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# Electrical transition in transport: Extent, causes and prospects for diffusion of electric bicycles in China

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**Approved by**

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## Abstract

What is the extent of diffusion of electric bicycles in China and the prospects for the future? What were the causes for that growth and the environmental impacts? Recently, electric bicycles have been an enormously successful in China, selling dozens of million units per year after a couple of years. Its installed capacity is so important that is consistent with the historical scaling dynamics observed in energy-supply technologies. Cost reductions and technology improvement, as well as income increase and air pollution in the cities helped to boost demand for those bicycles. The logistic model is used to understand the dynamic of diffusion. It was found that e-bicycles still have potential for diffusion in China and elsewhere, although the saturation level remains uncertain. At the regional level e-bikes could replace bicycles in the market. However, the increase of emissions in electricity generation—especially when the majority of it comes from coal—mitigates the benefits of e-bikes in terms of cheap and efficient mobility. Finally, the rapid diffusion of such a small, simple and affordable technology gives an important lesson for the diffusion of low-carbon innovations in the future.

**Keywords:** Technological change; diffusion; logistic model; economies of scale; electric bicycle.

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# Electrical transition in transport: Extent, causes and prospects for diffusion of electric bicycles in China

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## 1. Introduction

The need to reduce transport emissions in order to avoid "dangerous climate change" (IPCC, 2007) , as well as the raising awareness of the external cost of fossil fuels (e.g., air pollution, impact on health, security costs), challenge the current mobility paradigm while calling for a systematic response that comprises both technological and behavioral change. Rapid urbanization—the urban population is expected to reach 60% of the world population by 2030 (United Nations, 2010)—especially in the developing countries, exacerbates environmental and transit problems in the cities.

The recent diffusion of electric bicycles (e-bikes) in China provides an interesting field of research because it offers a solution to the rising need for (cheap) mobility without adding to increasing traffic and environmental problems in the cities. Annual sales passed from less than a hundred thousand units to 25 million units between 1998 and 2010 (Jamerson and Benjamin, 2011). China had around 500 million bicycles and in 2010, there were over 120 million e-bikes.[1]

The success of e-bikes gives hope that a large-scale transition in transportation is feasible in a reasonable period. That may be only possible under certain conditions, thus the study of those conditions is essential to understand the mechanisms that will be needed to promote a more sustainable transport system in the future.

This article is focused on the historical diffusion of e-bikes, discovering how the market evolved both in terms of time and space with the help of standard epidemic models. Particularly the investigation addresses the following questions: What is the scale of diffusion of e-bikes in China? What explains the rapid diffusion of e-bikes which only needed a couple of years to have a sizeable impact in the market? What are the impacts in terms of sustainability? And what are the prospects for the future? The diffusion of e-bikes gives a particularly interesting field of application for the technological change and innovation theories through the understanding of the mechanisms that interacted together to enable a fast diffusion of the technology. Understanding the way technologies evolve in transport allows the design of better informed policies that can help the development of more sustainable transportation, particularly in developing countries, where higher needs of transportation must be satisfied in the next decades.

The article starts with an overview of the recent story of e-bikes in China. The diffusion of e-bikes is examined in a quantified manner later in order to understand the technological progress in the cycle industry. The methodological framework is

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[1] "China's electric-bicycle boom - Pedals of fire", *The Economist*, 13/3/2010.

explained, preceding the presentation of results and a discussion of possible scenarios for the future before concluding.

## 2. The emergence of electric bicycles in China: An overview

Electric bicycles are two-wheel vehicles propelled by human pedalling and by electrical power from a storage battery—it can also include scooters moved exclusively by an electrical engine. E-bikes' main components are a hub motor, controller and battery. In regulatory terms e-bikes are normally considered as bicycles not requiring helmet or driver's license. Even though the maximum speed can be limited to 20 km per hour, in practice speed varies from 25 to 40 km/hr and range between 25-50 km (Weinert, 2007).

E-bikes are a convenient and inexpensive form of private mobility. They are more expedient than walking or cycling for urban commuting because e-bikes cover a longer range, are faster and more convenient for climbing uphill. It reduces the effort spent in travel, thus enabling women and elderly people to cycle more. In fact the main advantage over regular bicycles is the propulsion assistance given by an electric engine which can be activated whenever the rider faces a gradient, wants to go slightly faster or feels tired. The fact of not relying uniquely on human power allows for a more comfortable ride and a longer range compared with a regular bicycle. In addition, the use of e-bikes increases the access to other public transport infrastructures such as railways and bus stations (Parker, 2011).

E-bikes allows for a softer and greener urban commuting comparing to motorcycles, with the possibility of using cycling paths or special bus lanes. Very importantly, the operating costs are cheaper than for motorcycles and e-bikes can be refuelled at home without the need of conventional fuels, which is an interesting advantage in times of uncertain oil prices (although the superior performance of motorcycles are an important limiting factor for e-bikes). Electric bicycles can therefore be considered a substitution technology for the other two-wheeler technologies, although not entirely because it is very likely that owners also have a spare bicycle at home. Surveys indicate that 70-80% of e-bike users in China have switched from bicycles and public transport (Cherry, 2007; Weinert, 2007).

Environmental benefits in terms of zero carbon and air pollutant emissions, along with raising traffic concerns in rapidly growing cities, e.g., Beijing, have led to some political support for e-bikes in the form of the easing of regulations (e.g., drivers licenses are not required) and allowing the use of the infrastructure for bicycles or public transport (see box 1). Still there are some issues to solve, such as battery recycling and lead-emissions, particularly in China where 95% of the batteries used in e-bikes are of the lead type (Cherry, 2007). There are also some issues with safety and traffic management because e-bikes move quietly and fast with poor quality brakes, which can be dangerous in mixed traffic both for cars and e-bikers, with resultant accidents and fatalities.[2] In sum, the overall benefits of e-bikes tend to overtake their limitations, which explain why the two-wheelers are becoming an important alternative means of transport in some regions.

[2] Nevertheless, evidence shows that several bicycle and e-bikes friendly countries in Europe present low road death rates per 100,000 population, e.g., 2.9 in the United Kingdom or 3.9 in the Netherlands compared to 6.2 in Australia or even 10.5 in the U.S. (Parker, 2011).

**Box 1. Recent history of e-bikes in China: selected events**

| *Year* | *Event* |
|---|---|
| 1991 | National science Board names e-bike as one of 10 main technology projects during 9th 5 year plan period |
| 1993 | Hubei founded the "Leading Team for the electric vehicle (EV) development |
| 1993 | Shanghai founded electric vehicle industrialization development center |
| 1994 | Shanghai lost automobile research bid for developing electrical vehicles to Guangzhou, turns to developing e-bikes (Crane) |
| 1995 | Electric vehicles receive support from prime minister Li Pong. This led to Seminar for electric bike development in Light Industry General Society (part of Economy and Trade Committee) |
| 1995 | 100 Beta-test Crane bikes are deployed |
| 1996 | First national forum on e-bikes held |
| 1996 | Shanghai suspends license granting to gas-powered vehicles downtown, Mayor Xu Kuangdi declares to gradually eliminate gas-powered assist vehicle and actively develop and promote electro-assist technology |
| 1997 | Crane rolls out first batch of commercial e-bikes (150-180 W motor, 7Ah battery cap., 24V) |
| 1999 | Shanghai Economy and Trade Committee lists e-bikes as one of 12 main construction projects in the "Highland" |
| 1999 | E-bike licenses are granted in Shanghai, Tianjin, Jiangsu, Zhejiang, Guangdong, Cichang, Yunnan, Anhui, Hebei |
| 2000 | Legislation Office under Department of State Traffic Control Bureau drafted "Road Traffic Law" to allow e-bikes to use bikes lanes as long as they have pedals and that speed is no more than 20 km/hr |
| 2000 | Shanghai hosts first International EV and components Expo |
| 2000-02 | Beijing, Hanzhou, Tianjin, Guangzhou ban sale and driving of fuel assist vehicles |
| 2002 | Beijing issues a ban stating they will cease offering licenses beginning 2006, Beijing Communicative Administration Department |
| 2002 | "The Fuzhou Accident": Fuzhou government bans e-bikes from streets but is later taken to court by a group of e-bike OEMS and citizens. |
| 2003 | E-bike sales spike after the outbreak of SARS and abnormally hot summer |
| 2004 | Electric moped prices drop 15% (from 2200 to 1870 RMB average price) due to production surplus |
| 2005 | E-bikes banned in Zhuhai city of Guangdong Province. |
| 2006 | Jan 4, Beijing Public security Bureau lifts ban on e-bikes |
| 2007 | 2,500 e-bike-related deaths |
| 2010 | January, the number of e-bikes in-use reached 120 million units |
| 2011 | The China central government forced 90% of the country's Lead-Acid battery plants to shut down their operations |
| 2011 | The dramatic rise of costs for rare earth materials, specifically Neodymium (Nd, 60), puts pressure on the price of e-bicycles (Nd metal is about 35% of the content of a NdFeB magnet). |

Source: various press; Weinert, 2007; Guo, 2000.

## 3. Methodology

This study investigates the scale (actual and ultimate prospect) of diffusion of e-bikes, as well as causes and consequences of their adoption, particularly in China where most of the diffusion took place. The analysis applies epidemic logistic models to identify the rate and the extent of the diffusion of bicycles and electric bicycles. The logistic model is essentially descriptive and it does not provide any explanation for the factors that drove the diffusion. Therefore the causes of diffusion are interpreted using standard economic theories (e.g., economies of scale), as well as theories developed within the diffusion literature, particularly innovation and evolutionary theory.

### 3.1. Innovation diffusion and technological change theory

Technological change is usually represented in the literature as a process of several phases. The origins of this vision go back to Schumpeter (1942) who distinguished three stages in the complex process of innovation: invention, the time of the creation of the idea; innovation, the period of economic valuation of the new concept; and dissemination through user adoption and competitor imitation (Freeman, 1982). However, the new technology can only produce a sizeable effect in real life with diffusion.

The potential for diffusion depends on a multitude of factors including price and performance, which influence the relative advantage of a particular innovation over its competitors (Rogers, 1995). Those attributes are not static but rather evolve through time (Nelson and Winter, 1982). The technology development in the market is normally classified in three phases: childhood, adolescence, and maturity -followed eventually by substitution (Grubler, 1998). In the childhood phase the technology can only penetrate in a few niche markets. A diversity of models is experimented within a very dynamic environment. There is a lot of uncertainty surrounding the evolution of the technology and the market. Meanwhile the technology ameliorates in these niches through R&D and learning. Eventually a rupture innovation will improve the economics of a particular design allowing it to accumulate more niche markets (Geels, 2005). The adolescence period is characterized by a concentration of the industry in few numbers of designs which present better attributes (Abernathy and Utterback, 1978; Utterback, 1994). Incremental innovations both at the product and process level result in lower prices and better performances and lead to a rapid market growth. Finally, the technology reaches maturity when the growth rates of sales slowdown and it becomes more difficult to introduce incremental innovations. Therefore competition is focused on price and costs reductions, and production is concentrated in a few number of producers trying to benefit from scale economies. Eventually an innovation that has been previously developed at niche levels will scale up and replace the old technology in the main markets (Marchetti and Nakicenovic, 1979).

A few radical and incremental innovations were decisive in the evolution of bicycles (Freeman, 1982; Freeman and Perez, 1988). The invention of the rubber tire in 1888 marked a turning point in the competition between different types of pedaling machines, influencing decisively the beginning of a new trajectory in the cycling industry (Nelson and Winter, 1982; Dosi, 1988). In the 20th century, refinements in brakes, gears, upgrades and add-ons, frames, etc., further improved the safety, performance and comfort of the machine, contributing to sustain the diffusion for a longer time. However, by this time new competitors, such as motorcycles, had already begun to challenge the role of bicycles in personal transport. Meanwhile the introduction of electrical assistance to pedaling improves the comfort and the efficiency of the regular use of the bicycle, and may open a new trajectory for the future.

In the last decade electric bicycles (e-bikes) have been intensively diffused in China, thus raising the question of whether they are going to replace bicycles or act as a technological evolution in the "electricity era" to compete against motorized vehicles. If the latter is the case, the emergence of a new electric type would spark a new phase of growth for bicycles and delay the saturation stage.

### *3.2. The logistic model*

The analysis mobilizes theories and instruments from the innovation and diffusion theory. The research uses logistic growth models to fit actual data in order to identify patterns in the historical growth of bicycles and e-bicycles. The examination of simple growth rates would be quite volatile and influenced by short-term variations; instead fitting data with logistic functions can more reliably identify long term tendencies.[3] There is a wide range of evidence supporting the use of the three-parameter logistic function to represent long term technological transitions, namely in the energy and transport field (Grubler, 1999, 1998; Marchetti and Nakicenovic, 1979). This function is inspired by the logistic model (Fisher and Pry, 1971)—an S-shaped model assuming symmetry around the inflection point—representing technological diffusion as follows:

$$y = \frac{K}{1 + e^{-b(t-t_0)}}$$

where :

$K$ = saturation level (asymptote)

$t_0$ = inflection point at K/2

$b$ = diffusion rate (steepness of the S-curve)

$\Delta t$ = time period over which $y$ diffuses from 10% to 90% (or similarly from 1% to 50%) of its saturation level ($K$), and $\Delta t = \frac{1}{b} log81$

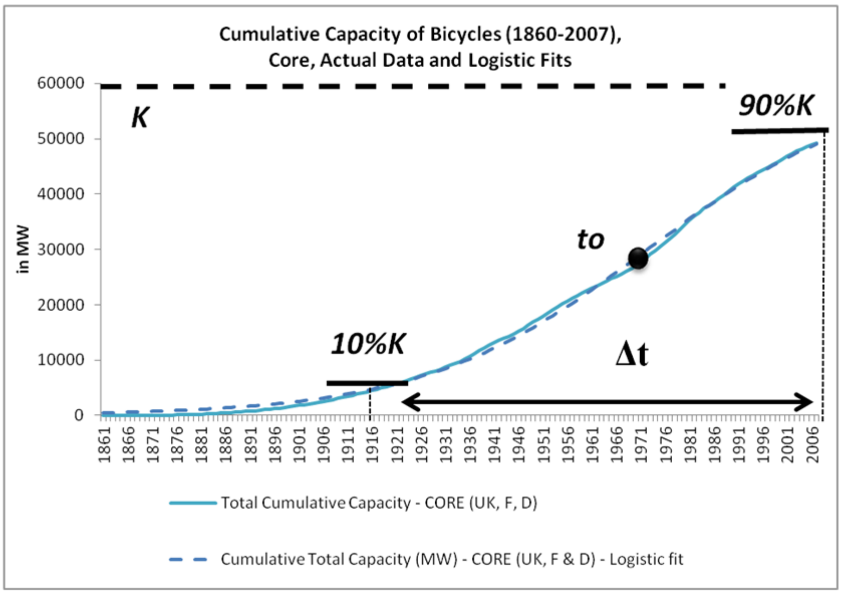
The procedure consists of fitting a logistic curve to variable $y$ which represents the cumulative production or technological capacity (in this case, megawatt (MW) is the specific unit). The logistic function provides information about the extension and the speed of diffusion. The parameter K gives the saturation level of diffusion, while the delta T (or Δt) is a measure of the time duration of diffusion—more precisely from 10% to 90% of saturation—which is inversely proportional to the rate of diffusion with higher Δt values meaning slower diffusion. Figure 1 provides an illustration of the use of logistic curves to fit the growth of cumulative capacity of "ordinary" bicycles in order to get the parameters of diffusion.

The comparison between the parameters K and Δt (extent-diffusion rate relationship) allows the understanding of the importance of economies of scale for the technological potential. Hence, the term 'scaling' as used in this context represents the technological growth that is both rapid and extensive and occurs at multiple levels (the technology unit and the industry as a whole). The historical scaling methodology has shown very

[3] Other models, such as the Gompertz or Sharif-Kabir, can also be used though the logistic function fits the data better and thus was chosen for this study. See Grübler (1998) for more details about diffusion models. Various diffusion models were tested with the help of the Logistic Substitution Model (LSM II) model developed in-house at the International Institute of Applied Systems Analysis (IIASA) which is also available online at http://www.iiasa.ac.at/Research/TNT/WEB/Software/LSM2/lsm2-index.html?sb=3

robust results in the case of energy technologies, such as nuclear plants or coal plants (Wilson and Grubler, 2011). Among other aspects, it showed clearly that technologies with greater overall market potential take more time to diffuse. One of the aims of the present research is to apply this methodology to the study of "soft" means of transportation, such as e-bikes, and to compare their diffusion with other technologies.

**Figure 1. Illustration of the fitting process with logistic curves: the case of bicycles**




The energy conversion assumed an average power of 100 W per bicycle. See Section 3.3 for more information on sources and assumptions.

Finally, the diffusion is analyzed both at global and regional level. Theoretical and empirical studies suggest that adoption originates in innovation centres within core areas and then spreads out via a hierarchy of subcenter regions until it reaches the periphery (Hägerstrand, 1967; Grubler, 1998). The timing and intensity of the diffusion are not uniform in space. The periphery benefits from the learning gained in former regions and presents faster diffusion rates, however, the intensity of diffusion is lower than in the core area (Grubler, 1998). Therefore the countries are organized into two main regions—Core and Periphery—according to the order of diffusion of e-bikes by region.

### *3.3. Data, main assumptions and sources*

The following analysis takes into account the number of electric bicycles produced instead of the volume of sales or the number of e-bikes in use. Several reasons explain that choice. The most important is that statistics on production are more available and reliable. Also the study of production is more relevant for the scaling analysis and the comparison between different technologies.

Data on the number of e-bikes came principally from Weinert (2007) as well as various sources for more recent years. The series starts in the late 1990s when the annual production passed from 10–20,000 units per year to several thousand to million units. For bicycles, data were mainly taken from the United Nations Industrial Commodity Statistics database—online and published by the United Nations (2008)—and the UN Statistics Yearbooks (various years). For the earlier years information was collected in the literature and in contemporary press. Further details on data sources can be found in the supplementary material.

There are different types of electric bicycles according to the size of the electrical motor. The more powerful e-bikes can look more like scooters while others appear more like regular bicycles (more common in Europe). In China the market is mainly split between two types of e-bikes: 250W or 500W. After research in the literature and in the press, as well as a personal communication from a Chinese e-bike expert (Jonathan Weinert), market shares were estimated at 25% and 75% for 500W and 250W e-bikes, respectively. On the other hand, the power of the conventional bicycle is fixed at 100 W, which corresponds to the average power that a normally fit person can sustain during an hour without feeling exhausted at the end (Wilson et al., 2004). Finally, missing data was completed using interpolation and best fit techniques. Results are presented in the following sections.

## 4. The diffusion of electric bicycles

This section is focused on the quantification of the electric bicycles' diffusion, as well as the understanding of the factors that enable the rapid transition. A comparison to other technologies, such as bicycles and energy supply-technologies, permits to assess the scale and speed of the diffusion. The section ends with a discussion on the impacts that the massive diffusion of e -bikes has on the environment and transportation.

### *4.1. Actual data and fits*

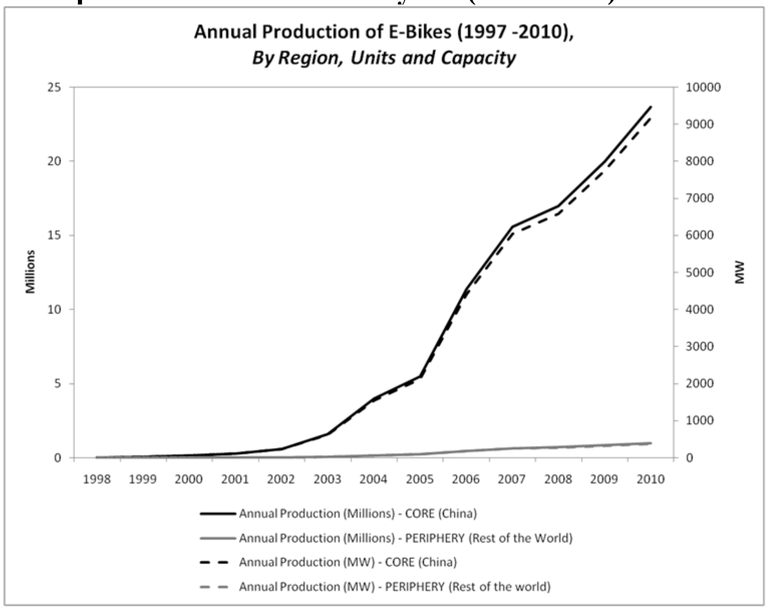
Electric bicycles saw an enormous acceleration of diffusion in the last fifteen years. This is particularly the case in China where about 120 million units are in use today, which comprise 96% of the global market.[4] Therefore, China is defined as the Core region of the diffusion, and the rest of the world (e.g., United States, Western Europe, India) is included in the Periphery area. Figure 2 shows the evolution of e-bikes production since 1997—production numbers are a good proxy for domestic sales because exports were relatively small during that period.

The market for e-bikes has soared over the past 15 years, passing from a couple of thousands of units in 1997 to more than 20 million in 2010. In terms of cumulative capacity (electric motor – equivalent), around 10 Gigawatts were produced globally by 2010 of all different types of electric bicycles (Figure 3).

Figure 4 shows the evolution of cumulative production between 1997 and 2010, as well as the logistic fits, both in terms of million units (upper graph) and capacity measured in megawatts (bottom graph).

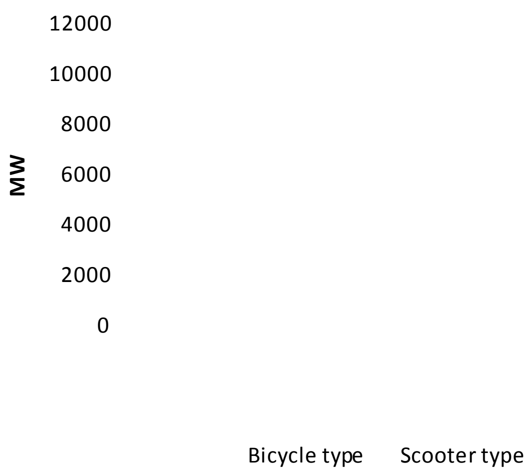
[4] cf. "An Electric Boost for Bicyclists", The New York Times, 31/1/2010, http://www.nytimes.com/2010/02/01/business/global/01ebike.html (last accessed in 7/10/2011)

**Figure 2. Annual production of electric bicycles (1997-2010)**



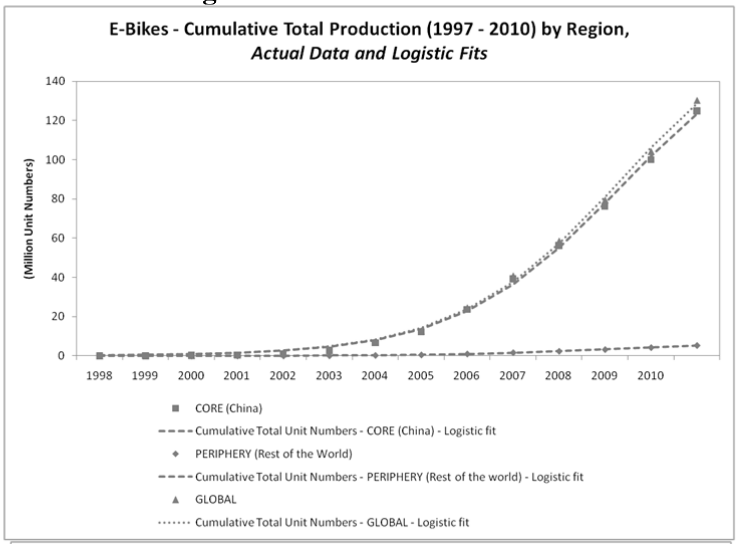

Sources: Jamerson and Benjamin, 2011 ; Weinert, 2007.

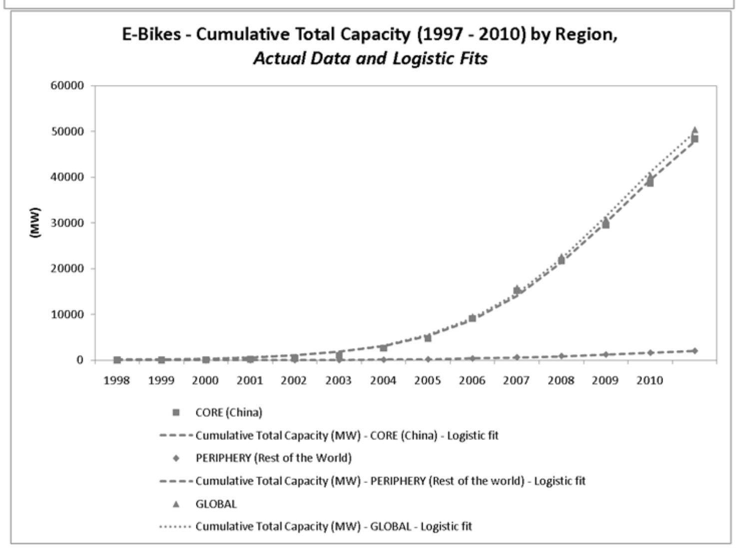
**Figure 3. Cumulative production of e-bikes in China (1996-2010), by type**




Source: idem; see text.

**Figure 4. Cumulative production of e-bikes expressed both in unit numbers and capacity – actual data and logistic fits**




The parameters of the logistic curves are presented in Table 1. The projected saturation levels (K) of total cumulative millions of sales—if e-bike growth continued to follow an S-shaped logistic curve—are 171.6 (Core), and 7.2 (Periphery), corresponding to 66,498 and 2,770 MW, respectively. The diffusion rates (Δt), defined as the number of years necessary to pass from 10% to 90% of the saturation point (or equivalently from 1% to 50%), areidentical for both regions and equal to 8 years. The inflection points ($t_o$) where the cumulative production reaches 50% of its potential (coinciding with the point of maximum growth) are also similar and correspond to year 2008. The fact that all parameters but one (saturation) are the same reflects the method used to breakdown production between the different regions, assuming that the share of China in global production (96%) remains the same over time. The reliability of the logistic curves are ensured by a coefficient of determination ($R^2$) higher than 99% for all fits, and existing data up to 2010 covering more than 60% of the saturation levels (see "Actual % of K").

**Table 1. Parameters of the logistic curves**

| | Actual % of K (as of 2010) | K | $t_0$ | $\Delta t$ | $R^2$ |
|---|---|---|---|---|---|
| *GLOBAL* | | | | | |
| Gross Total Capacity (MW) | 73% | 69270 | 2008 | 7.9 | 99.9% |
| Gross Total No of Units (#) | 73% | 179 | 2008 | 7.9 | 99.9% |
| *CORE (China)* | | | | | |
| Gross Total Capacity (MW) | 73% | 66499 | 2008 | 7.9 | 99.9% |
| Gross Total No of Units (#) | 73% | 172 | 2008 | 7.9 | 99.9% |
| *PERIPHERY (Rest of World)* | | | | | |
| Gross Total Capacity (MW) | 73% | 2771 | 2008 | 7.9 | 99.9% |
| Gross Total No of Units (#) | 73% | 7.1 | 2008 | 7.9 | 99.9% |

The diffusion was very rapid, taking on average 8 years to reach half the market potential ($t_0$) in the different regions. The domination of the Core may continue in the following years. Unless there are any structural changes, annual production should saturate at 172 million units in China (Core), and 7 million in other regions (Periphery). Let us turn now to the analysis to the factors that explain this spectacular performance.

### 4.2. Drivers of the diffusion

The rapid diffusion of e-bikes in China is due to a combination of several factors that act together to create a favourable context for adoption, among them: low costs of the technology, rising transport demands, and local regulation.

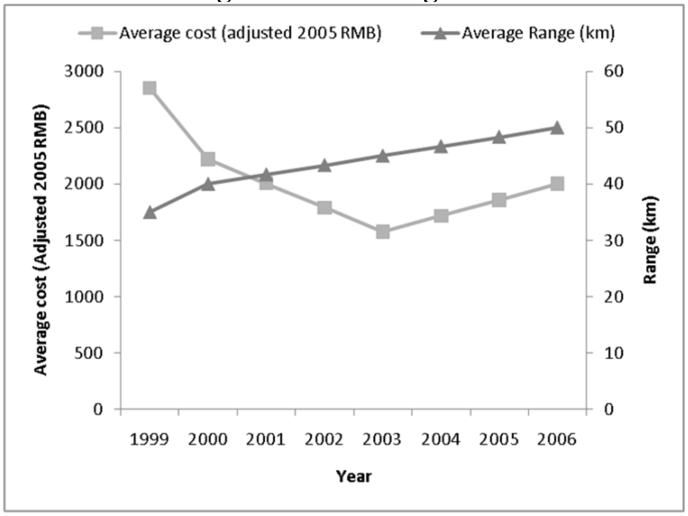
The low and declining cost of e-bikes has been an important factor in boosting sales and production (Figure 5). The average price of the bicycle–a good proxy of production costs in a very competitive market with low profit margins—declined one third from 2900 to 2000 RMB (constant prices of 2005) between 1999 and 2006.[5,6] Furthermore, the increase in fuel costs (e.g., in 2002 fuel prices increased 45% in Shangai) worsened the operational costs of motorized vehicles. This trend consolidated the price advantage of e-bikes over technologies such as motorcycles or cars, while making it even more attractive to bicycle commuters and public transport users. At the same time, the average performance of e-bikes measured in terms of range autonomy with only one

[5] Converting to Euros (2005): 280 EUR in 1999 and 197 EUR in 2006, at the rate (RMB/EUR) of 10.1955. Source: European Central Bank, http://sdw.ecb.europa.eu/quickview.do?SERIES_KEY=120.EXR.A.CNY.EUR.SP00.A, last accessed in July 12, 2011. Or alternatively in US dollars (2005): 348 and 244 USD respectively, at the rate (RMB/USD) of 8.1917. Source: National Bureau of Statistics of China, 2011. In 2012, an entry-level electric bicycle sold in the U.S. is priced around 1,000 USD, while a higher-end e-bike can cost 5,000 USD. Source: "Can E-Bikes Displace Cars?," Scientific American, 22/2/2012 http://www.scientificamerican.com/article.cfm?id=can-ebikes-displace-cars (last accessed in 19/12/2011)

[6] The prices shown are average prices of e-bikes and thus should be read with care. The low-end products cost 30% less than average, and the high-end e-bikes 30% more. Thus the increase of the price (in real terms) between 2003 and 2005 can have multiple explanations. For instance, in 2004 the electric moped prices dropped 15% from 2200 to 1870 RMB due to production surplus (Weinert, 2007).

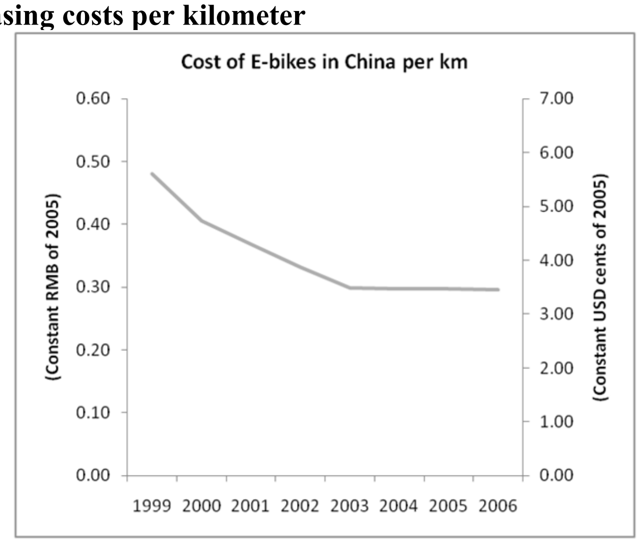
charge increased significantly from around 35 to 50 km, while battery life expanded 35% to over 300 cycles (Weinert, 2007).

**Figure 5. The evolution of average costs and range of e-bikes* in China**




Source: Weinert, 2007; Jamerson and Benjamin, 2011.
*Featuring lead-acid type of batteries.

**Figure 6. Decreasing costs per kilometer**




Note: Owning and operating costs of e-bikes, assuming annual mileage of 3000 km and vehicle lifetime of 5 years. In 2006 lead-acid type batteries could last for 300 cycles (~2 years), which is roughly twice longer than 10 years before (Weinert, 2007). Thus it was assumed a continuous annual improvement of batteries of 10%. Battery costs were assumed stable across the period of 80 USD (655 RMB). Constant prices of 2005 were considered and the exchange rate for that year was 8.2 RMB per one USD. Fuel costs were calculated assuming a consumption of 0.016 kWh/km and the cost of 0.696 RMB per kWh (Cherry, 2007).

Both the decreasing vehicle cost and continual incremental innovations, especially at the battery level, were important for the success of e-bikes in China. In fact the cost per km dropped between 1999 and 2006, contributing to higher sales (Figure 6). However the success would have not been possible if the industry had not scaled up quickly and mass commercialized e-bikes in a matter of years. The modular architecture of e-bikes—integrating well-known battery technology in existing bicycles or moped models—enabled a rapid standardization of the product and a flexible production system, which explains the existence of a large number of producers and assemblers in China. In turn the competitive market was favourable to a rapid adoption of incremental innovations and to keeping prices low (Weinert, 2007).

The cheap price of e-bikes was a decisive factor in the context of a low, though rapidly increasing, income country. Between 1997 and 2008, annual per capita disposable income of urban households increased around 145%, which contributed to raise the demand for mobility in the cities.[7] During this period, the part of income spent on transportation and communication increased 142% from 5.2% to 12.6% (National Bureau of Statistics of China, 2009). The growing urban and traffic patterns were further enhanced by the liberalization of the housing market after the mid-1990s which gave workers the ability to live farther from workplaces.

The rapid urbanization worsened traffic problems and air quality of the cities. In response some local authorities, e.g., Shanghai and Beijing, promoted e-bikes by the means of motorcycle bans or loose enforcement of e-bike standards. Hence, regulation provided further impetus for growth in demand and technological improvements of e-bikes.

### 4.3. Are e-bikes slowly replacing bicycles?

We turn now the analysis to the comparison between the diffusion of e-bikes and the diffusion of other technologies to assess the real scope of the technological change. This point is focused on the diffusion of e-bikes related to the previous diffusion of bicycles, one hudred years earlier. An additional question is raised about whether electrical bicycles are a complement or a substitute for bicycles. The comparison with other technologies, namely energy technologies, is explored in the next section.

Table 2 summarizes the results of the logistic curves that fit the actual data on the global diffusion of bikes and e-bikes.

**Table 2. Parameters of diffusion of bicycles and e-bikes globally**

| Technology | Saturation (K) - millions | Actual % of Saturation* | Δt (years) | $t_0$ (year) |
|---|---|---|---|---|
| Bicycles | 4,501 | 77% | 62 | 1994 |
| E-bikes | 179 | 73% | 8 | 2008 |

* Calculated at 2010 for e-bikes and 2007 for conventional bicycles.

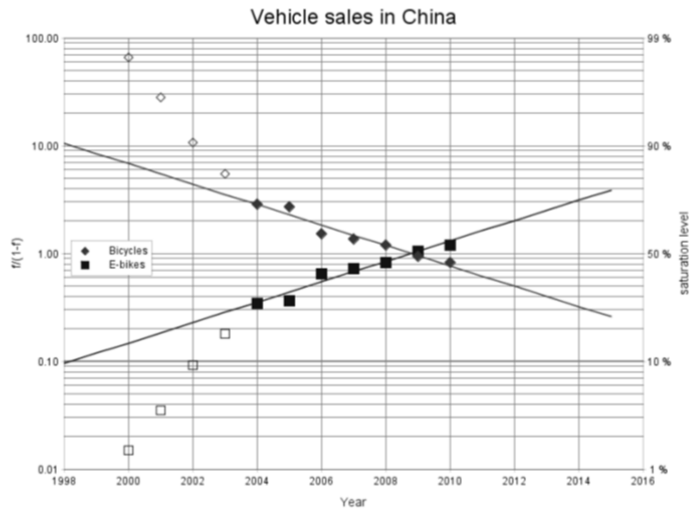
The analysis confirms the spectacular diffusion of e-bikes in the past decade taking only 8 years to reach more than 73% of saturation. Bicycles took much more time to diffuse than e-bikes, though the intensity of diffusion is incomparably higher. The logistic analyses suggest that there is still room for diffusion of both technologies, but bicycles

[7] The index of per capita annual disposable income of urban households increased 162% from 311.9 to 815.7 between 1997 and 2008 (1978=100), while the Consumer Price Index (CPI) rose 17% from 481.9 to 563.5 over the same period (1978=100). See: National Bureau of Statistics of China, 2009.

will have more potential to grow—in unit terms—than e-bikes. This growth may come from actual bigger manufacturers like China and India, as well as emerging economies in Africa and South America.

It is interesting now to investigate the situation in China which is the biggest market for both types of bicycles. The following graph shows a likely evolution of sales of e-bikes and bicycles in China in the years to come taking into account recent trends.

**Figure 7. The competition between bicycles and e-bikes in China**




Note: The graph is plotted accordingly the *logit transform* as in Fisher and Pry (1971). The division of the market share (F) by the remaining market share (1-F) yields a straight line when plotted on a logarithmic scale.
Sources: Weinert, 2007; National Bureau of Statistics of China, 2009; Jamerson and Benjamin, 2011.

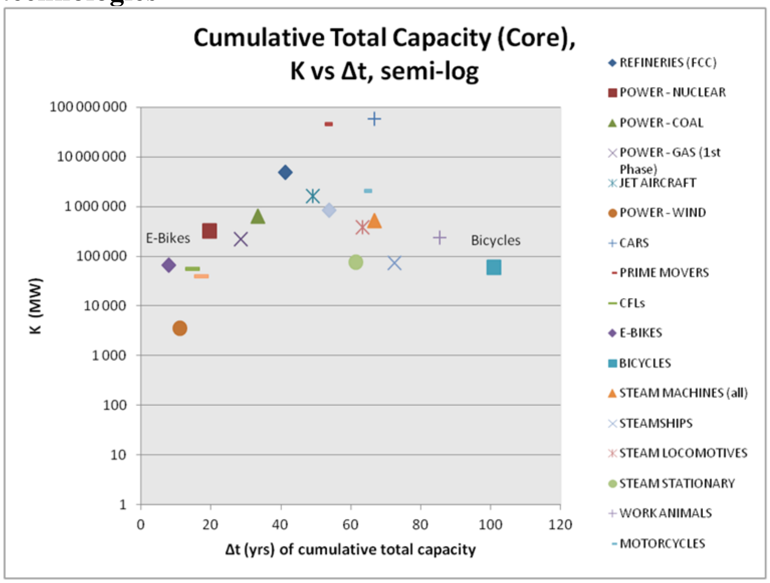
If the current trend is going to be followed, e-bikes would take a significant share of the overall bicycle market by 2020 (Figure 7). Even though the production of conventional bicycles is going to increase in China, e-bikes are becoming more popular than bicycles in the domestic market. This would mean that an increasing share of bicycle production will go to exports. On the other hand, the substitution of bicycles by e-bikes is likely to have consequences in terms of sustainability. Before analyzing those impacts, let us compare the diffusion dynamics of e-bikes with the historical diffusion of a few key energy technologies.

### 4.4. Comparing the scale of diffusion with other energy technologies

How the diffusion of electric bicycles compare with other technologies? One important feature in diffusion of technologies is the relation between the scale and the rate of the diffusion (Wilson and Grubler, 2011). If the scale and the time of diffusion are related, then it is expected that the potential of a technology is related to the time it needs to diffuse, i.e. a technology with a tremendous absolute market potential would take more time to diffuse than another one with a lower saturation level. Previous analyses have confirmed this effect for energy technologies (Wilson and Grubler, 2011).

Figure 8 compares the scaling effect in bicycles and e-bikes globally with other technologies especially energy technologies. The saturation level (K) is expressed in terms of power capacity in megawatts.[8] In the case of bicycles, the conversion of the number of bicycles into power capacity was done assuming the rate of 100 watts per unit, corresponding to the average power a person can deliver continuously during one hour without being exhausted (Wilson et al., 2004).

**Figure 8. Historical scaling comparison at industrial level between bicycles, e-bikes and energy technologies**




Source: author; Wilson and Grubler, 2011.

The diffusion of e-bikes was so intensive within a decade that followed the same trend as energy technologies. The latter naturally have much more importance in terms of power capacity, so they needed more time to diffuse. This empirical analysis reveals a trend towards the upward right-side of the graph. If the relation seems strong for electric technologies, the same does not hold for bicycles, which took more time to diffuse for a lower capacity potential. This is particularly the case when compared with e-bikes, which needed much less time than bicycles to have a bigger effect in terms of capacity installed. Nevertheless, one should keep in mind that bicycles are a human-propelled technology affected by the low energetic efficiency of humans.[9,10]

Another conclusion can be drawn from the comparison between the diffusion of e-bikes and other technologies. The intensive diffusion of e-bikes provides some valuable insights for the transition to low-carbon (electric) transportation or energy technologies.

[8] For a more complete explanation of the scaling methodology see Wilson and Grübler, 2011.
[9] In that case, e-bikes should be considered as "partial" human propelled vehicles because they give to users the possibility of switching from the electric propulsion mode to electric assistance pedalling or pedalling without assistance. This debate is not addressed in the present paper.
[10] An alternative explanation for this apparently contradictory result takes into account the power of alternative technologies to perform the same service (mobility) instead of taking the unit capacity of the bicycle (100 W). One can argue that e-bikes and motorbikes are a suitable substitute for bicycles. In that case, the unit capacity of a bicycle would pass from 100 watts to 250 or 500 watts—a factor of 2.5 or 5 more—equivalent to regular e-bikes that are sold in China. Alternatively, bicycles could be compared to mopeds and motorcycles with more than 2 kilowatts of power, thus multiplying by 20 the unit capacity of bicycles. This would bring bicycles closer to the overall trend observed in other technologies.

This result suggests that innovation penetration may be faster in the case of a small, simple and affordable technology, over more centralized and large-scale projects. The production of the smaller ones is much easier to start and scale up without the need of a costly public support, while the failure is less costly compared to the technologies of a bigger size. More research is needed in the future regarding the comparison between the historical diffusion of small and large-scale technologies.

In sum, the growth of e-bikes in the last decade was enormous, both in terms of units and installed capacity, and was comparable to the extent of diffusion of supply-energy technologies. Even though the production of both technologies may increase in the coming years, bicycles seems to have more potential to grow globally than e-bikes. This tendency may vary at regional level, as in China where e-bikes are expected to take a significant share of the market with important impacts in transportation and energy consumption.

### 4.5. Sustainability impacts

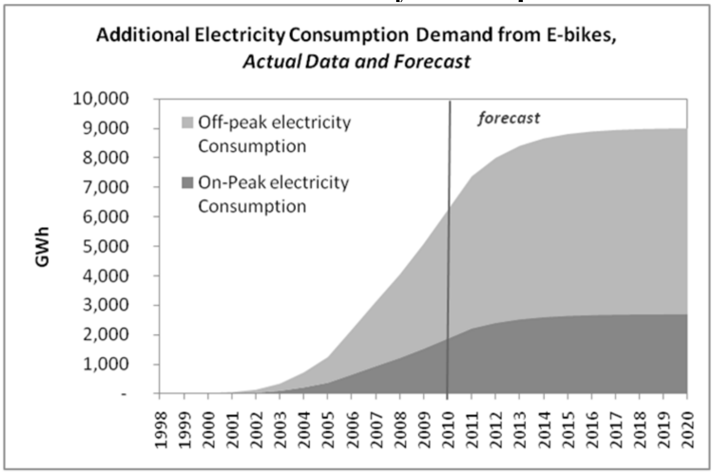
The diffusion of e-bikes at large-scale in China helped to alleviate the pressure on China's public transport system and lower the number of motorized vehicles, e.g., motorcycles, on the roads of its main cities. Therefore it played a significant role in terms of traffic management and air quality improvement in urban areas. Nevertheless, the diffusion of electric bicycles raised also other issues mostly related to the emissions originated by the additional electricity production, as well as the use of pollutant materials in the batteries.

Firstly, the growing fleet of e-bikes in China multiplies the need to recharge from the grid. The increased electricity consumption will add to the already rising power needs in other sectors. E-bike electricity consumption was 6.2 TWh in 2010, more than 22 GWh per day, which is far from being negligible (Figure 9).[11] Considering the number of e-bikes previewed for the coming years, it is expected that the consumption will reach 9 TWh per year by 2020. Because of the role that coal power plants have in the Chinese electric mix, the additional power demanded from e-bikes will rise carbon emissions.[12] Moreover it is important to know which transport e-bikes are likely to substitute: if they replace bicycles in the cities the overall greenhouse emissions will end-up being higher in the terms explained above; while if e-bikes substitute cars the impact on emissions will be positive, since $C0_2$ emissions per passenger-km of vehicles are an order of magnitude higher than of e-bikes (Ji et al., 2011) .

[11] This is in the scale that a 1GW nuclear reactor running 90% of time generates during a year (7,889.4 GW).

[12] Assuming 80% share of coal in the electricity mix, and an average conversion factor for coal power plants of 1 tonne of $CO_2$ ($tCO_2$) per 1 MWh produced, the 6.2 TWh of additional electricity consumed by e-bikes translates into 5 million $tCO_2$ or 0.06% of the $CO_2$ emissions in China in 2010 (cf. BP Workbook of Historical Data retrieved from www.bp.com last accessed in 4/11/2011). If the number of e-bikes increases as forecasted for the coming years, emissions would raise to 9 million $tCO_2$ in 2020.

**Figure 9. Estimate of the additional electricity consumption from e-bikes**




Note: The number of e-bikes in use was calculated from various sources. The time of recharge was split between off-peak and on-peak assuming 70% and 30%, respectively. The average mileage was assumed to be 12 Km per day, corresponding to an average speed of 12 km/hr and a daily travel time budget of one hour. Finally the energy consumption of Chinese e-bikes is assumed to be 0.016 kWh per Km including charger efficiency (Cherry, 2007).

Secondly, most of the e-bikes that have been sold in China are equipped with lead-acid batteries. This type of batteries is considerably cheaper than the lithium ones, what was a key factor in keeping the prices low (Weinert, 2007). Thus each bike uses an average of 13 kg (28.7 pounds) of lead[13] and is likely to change the battery at least once during the lifetime. In the absence of a well-established infrastructure that collects and treats old batteries, the risk of lead pollution is very high with important impacts on the environment.

In sum, the carbon emissions from the electricity generation and the disposable of batteries problem are both important issues that deserve a special treatment whenever the diffusion of e-bikes is going to be stimulated to improve air quality in the cities or manage traffic problems. In addition, the impact of e-bikes should be compared to the mode of transport that is likely to be substituted by this vehicle. In China, surveys indicate that e-bike riders were formerly using the bicycle or public transportation for daily commuting. Therefore, the transition to e-bikes should be carefully planned in order to ensure that the additional environmental problems raised by the diffusion will not outweigh the benefits of its utilization.

## 5. Scenarios for the next years: Is the future of the bicycle going to be electric?

The previous sections showed the impressive diffusion of electric bicycles, which reached significant levels of installed capacity in a very short period of time compared to the longer time that bicycles took to diffuse. This revolution was mainly restricted to a fast developing country, i.e., China, highly populated and facing increasing problems of air pollution and urban traffic management. Comfortable mobility and lower up-front

[13] According to Mackenzie Ltd. cited by "China's 150 Million Electric Bikes Bolstering Lead: Commodities," Business Week, Bloomberg, 14/12/2011, http://www.businessweek.com/news/2011-12-15/china-s-150-million-electric-bikes-bolstering-lead-commodities.html (last accessed in 19/12/2011).

capital and operational costs were the main drivers of the diffusion. Now that e-bikes are produced and sold on the order of tens of millions per year, it is interesting to investigate the ultimate impact of the diffusion in terms of transportation and energy consumption.

Several scenarios were considered for the development of e-bikes in the Core region (China). Firstly, there is a lot of uncertainty concerning the stabilization level of the market because the diffusion is relatively recent. Secondly, it is important to test the sensitivity of the logistic model to changes in parameters such as the rate of diffusion and saturation. The following points present a brief explanation of each scenario:

1) the first scenario considers a growth in e-bike production to a level that allows for the substitution of all bicycles in use in China (around 450 million). This is an optimistic exercise that underlines some substitution aspects between the two technologies. This assumption might be polemical since a lot of e-bike owners may have a second bicycle at home, which would be an argument more for the complementarity of both types of bicycles. However, if one thinks in terms of the purchasing decision of a poor household choosing between the two technologies for regular commuting, an obvious substitution process arises;
2) the second scenario looks at the sensitivity of results to a slight delay in the inflection point ($t_0$) of the diffusion curve from 2008 to 2011, i.e. 3 years later;
3) the third scenarios study the impact of a higher (3.a) and lower (3.b) rates of diffusion;
4) the last scenario assumes that e-bikes are going to substitute all two-wheelers, i.e. bicycles and motorcycles, in China (K=650 millions). This scenario analyses what could be the ultimate impact of e-bikes in this country, as well as the time it would take to produce enough machines to capture all the market.

The first scenario considers neither exports nor retirements of models produced in early years. Those assumptions are clearly unrealistic because China is the biggest exporter of e-bikes—though the weight of exports on production is still relatively small, i.e., less than a million e-bikes are exported annually while more than 30 million were produced in 2011—and the lifespan of e-bikes ranges between 5 to 10 years, lower in the case of the battery (Weinert, 2007). But these scenarios are helpful in order to estimate in a simple manner the maximum potential level of production as well as understand clearly how the diffusion would look like if the industry were going to supply such high numbers of e-bikes.

Figure 10 and table 3 summarizes the results for all scenarios under consideration.

**Figure 10. Scenarios for the evolution of the cumulative production of e-bikes in China**

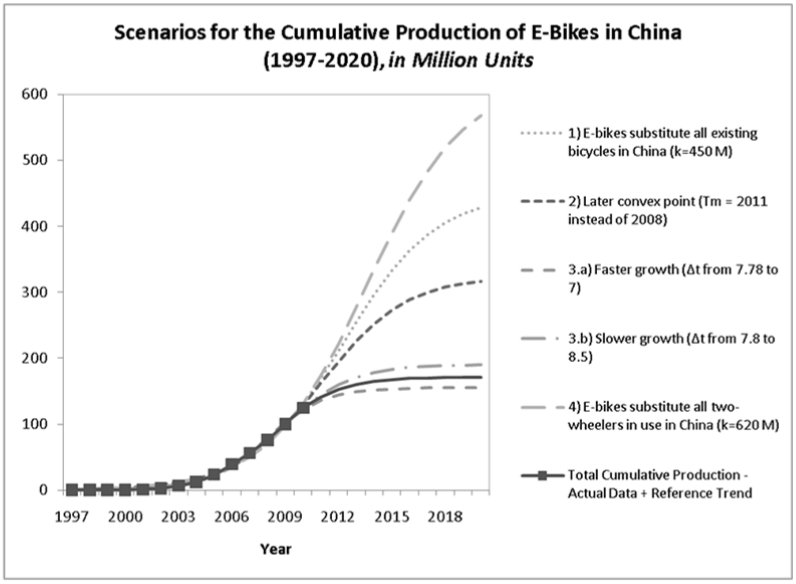



**Table 3. Logistic parameters of the diffusion curves from the scenarios**

| *Scenarios* | *Actual %K* | *K* | $t_0$ | *Δt* | *b* |
|---|---|---|---|---|---|
| 1) E-bikes substitute all existing bicycles in China (k=450 M) | 27.75% | 450 | 2012 | 11 | 0.39 |
| 2) Later convex point ($t_0$ = 2011 instead of 2008) | 38.51% | 324 | 2011 | 11 | 0.42 |
| 3.a) Faster growth (Δt from 7.78 to 7) | 80.44% | 155 | 2008 | 7 | 0.63 |
| 3.b) Slower growth (Δt from 7.78 to 8.5) | 65.54% | 191 | 2009 | 9 | 0.52 |
| 4) E-bikes substitute all two-wheelers in use in China (k=620 M) | 20.14% | 620 | 2014 | 12 | 0.37 |
| Total Cumulative Production: Actual + Logistic fit (reference trend) | 72.77% | 172 | 2008 | 8 | 0.56 |

Not surprisingly, assumptions concerning the ultimate saturation level have an enormous impact on the results. This might not concern uniquely e-bikes as the same conclusion may apply to other technologies using similar diffusion models. What is interesting about the two scenarios 1) and 4) is how the production growth would look like if e-bikes were going to become a serious substitute of bicycles, specifically, or two-wheelers in general. Particularly noteworthy is when the production milestones would be reached depending on which of the two growth paths the diffusion follows.

The main finding is that those saturation levels are both feasible and compatible with actual trends of production. Of course the diffusion will take longer in the case of a higher market potential, as is shown by a lower rate of diffusion (higher ΔT), though it would not be very different from the reference scenario going from about 7 to 11 years. Additionally the inflection points ($t_0$) of scenarios 1) and 2) are quite similar in that the continuation of currently high growth rates for 3 to 4 more years may have significant effects on the final saturation level.[14] Hence there is still much uncertainty on the ultimate potential of the technology. The next years are essential for the diffusion of e-bikes in the sense that the continuation of the same growth rates will delay saturation until later, with higher unit levels ultimately reached.

However, there are already signs of important changes coming in the cycling industry in China. For instance, recent developments in the area of batteries production show a significant number of manufacturers being closed by the authorities as an effort to limit lead poisoning cases. In 2011 the Chinese government forced 90% of the country's lead-acid battery plants to shut down their operations.[15] As so it is expected that a large number of e-bikes will be fitted with more expensive lithium batteries. In addition the dramatic rise of costs for rare earth materials, specifically Neodymium (Nd, 60) which is about 35% of the content of a NdFeB magnet, puts pressure on the final price of electric bicycles.[16] How Chinese consumers will respond to a price increase is still unknown.

On the other hand, the rise in exports will depend both on regulation and the development of demand in the main markets in Europe and in the U.S. The perspective of selling electric bicycles abroad twice as expensive as the 150-200 dollars they can sell in the domestic market opens profitable opportunities to Chinese manufacturers, though these prospects may be weakened by local legislation in Europe and the U.S. that impedes the imports of low quality vehicles. The way that manufacturers will improve the quality of the bicycles in order to meet local requirements without penalising the price of the product will be a key issue for Chinese e-bike manufacturers in the coming years. This will have an important impact on the local production of e-bikes, as well the development of demand in those countries. The demand for e-bikes in industrialized countries is not likely to develop only on the basis of the price of the bicycles. In fact the development of a more ecological or "soft transportation" in the cities will be also dependent on other factors, such as the existence of an infrastructure capable to ensure an efficient and safe commute, the cost and regulation of using motorized vehicles inside the cities, and economic incentives. The development of production outside China is much more uncertain and from this will determine the ultimate diffusion prospect of electrical bicycles in the world.

## 6. Conclusions

This article studies the diffusion of electric bicycles by addressing the following questions: What is the extent of the diffusion of e-bikes in China? What were the causes for the fast development and the consequences in terms of sustainability? What are the prospects for the future? Electric bicycles experienced an intensive development in

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[14] The scenario that considers a slight delay in the inflection point (scenario 2) presents results similar to previous ones in terms of saturation. Basically it acts by constraining the speed of growth, which has a direct impact on the market development of the technology. Therefore, a slightly later $t_0$ of about 3 years doubles the market potential of e-bikes from 172 million to 324 million. On the other hand, the logistic dynamic model is less sensitive to changes in the diffusion rate ($\Delta t$), producing almost proportional variations in the saturation level.

[15] cf. "China's Lead-Acid Battery Plants Forced to Close," Bike Europe, 22/11/2011, http://www.bike-eu.com/news/chinas-lead-acid-battery-plants-forced-to-close-5430.html (last accessed in 19/12/2011).

[16] cf. "More Price Increases Expected for E-Bikes and E-Scooters," Bike Europe, 22/11/2011 http://www.bike-eu.com/news/more-price-increases-expected-for-e-bikes-and-e-scooters-5432.html (last accessed in 19/12/2011).

China within only one decade. In fact sales passed from less than a hundred thousand units per year to more than 20 million in the first decade of the Millennium. The enormous success of e-bikes helped local authorities to manage traffic problems and atmospheric pollution in the cities. It was shown that the diffusion is consistent with the scaling dynamics in other technologies, e.g., energy technologies, in terms of the time needed to scale up the industry and install enough capacity. Compared to bicycles, for which diffusion took decades, the rate of growth is much higher in the case of e-bikes, though the intensity of diffusion in terms of the projected maximum number of units is much lower.

Concerning the potential of e-bikes to replace or complement regular bicycles, the future is still unclear. E-bikes are more comfortable and faster than bicycles, and they are cheaper to operate than motorcycles. Moreover the rising transport needs in the cities and the support from local authorities with favorable regulation will boost sales. While e-bikes in China have seemed to take the place of bicycles in the market, the ultimate potential for growth remains uncertain, as well as ability of e-bikes to substitute for bicycles or other two-wheelers. At the global level, there is some evidence suggesting that bicycles still have more potential to grow than e-bikes. In addition, new facts have arisen in the batteries industry in China that may strongly impact the price of e-bikes and therefore limit their diffusion in the coming years. That will be consistent with the saturation level estimated in this study at 179 million units globally, though much uncertainty exists on the evolution of the market in developed countries.

On the other hand the substitution of bicycles by e-bikes is not exempt from sustainability impacts. The disposal of lead batteries is an important environmental issue in China and could be important in other countries as well. Another issue is the increase of emissions in electricity generation, especially when the majority of the electricity is generated from coal. The amount of emissions due to e-bikes in China may be low compared to the overall emissions (around 0.06% in 2010), though it is already non-trivial and slowly increasing. This should be taken into account whenever e-bicycles are endorsed to solve mobility and environmental problems in urban areas.

The rapid diffusion of e-bikes gives a valuable field of study regarding the conditions that may boost the diffusion of low-carbon technologies, such as electric vehicles and renewable supply-energy technologies. More research is needed, particularly on the effect of the unit scale on the rate of diffusion, in order to elaborate strategies to foster the transition to a more sustainable society.

## Supplementary material

The spreadsheets containing the long-term series of "ordinary" and electric bicycles production as well as all the analysis can be found at http://webarchive.iiasa.ac.at/~bento/Bikes%20and%20E-bikes-Supplementary%20material_v3.xlsx

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