5.7 %). This contrasts starkly with Europe, where purchase subsidies increased, with the effect that Europe overtook China as the largest market in 2020 (from 0.38 in 2018 million to 1.38 million) and EV shares skyrocketed from 2.2 to 10.0 % (IEA, 2021). As a result, the global market share of Chinese EV manufacturers decreased.

To assess competitiveness, we looked at two trends. First, the performance of Chinese EV manufacturers vis-à-vis foreign EV manufacturers in China. Among the top-selling EV models, most are Chinese and some are Joint Ventures with international automotive OEMs. Among international brands, Tesla plays a special role. Starting production in China as late as 2000, Tesla already accounts for the 2nd and 3rd best-selling models (Cheng, 2021). Second, ability to export. So far, China's passenger EVs are almost exclusively sold locally. Only since 2020 are some Chinese EV manufacturers trying to export at scale. SAIC Motor, with its British subsidiary MG, reached a 2 % market share in the European EV market with a small and affordable SUV. BYD, Nio, Kandi and several other brands announced the launch of EV models for Europe and the US around 2020 (Gibbs, 2020).

At the same time, all the big foreign carmakers are expanding their EV production in China. Following a change in regulations that allows overseas firms to wholly own local manufacturing plants, some foreign brands, including Tesla, BMW and Toyota, started to use China as an export hub for electric models. This reflects increasing competitiveness and diversification of the battery supply chain; the supply of highly trained engineers and R&D personnel, which makes it cost-competitive to shift even R&D functions to China; and the expectation that China may become a lead market for autonomous and connected driving (Zhou, 2020).

In sum, Chinese EV have greatly improved and are successfully competing with foreign brands in their home market. Also, foreign firms are using China as an export hub; yet, Chinese electric passenger vehicle manufacturers still need to prove their ability to compete in international markets.

5.2. *Electric buses*

China is by far the global lead market for electric buses. Of the 513,000 electric buses operating worldwide in 2019, 98 % were in China. In most of the big cities, the EV share in the overall public bus vehicle fleet exceeded 50 %. Shenzhen is the most progressive city in this regard, achieving full electrification of its 17,000 bus fleet in 2017 (Berlin et al., 2020). This required considerable subsidization, as the total cost of ownership of an e-bus is 21 % higher than that of a diesel bus (ibid.). Until 2016, the Shenzhen government subsidised 50 % of the price of a 12-meter e-bus (Lu et al., 2018). With this subsidy, the total cost of ownership was 36 % less than that of a diesel equivalent (Berlin et al., 2020). The construction of charging stations was also subsidised and an innovative leasing model developed.

Backed by this strong policy support, Chinese e-bus manufacturers became global leaders. Five bus manufacturers dominate the Chinese market. Two of them, BYD and Yutong are successfully exporting. While there is no global and up-to-date export statistics for e-buses, specialised media[9] suggest that most large-scale e-bus deals globally are currently signed with one of these two companies, which are also rapidly expanding their global networks of assembly plants. BYD sold >1500 e-buses in Colombia, and >1000 in Europe in 2019 alone.[10] BYD is producing e-buses in the US, Canada, Brazil and Hungary. BYD Company Ltd. is one of China's largest privately owned enterprises. It has pioneered several technological innovations, including the lithium-iron-phosphate (LiFePO4) battery for use in buses, the first bi-articulated e-bus and the first electric double decker buses. Similarly, Yutong is selling large batches abroad, including a recent sale of 741 e-buses to Quatar's public transport company.[11] Yutong has so far produced about 130,000 e-buses and has set up assembly plants in the US, Brazil, Japan, Hungary, France, and India. In Europe, the home market of leading diesel bus manufacturers including Volvo, MAN, Mercedes and Solaris, BYD (29 % e-bus market share, including a joint venture) and Yutong (7 %) successfully compete with incumbents, despite the latter's long-established service networks and ties with local transport operators (Sustainable Bus, 2021).

Between 2016 and 2019, subsidies for electric buses in China have been cut by 40 %, leading to declining sales in China, while global sales are increasing (IEA, 2020b). Yet, the Chinese market is expected to recover as emissions regulations and steeply declining cost of lithium batteries are tilting the balance in favour of e-buses. As the global market is developing, established international manufacturers of diesel buses are entering the global e-bus market, including Volvo, Mercedes and Solaris. If and how fast they can catch up with the Chinese pioneering corporations remains to be seen. Chinese e-bus manufacturers are benefitting from considerable early mover advantages. For about ten years, they have tested fleet operations at scale, collected data on driving profiles and battery life-cycles under different conditions in terms of range, temperature and charging conditions; they have developed institutional arrangements with bus operators, charging-infrastructure developers and financial intermediaries, which enable them to sell entire systems consisting of e-buses plus infrastructure and services; and they have set up assembly operations and established service agreements in many potential e-bus markets. Acquiring this know-how and building these network effects will not be easy for those corporations entering the market today. On the other hand, it should be noted that manufacturing of buses manufacturing is less complex than that of (especially high-end) passenger vehicles, which partly explains why Chinese industries managed to leapfrog in the former while still trying to catch up in the latter.

5.3. *Batteries*

Lithium-ion batteries account for a large part of the cost of an EV, and their performance in terms of energy density, life-cycle, safety and cost is essential to make EV more attractive than conventional cars. Technological capabilities in the industries are therefore important for a country wanting to reap innovation rents and technology spillovers from the electric vehicle industry. Lithium batteries are highly complex, as they involve a variety of input materials for cathodes, anodes and electrolytes that can be combined and optimised for specific battery characteristics; they also require capabilities for manufacturing cells and packaging them into modules as well as electronics and software capabilities to design battery management systems, which in turn need to be tailored to specific performance requirements of each car model. Malhotra et al. (2019) show in detail how innovation in this industry is strongly dependent on “inter-sectoral learning among the upstream segments of cell design and manufacturing, production equipment supply, and material supply on the production side, as well as among the downstream segments of battery design and manufacture, system integration, and end use.” This systemic nature makes catching-up particularly challenging.

When lithium-on batteries for cars emerged as a viable new technology, Japan's Panasonic and Korea's Samsung and LG Chem were the technological leaders. Panasonic stroke a deal with Tesla to build a large

---

[9] Such as: https://insideevs.com/news/.

[10] https://insideevs.com/news/378584/byd-sold-1000-buses-europe/ and https://insideevs.com/news/466616/colombia-byd-cumulative-orders-1002-ev-buses/.

[11] https://insideevs.com/news/481987/ev-buses-sales-2020-china-byd-yutong/.

battery cell factory in the USA. Yet, with the booming demand for EV in China, China became the leader in production. 73 % of world lithium-ion battery cell manufacturing is concentrated in China, and of the 136 lithium-ion battery plants that by May 2020 were in the pipeline globally to 2029, 101 were based in China.[12] Contemporary Amperex Technology Co Ltd. (CATL), a Chinese newcomer to the industry founded as late as 2011, has become the world's largest battery maker since 2017. So far, CATL's production is almost entirely sold in China, but the big foreign carmakers, from Tesla to Volkswagen, Toyota and BMW are using CATL batteries for their China-made cars. CATL is now investing and purchasing companies in the US, Canada and Japan and recently started a 1.8 billion US$ investment in a battery factory in Germany, for which it has already signed contracts with BMW. This clearly shows the company's competitiveness outside the protected Chinese market. China's second largest Chinese battery producer is BYD, manufacturing mainly for its own bus and passenger vehicle factories. Two other Chinese battery manufacturers, Lishen Battery and Guoxuan High-Tech, are also among the world's top manufacturers.

Market analysts agree that the technological gap vis-à-vis the technologically advanced Japanese and Korean companies technological leaders is now almost closed.[13] Chinese manufacturers have developed several valuable innovations. One example is the development of iron-phosphate batteries with a commercially viable energy density, developed and gradually improved by Guoxuan, CATL, BYD and other Chinese manufacturers, which are cheaper than traditional battery chemistries and do not require cobalt and nickel.[14] Other examples include CATL's cost-saving cell-to-pack technology and BYD's ‘Blade Battery’ which is less susceptible to fires and requires much less space than previous generations of batteries (IEA, 2020b). Chinese firms are set to expand their dominant position in the lithium-ion battery industry due to China's control of the entire supply chain. From refining and chemical processing of nickel, cobalt, graphite, lithium and manganese to the production of cathode and anode material and the manufacturing of cells, China accounts for about 60–90 % (2019) of world capacity in each category.[15]

Lithium batteries have relatively short technology life-cycles, as new battery chemistries are constantly being developed. This favours industrial newcomers, as the incumbent's competitive advantages are frequently challenged by new developments and new pathways emerge that are different from those of the forerunners. Lee (2013) regards short cycle times of technologies as one of the most important enablers of catching up. The Chinese industry's success in lithium batteries – in contrast to passenger EV – may support his case.

Again, catching up in the battery industry has been supported by industrial policy. For example, EV purchase subsidies had only been granted for cars using batteries manufactured in China. In a second phase, preferential policy support was made conditional upon meeting certain critical battery performance targets (IEA, 2019, 89f.). Furthermore, the government very actively secured access to critical input materials through long-term contracts with the international mining industry.

6. Conclusions and policy lessons

The case study confirms that radical technological change may create new windows of opportunity for catch-up and leapfrogging. Chinese firms and policymakers recognised the technological paradigm shift from conventional cars powered by internal combustion engines to electric vehicles as an opportunity to catch up with, and leapfrog ahead of, the globally leading automotive and related industries which so far had been technologically advanced and more competitive than China's industry.

It is methodologically challenging to assess technological catch-up and competitive performance amidst the typical “era of ferment” characteristic of paradigm changes, where established markets are shaken up, some of the key players are newcomers to the industry, and major investors are willing to accept temporary financial losses in the pursuit of long-term objectives. Appraising competitiveness is further complicated by the facts that China's market is large and partly captive and the EV world market is highly dependent on subsidies and regulations. Against this background, we combined patent analysis and use of descriptive data on key market segments to get as close as possible to an evidence-based assessment of China's competitive performance. This approach has its limitations. Patent data are only imperfect proxies of innovation performance, and descriptive case study data can only indicate select trends in the competitiveness of an industry. Yet, given the incipient development stage of electromobility and manifold existing market distortions, this is the best approximation at hand.

Our analysis shows that a considerable number of Chinese firms successfully were able to catch-up in a range of market segments related to electromobility, and in some cases even managed to leapfrog ahead of the international competition. Not only is China's share of patents in the EV and related industries increasing, but all indicators point towards higher quality of these patents. Industry studies show that technological leadership has been achieved in the production of electric buses. Chinese firms are at parity with leading Japanese and Korean multinationals in various stages of the lithium car battery value chain. In other market segments, Chinese firms are not yet among the technological leaders, but starting to challenge them. This includes the large and growing market for electric passenger cars. The fact that foreign carmakers are progressively developing, testing and deploying new technologies and models in China, often in joint ventures with Chinese partners, also indicates increasing sophistication of China's sectoral system of innovation.

Particularly striking is the speed of catching up. It took China little more than a decade from starting to invest in traction batteries to becoming the largest manufacturer and challenging the foreign technology leaders; from producing the first electric bus to capturing 96 % of the world market; from operating the first electric bus in Shenzhen to achieving fully-electrified public transport in that megacity. Companies such as CATL in batteries and BYD in bus manufacturing needed only a decade from market entry to becoming globally leading companies in their fields. This speed makes it difficult to predict future competitive performance, but suggests that catching up and leapfrogging may be expected in other market segments as well, especially where change is radical and technology cycles are short. In line with this argument, analysts expect China to challenge and eventually outcompete globally leading technology companies in the emerging fields of autonomous and connected driving as well as new mobility services (which are beyond the scope of this paper). While the respective technologies are still at an infant stage globally, the large number of start-up companies with financial backing from internet giants Tencent, Baidu and Alibaba make these market segments likely candidates for the next Chinese leapfrogging success. On a more cautionary note, some of the new businesses are still heavily cross-subsidised and long-term profitability has not been proven.

China's impressive competitive performance in this wide range of market segments holds important policy lessons. In the first place, it confirms that policies aimed at a profound sectoral transformation towards more sustainable technologies can become a source of innovation and new competitive advantage, rather than a burden constraining the

---

[12] Data from the specialist firm Benchmark Mineral Intelligence, https://www.voanews.com/silicon-valley-technology/how-china-dominates-global-battery-supply-chain, retrieved Feb 7, 2021.

[13] Menahem Anderman, President of Total Battery Consulting in California, cited in in Ma et al. (2018).

[14] https://cleantechnica.com/2020/02/18/tesla-shanghai-model-3-may-go-cobalt-free-using-catls-lfp-cells-diving-deeper/.

[15] Same source, https://www.mining.com/chart-chinas-stranglehold-on-electric-car-battery-supply-chain/, retrieved Feb 7, 2021.

competitiveness of national industries. In addition, the study confirms many of the lessons learned regarding how to implement industrial policy successfully. Many authors have tried to condense the lessons learned from past decades of industrial policymaking (Rodrik, 2004; Altenburg and Lütkenhorst, 2015). These include the importance of a clear vision and societal consensus to take determined action to coordinate public and private action for developing emerging technologies. Many countries and corporations recognised the inevitability of electrifying cars, but only few had the will and determination to translate this into ambitious plans. China's central government grasped the opportunity earlier than others, offering a comprehensive policy package. Striking examples of its policy determination and comprehensiveness include the development on an entire lithium battery value chain (from securing access to strategic minerals to large-scale R&D) as well as the creation of systemic preconditions for the electrification of bus services. China's experience also confirms the importance of experimentation and continuous policy adjustment, as exemplified in its large-scale city experiments and periodic revisions of targets and incentives. As another sign that China has learned its industrial policy lessons, the government recognised the need to ensure market discipline after a phase of providing generous subsidies, reducing purchase subsidies and making remaining incentives conditional upon performance.

Overall, China's government approach was very comprehensive. It combined polices to phase ICE technologies out (e.g. restricting circulation and introducing fuel economy standards) with generous support for the technological alternatives (from purchase subsidies and public procurement to R&D support, s. Section 2). The integration of phasing-in and phasing-out policies has been identified as a key feature of *green* industrial policies (Altenburg and Rodrik, 2017). Moreover, the government combined determined support for the sectoral innovation system with measures for sustaining demand, thereby creating an environment in which domestic firms had long-term incentives for technological learning and capability building.

Future research should reassess China's competitive performance once electromobility technologies are mature and market distortions, such as national purchase subsidies and market reservation policies, have largely been eliminated. Then, proven measures of competitiveness (such as Revealed Comparative Advantages) can be applied. Also, comparisons with catch-up experiences in other green industries are needed to improve our understanding of how green transformation affects competitive advantage in industry more broadly. Our case study of one field of green technologies does not allow for generalisations, as catch-up depends on a vast range of sector-specific determinants. Cross-sectoral comparisons would help to disentangle effects of generic green transformation reforms (such as carbon pricing) and those that are technology-specific.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

Nicoletta Corrocher and Franco Malerba acknowledge the support by the Italian Ministero dell'Istruzione, dell'Università e della Ricerca, PRIN-2017 project 201799ZJSN: "Technological change, industry evolution and employment dynamics".

Appendix A

List of technological classes used for the initial selection of patents

Class Y

- Detailed control on technological classes
- Search in Espacenet with keywords: "electric vehicles", "HEVs", "PHEVs"

Other classes different from Class Y

- Yang et al. (2013) + Pilkington et al. (2002)
- Detailed control on technological classes
- Search in Espacenet with keywords: "electric vehicles", "HEVs", "PHEVs"

CPC CLASS Y

Y02T 10/60 (Other road transportation technologies with climate change mitigation effect: include Hybrid 10/62 e Electric machine technologies for applications in electromobilty 10/64)

Y02T 10/70 (Energy storage for electromobility)

Y02T 90/10 (Technologies related to electric vehicle charging: include Electric charging stations 90/12; Plug-in electric vehicles 90/14; Information or communication technologies improving the operation of electric vehicles 90/16)

Y02T 90/34 (Fuel cell powered electric vehicles)

Y10S 903/00 (Hybrid Electric Vehicles, HEVs)

CPC other classes

B60L 11/00 (Electric propulsion with power supplied within the vehicle)

Battery technology

H01M 2/00 (Constructional details or processes of manufacture of the non-active parts)
H01M 4/00 (Electrodes)
H01M 6/00 (Primary cells; Manufacture thereof)
H01M 8/00 (Fuel cells; Manufacture thereof)
H01M 10/00 (Secondary cells; Manufacture thereof)

Battery management technology

H02J (CIRCUIT ARRANGEMENTS OR SYSTEMS FOR SUPPLYING OR DISTRIBUTING ELECTRIC POWER; SYSTEMS FOR STORING ELECTRIC ENERGY)
B60L 3/00 (Electric devices on electrically-propelled vehicles for safety purposes; Monitoring operating variables, e.g. speed, deceleration, power consumption)
G01R 19/00 (Arrangements for measuring currents or voltages or for indicating presence or sign thereof)
G01R 31/02 (Testing of electric apparatus, lines or components, for short-circuits, discontinuities, leakage of current, or incorrect line connection)
G01R 31/04 (Testing connections, e.g. of plugs, of non-disconnectable joints)
G01R 31/06 (Testing of electric windings, e.g. of solenoids, inductors, e.g. for polarity)
G01R 31/07 (Testing of fuses)
G01R 31/36 (Apparatus for testing electrical condition of accumulators or electric batteries, e.g. capacity or charge condition)

Motor technology

H02K 17/00 (Asynchronous induction motors; Asynchronous induction generators)
H02K 19/00 (Synchronous motors or generators)
H02K 21/00 (Synchronous motors having permanent magnets; Synchronous generators having permanent magnets)
H02K 23/00 (DC commutator motors or generators having mechanical commutator; Universal AC/DC commutator motors)
H02K 25/00 (DC interrupter motors or generators)
H02K 27/00 (AC commutator motors or generators having mechanical commutator)
H02K 29/00 (Motors or generators having non-mechanical commutating devices, e.g. discharge tubes or semiconductor devices)
H02K 41/00 (Propulsion systems in which a rigid body is moved along a path due to dynamo-electric interaction between the body and a magnetic field travelling along the path)

Motor controlling technology

H02P 1/00 (Arrangements for starting electric motors or dynamo-electric converters)
H02P 3/00 (Arrangements for stopping or slowing electric motors, generators, or dynamo-electric converters)
H02P 5/00 (Arrangements specially adapted for regulating or controlling the speed or torque of two or more electric motors)
H02P 6/00 (Arrangements for controlling synchronous motors or other dynamo-electric motors using electronic commutation dependent on the rotor position; Electronic commutators therefor)
H02P 7/00 (Arrangements for regulating or controlling the speed or torque of electric DC motors)
H02P 9/00 (Arrangements for controlling electric generators for the purpose of obtaining a desired output)
H02P 21/00 (Arrangements or methods for the control of electric machines by vector control, e.g. by control of field orientation)
H02P 23/00 (Arrangements or methods for the control of AC motors characterised by a control method other than vector control)
H02P 25/00 (Arrangements or methods for the control of AC motors characterised by the kind of AC motor or by structural details)
H02P 27/00 (Arrangements or methods for the control of AC motors characterised by the kind of supply voltage)
H02P 29/00 (Arrangements for regulating or controlling electric motors, appropriate for both AC and DC motors)
H02P 31/00 (Arrangements for regulating or controlling electric motors not provided for in groups)

Entire vehicle controlling systems

B60K 6/20 (the prime-movers consisting of electric motors and internal combustion engines, e.g. HEVs)
B60L 15/00 (Methods, circuits, or devices for controlling the traction-motor speed of electrically-propelled vehicles)
B60L 7/00 (Electrodynamic brake systems for vehicles in general)
B60W 10/10 (Conjoint control of vehicle sub-units of different type or different function)
B60W 10/20 (Control systems specially adapted for hybrid vehicles)
H02J 7/00 (Circuit arrangements for charging or depolarising batteries or for supplying loads from batteries)
B60W 20/00 (Control systems specially adapted for hybrid vehicles)
B60W 30/00 (Purposes of road vehicle drive control systems not related to the control of a particular sub-unit, e.g. of systems using conjoint control of vehicle sub-units)

Table A1
Forward citations by country and time.

Year	China	USA	Japan	Germany
1991	39	120	51	37
1992	53	292	195	90
1993	42	361	243	129
1994	50	419	288	121
1995	38	486	325	142
1996	31	575	422	165
1997	43	552	536	192
1998	38	685	583	226
1999	60	700	663	265
2000	97	709	681	297
2001	151	858	1.053	327
2002	195	1.080	1.232	360
2003	319	1.274	1.031	399
2004	402	1.517	1.337	370
2005	615	1.785	1.681	454
2006	938	1.744	1.702	470
2007	1.315	1.813	1.872	613
2008	1.809	2.215	2.064	707
2009	2.491	2.536	2.060	960
2010	2.853	2.891	2.180	940
2011	3.407	2.881	2.648	1.176
2012	5.119	3.136	3.539	1.399
2013	6.042	3.337	3.834	1.371
2014	7.259	3.427	3.496	1.221

Table A2
Forward citations regressed over country and time variables.

	(1)	(2)	(3)	(4)
China		−0.676*** (0.00677)	−0.577*** (0.00966)	−0.252*** (0.0118)
Germany				−0.106*** (0.0171)
USA				0.823*** (0.0218)
Japan				0.376*** (0.0149)
chinatime			−0.0288*** (0.00118)	−0.0248*** (0.00147)
gertime				0.0101*** (0.00189)
ustime				−0.0154*** (0.00207)
japtime				0.0107*** (0.00161)
timefromgrant	1.93e−09* (0.000626)	−0.0134*** (0.000673)	−0.0105*** (0.000741)	−0.0145*** (0.00115)
Constant	1.000*** (0.00565)	1.226*** (0.00711)	1.209*** (0.00747)	0.884*** (0.0101)
Observations	147,469**	147,469	147,469	147,469
R-squared	0.000	0.039	0.040	0.081

Robust standard errors in parentheses.
*** $p < 0.01$.
** $p < 0.05$.
* $p < 0.1$.

Table A3
Backward citations by country and time.

Year	China	USA	Japan	Germany
1991	39	120	51	37
1992	53	292	195	90
1993	42	361	243	129
1994	50	419	288	121
1995	38	486	325	142
1996	31	575	422	165
1997	43	552	536	192
1998	38	685	583	226

(continued on next page)

Table A3 (*continued*)

Year	China	USA	Japan	Germany
1999	60	700	663	265
2000	97	709	681	297
2001	151	858	1.053	327
2002	195	1.080	1.232	360
2003	319	1.274	1.031	399
2004	402	1.517	1.337	370
2005	615	1.785	1.681	454
2006	938	1.744	1.702	470
2007	1.315	1.813	1.872	613
2008	1.809	2.215	2.064	707
2009	2.491	2.536	2.060	960
2010	2.853	2.891	2.180	940
2011	3.407	2.881	2.648	1.176
2012	5.119	3.136	3.539	1.399
2013	6.042	3.337	3.834	1.371
2014	7.259	3.427	3.496	1.221

Table A4
Backward citations regressed over country and time variables.

	(1)	(2)	(3)	(4)
China		−0.963***	−0.881***	−0.516***
		(0.00528)	(0.00704)	(0.00887)
Germany				0.0152
				(0.0138)
USA				0.972***
				(0.0193)
Japan				0.325***
				(0.0114)
chinatime			−0.0239***	−0.0287***
			(0.000896)	(0.00116)
gertime				0.00713***
				(0.00163)
ustime				−0.0202***
				(0.00193)
japtime				−0.0140***
				(0.00129)
timefromgrant	−1.39e−09*	−0.0191***	−0.0167***	−0.0119***
	(0.000583)	(0.000610)	(0.000675)	(0.00101)
Constant	1.000***	1.323***	1.308***	0.942***
	(0.00486)	(0.00611)	(0.00642)	(0.00839)
Observations	147,469**	147,469	147,469	147,469
R-squared	0.000	0.090	0.090	0.148

Robust standard errors in parentheses.

*** $p < 0.01$.

** $p < 0.05$.

* $p < 0.1$.

References

Altenburg, T., 2014. From Combustion Engines to Electric Vehicles. A Study of Technological Path Creation and Disruption in Germany. DIE Discussion Paper 23/2014. DIE, Bonn retrieved 28 January 2021.

Altenburg, T., Feng, K., Shen, Q., 2017. Electric mobility and the quest for automobile industry upgrading in China. In: Altenburg, T., Assmann, C. (Eds.), Green Industrial Policy. UNEP/UNIDO/UNDP/ILO/UNITAR/DIE, Geneva, pp. 185–198.

Altenburg, T., Lütkenhorst, W., 2015. Industrial policy in developing countries. In: Failing Markets - Weak States. Cheltenham/Northampton.

Altenburg, T., Rodrik, D., 2017. Green industrial policy: accelerating structural change towards wealthy green economies. In: Altenburg, T., Assmann, C. (Eds.), Green Industrial Policy: Concepts, Policies, Country Experiences. UN Environment, Deutsches Institut für Entwicklungspolitik, Geneva, Bonn, pp. 1–20.

Altenburg, T., Schamp, E.W., Chaudhary, A., 2016. The emergence of electromobility: comparing technological pathways in France, Germany, China and India. Sci. Public Policy 43 (4), 464–475.

Ambec, S., 2017. Gaining competitive advantage with green industrial policy. In: Altenburg, T., Assmann, C. (Eds.), Green Industrial Policy. UNEP/UNIDO/UNDP/ILO/UNITAR/DIE, Geneva, pp. 38–49.

Anderson, P., Tushman, M.L., 1990. Technological discontinities and dominant designs: a cyclical model of technological change. Adm. Sci. Q. 35, 604–633.

Balassa, B., 1965. Trade liberalisation and "Revealed" comparative advantage. Manch. Sch. 33 (2), 99–123.

Beise, M., Rennings, K., 2003. Lead markets of environmental innovations: a framework for innovation and environmental economics. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=428460.

Berlin, A., Zhang, X., Chen, Y., 2020. Case study: electric buses in Shenzhen, China; extracted from World Bank, Shenzhen Bus Group, UC Davis, China Development Institute: the electrification of public transport –a case study of Shenzhen Bus Group. https://iea.blob.core.windows.net/assets/db408b53-276c-47d6-8b05-52e53b1208e1/e-bus-case-study-Shenzhen.pdf.

Bloomberg NEF, 2019. Electric vehicle outlook 2019. https://about.bnef.com/electric-vehicle-outlook/.

Bloomberg NEF, 2020. Battery pack prices cited below $100/kWh for the first time in 2020, while market average sits at $137/kWh. https://about.bnef.com/blog/battery-pack-prices-cited-below-100-kwh-for-the-first-time-in-2020-while-market-average-sits-at-137-kwh/ retrieven 21 Devember 2020.

Burck, J., et al., 2019. Climate change performance index. Results 2019. Bonn et al. NewClimate Institute & Climate Action Network, Germanwatch. https://germanwatch.org/sites/germanwatch.org/files/CCPI2019_Results_WEB.pdf.

Cheng, E., 2021. Here are the best-selling electric cars in China so far this year. CNBC. https://www.cnbc.com/2021/10/14/china-ev-tesla-xpeng-nio-byd-are-best-selling-electric-cars-in-2021-.html.

Corrocher, N., Malerba, F., Morrison, A., 2021. Technological regimes, patent growth and catching-up in green technologies. Ind. Corp. Chang. 30 (4), 1084–1107. https://doi.org/10.1093/icc/dtab025.

Faria, L.G.D., Andersen, M.M., 2017. Sectoral patterns versus firm-level heterogeneity - the dynamics of eco-innovation strategies in the automotive sector. Technol. Forecast. Soc. Chang. 117, 266–281.
Fernández, V., 2017. Rare-earth elements market: a historical and financial perspective. Resour. Policy 53, 26–45.
Freeman, C., 1992. A green techno-economic paradigm for the world economy. In: Freeman, C. (Ed.), The Economics of Hope: Essays on Technical Change, Economic Growth and the Environment. Pinter, London, pp. 190–211.
Gibbs, N., 2020. How Chinese brands are using EVs to gain foothold in Europe. Automotive news Europe retrieved 28 January 2021. https://europe.autonews.com/automakers/how-chinese-brands-are-using-evs-gain-foothold-europe.
GIZ, 2019. Mobility in 21st Century China: Snapshots, Dynamics, and Future Perspectives, Beijing.
Goncalves Muniz, S.T., Belzowski, B.M., Zhu, J., 2019. The trajectory of China's new energy vehicles policy. Int. J. Automot. Technol. Manag. 19 (3–4), 257–280. https://doi.org/10.1504/IJATM.2019.100913.
Harhoff, D., Scherer, F.M., Vopel, K., 2003. Citations, family size, opposition and the value of patent rights. Res. Policy 32 (8), 1343–1363.
Holweg, M., Luo, J., Oliver, N., 2005. The Past, Present and Future of China's Automotive Industry: A Value Chain Perspective. Working Paper: UNIDO.
IEA, 2019. Global EV outlook 2019. International Energy Agency, Paris. https://www.iea.org/reports/global-ev-outlook-2019.
IEA, 2020b. Global EV outlook 2020. International Energy Agency, Paris. https://webstore.iea.org/download/direct/3007.
IEA, 2020a. Tracking transport 2020. International Energy Agency, Paris. https://www.iea.org/reports/tracking-transport-2020.
IEA, 2021. Global EV outlook 2021. https://www.iea.org/reports/global-ev-outlook-2021.
Kao, E., 2018. Air pollution is killing 1million people and costing Chinese economy 267 billion yuan a year, research from CUHK shows. Retrieved from South China Morning Post, October 2. https://www.scmp.com/news/china/science/article/2166542/air-pollution-killing-1-million-people-and-costing-chinese.
Lee, K., 2013. Schumpeterian Analysis of Economic Catch-up: Knowledge, Path-Creation, and the Middle-Income Trap. Cambridge University Press, Cambridge.
Lee, K., Malerba, F., 2017. Catch-up cycles and changes in industrial leadership: windows of opportunity and responses by firms and countries in the evolution of sectoral systems. Res. Policy 46 (2), 338–351.
Lema, R., Lema, A., 2012. Technology transfer? The rise of China and India in green technology sectors. Innov. Dev. 2, 23–44.
Lema, R., Rabellotti, R., Fu, X., 2020. Green windows of opportunity. Latecomer development in the age of transformation towards sustainability. Ind. Corp. Chang. 29 (5) https://doi.org/10.1093/icc/dtaa044.
Leggewie, C., Messner, D., 2012. The low-carbon transformation—a social science perspective. J. Renewable Sustainable Energy 4, 041404. https://doi.org/10.1063/1.4730138.
Leung, F., 2019. How China is winning its battle against air pollution, 14 Aug 2019. Earth.org. https://earth.org/how-china-is-winning-its-battle-against-air-pollution/.
Lu, L., Lulu, X., Zhou, W., 2018. How did Shenzhen, China build world's largest electric bus fleet? World Resources Institute. www.wri.org/blog/2018/04/how-did-shenzhen-china-build-world-slargest-electric-bus-fleet.
Ma, J., Stringer, D., Zhang, Y., Kim, S., 2018. The breakneck rise of China's colossus of electric-car batteries. In: Bloomberg Business Week, 1 Feb 2018 retrieved 23 August 2019.
Malerba, F., Lee, K., 2021. An evolutionary perspective on economic catch-up by latecomers. Ind. Corp. Chang. 30 (4), 986–1010.
Malhotra, A., Schmidt, T., Huenteler, J., 2019. The role of inter-sectoral learning in knowledge development and diffusion: case studies on three clean energy technologies. Technol. Forecast. Soc. Chang. 16, 464–487.
McKinsey&Company, 2020. McKinsey Electric Vehicle Index: Europe Cushions a Global Plunge in EV Sales, No Place.
OECD, 2018. Environmental Policy Stringency Index (Edition 2017). OECD Environment Statistics (database). https://doi.org/10.1787/b4f0fdcc-en (accessed on 02 January 2020).
Pegels, A., Altenburg, T., 2020. Latecomer development in a "greening" world: introduction to the special issue. World Dev. 135, 105084 https://doi.org/10.1016/j.worlddev.2020.105084.
Perez, C., 2013. Unleashing a golden age after the financial collapse: drawing lessons from history. Environ. Innov. Soc. Trans. 6, 9–23.
Pilkington, A., Dyerson, R., Tissier, R., 2002. The electric vehicle: patent data as indicators of technological development. World Patent Inf. 24 (1), 5–12.
Pilkington, A., Dyerson, R., 2006. Innovation in disruptive regulative environments. Eur. J. Innov. 9 (1), 79–91.
Retzer, S., Huber, M., Wagner, M., 2018. The E-mobility race and China's determination to win - measurements by the Chinese government to accelerate e-mobility development. In: Deutsche Gesellschaft für Internationale Zusammenarbeit.
Rodrik, D., 2004. Industrial Policy for the Twenty-First Century. CEPR Discussion Paper 4767.
Schloblach, M., Retzer, S., 2018. Defining the Future of Mobility: Intelligent and Connected Vehicles (ICVs) in China and Germany. Deutsche Gesellschaft für Internationale Zusammenarbeit.
Sustainable Bus, 2021. The Pandemic doesn't stop the european e-bus market: +22% in 2020. February 19, 2021. Sustainable Bus (blog). https://www.sustainable-bus.com/news/europe-electric-bus-market-2020-covid/.
Teece, D.J., 2018. Tesla and the reshaping of the auto industry. Manag. Organ. Rev. 14 (3), 501–512.
Yang, L., Xu, J., Neuhäusler, P., 2013. Electric vehicle technology in China: an exploratory patent analysis. World Patent Inf. 35 (4), 305–312.
Zhang, L., Qin, Q., 2018. China's new energy vehicle policies: evolution, comparison and recommendation. Transp. Res. A Policy Pract. 110, 57–72.
Zhou, C., 2020. China-made exports of Ford, Tesla, BMW set to surge as Beijing opens auto industry, government says. South China Morning Post. https://www.scmp.com/economy/china-economy/article/3044465/china-made-exports-ford-tesla-bmw-set-surge-beijing-opens.

Tilman Altenburg is Head of the Department "Sustainable Economic and Social Development" at the German Development Institute. He received his doctorate in Economic Geography in 1991. Mr. Altenburg was a research fellow at the Free University Berlin and the Philipps University Marburg. He has published extensively on industrial policy, economic development and innovation systems. Recent publications include a Special Issue on Latecomer development in a "greening" world (World Development), a UN flagship report on Green Industrial Policy and a Special Issue on Low carbon innovation paths in Asia and Europe (Science and Public Policy).

Nicoletta Corrocher is Lecturer in Applied Economics at Bocconi University. She holds degrees in Economics from Bocconi, a Master of Science in Science and Technology Policy, from SPRU, University of Sussex and a PhD in Economics and Management of Innovation, Scuola Superiore Sant'Anna di Studi Universitari e Perfezionamento, Pisa. She has widely published on economics of innovation, industrial economics, and green innovations and sustainable development.

Franco Malerba is Full Professor of Applied Economics and President of ICRIOS, Bocconi University. He is editor of several technology journals. He has been President of the European Association of Research in Industrial Economics and of the International Schumpeter Society. He has worked at Stanford University; Max Plank Institute-Jena; University of Queensland; University of Stellenbosch and among others. He won the Schumpeter Prize in 2012. Research interests include innovation and technological change, industrial dynamics, economic development and catch-up.