# Sustainable Energy Systems - SELECT

## MSc Thesis

# Technical analysis and market study of electric bicycles

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# Abstract

This thesis project was done in collaboration with a Prismattery LLC, which is based in Tallinn, Estonia and is interested in entering the market of electric bicycles. For that reason in this report a detailed study concerning the market of electrical bicycles, its current situation and trends were performed and a promising target market was indicated. The market study showed that although in different countries the specifications and preferred types of electric bicycles may vary, in general the popularity of this type of transportation rises over the world. Furthermore, as nowadays bicycle sharing systems are very common in many cities, the working principles of these systems and companies who produce them were also investigated within the scope of the project. Subsequently, based on the information examined an electric bicycle sharing systems were detected to be the best market choice for the company to aim, and therefore further work in the technical and environmental analysis was done taking into consideration the requirement of the selected market. Moreover, although compared to regular bicycle sharing systems electric ones require higher capital investment, the cost of operation can be lower due to the savings on the redistribution of bicycles. It is explained by the fact that users of electric bicycles can go uphill without much physical effort and as a result the natural distribution of electric bicycles in stations can be more equal than it is for regular bicycle sharing systems. Therefore, both investment and operation costs were compared for regular and electric bicycle sharing system for 10 years of exploitation and results proved the cost competitiveness of the electric bicycle sharing system.

Different technological solutions concerning the components of electric bicycles were studied in the report in order to understand their working principle, functionality, advantages and disadvantages, etc. Thus, the choice of these components was done in a way to suit the needs of electric bicycles which will operate in a sharing system. In addition an electric circuit which is necessary for the power supply at the bicycle docking station was designed and an automatic charging solution was suggested to charge the battery of the bicycle through special contacts connected to the locking system.

Finally, in the environmental analysis it was estimated the possible reduction of greenhouse gases and air pollutants in case of using an electric bicycle sharing system as an option for urban transportation for short distances. It was calculated that this types of systems in a large scale of operation can have some input in reducing these emissions, and hence improving the health of the local population as well as the global climatic conditions.

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# 1 Introduction

This master thesis is conducted in cooperation with Prismattery LLC, which is based in Tallinn, Estonia and is specialized in designing and manufacturing custom battery packs, along with Battery Management Systems, charging solutions and developments. What is more, it has an intention of entering the market of electric bicycles in future, and therefore is interested in a study concerning the technical and market opportunities of electric bicycles. Before the main study, a brief introduction to electric bicycles, as well as the scope and objectives of the project are provided below.

An electric bicycle or e-bike is a bicycle which has an electric motor integrated that can be used for propulsion (1). Electric bicycles are classified according to the power their electrical motor can deliver and the control system applied in the bicycles. Also the legal definition can vary in different countries where is stated which are bicycles and which are mopeds or motorcycles. Moreover, based to the way how motor assists rider electric bicycles can be divided in pedal-assist or power-on-demand systems. Thus, they can be classified as (1):

- Electric bicycles with pedal-assist only
- Electric bicycles with power-on-demand (i.e. with throttle) and pedal-assist
- Electric bicycles with power-on-demand only (i.e. throttle controlled)

Electric bicycle with only pedal-assist motor is also called pedelec.
Additionally it is vital to know that based on the type of the electric motor the characteristics and targets which electric bicycle tends to meet are changed significantly. Generally, depending on the motor type they can be classified as follows

- Hub motor
  - Direct drive
  - Geared
- Mid-drive motor

While hub motors are affordable and simple to install, they are not as efficient as mid-drive motors, especially in case of riding uphill and mountain biking. Thus, based on the need of the customers, considering also the landscape of the site where electric bicycle will be used each of the above mentioned types has their benefits. It is also worth to mention that normally electric bicycles with mid-drive motor are more expensive compared with the hub-motor ones (2).

Different countries have different legal regulations concerning electric bicycles. For instance in European Union and China the power limit for the electric motor is 250 W, while in the USA it is 750 W. The highest speed at which motor can assist the rider in the USA is ~32 km/h (20 miles/h), in the

EU the limit is 25 km/h and in China the limit is only 20 km/h. Moreover, in European Union electric motor of the bicycle should operate only during pedalling, otherwise it is not considered as an electric bicycle (3).

There are many reasons why people use electric bicycles; some of these are for instance the higher speed which they can reach with electric bicycles, the less effort which is necessary to apply in comparison to regular bicycle or the physical activity with the intention to boost the health. It was proved that riding a pedal-assist electric bicycle does not provide as much health benefit as regular bicycle, however, it is similar one can get by walking (4). Moreover, the less physical effort needed for riding an electric bicycle makes it accessible for people who due to some health problems or limitations are not able to ride a regular bicycle.

While talking about the use of electric bicycles it is equally important to mention that they are a sustainable systems for transportation and can replace some of car trips and therefore reduce emissions generated by the internal combustion engine of these vehicles.

Within the scope of this project market, technical and environmental issues related to electric bicycles will be studied in order to evaluate the current situation and trends. What is more, business models and working principles of sharing systems with electric bicycles will also be studied. The objectives of the work are to suggest a promising market segment to which Prismattery can target, estimate the business feasibility and suggest necessary technological solutions.

# 2 Market analysis

## 2.1 Current market of electric bicycles, trends and forecasts

Current situation in the market of bicycles powered by electric motor or simply electric bicycles varies a lot based on the countries. More than 30 million electric two-wheelers were sold in 2012 (5) , according to Pike Research this number will increase to 47 million by 2018 generating a total revenue of $ 11.9 million (5). The largest market is China, according to some studies it had around 90% of the worldwide sales in 2010, with 21.6 million electric bicycles (6). The huge popularity of the electric bicycles in China can be explained by traffic regulations by the government, which restricts the number of the cars in some cities for avoiding traffic jams. In addition according to the national law electric bicycles are considered as a non-motorized vehicles, which means that no driving license or hamlet is required for riding (7). What is more, the important factor is the affordable price of electric bicycles in China, which can be as low as $ 167, compared with the average cost $ 815 in the USA or $ 1546 in West Europe. Furthermore, considering the high demand and the attractiveness of electric bicycle market in China, it is occupied with around 2600 licensed manufacturers whereas 50% of output belongs to only 50 companies (8).

Despite high popularity and cheap price, electric bicycles in China do not have the same quality as the ones in the USA or Europe. For instance in Western Europe and North America the penetration of the Lithium-ion (Li-ion) batteries for electric bicycles as of 2012 were 65% and 56% respectively, while in China it was only 4% (9). The rest are low quality (compared to Li-ion) sealed lead acid batteries (SLA), which are heavier, have long charging time and low life-time, what is more, there is a risk of lead poisoning.

Although the market of electric bicycles in Europe is not as large as in China, still it has a huge potential. According to COLIBI, the Association of the European Bicycle Industry the sales of electric bicycles in European Union from 2006 to 2012 rose almost tenfold and reached 854000 units (Figure 1) (10).

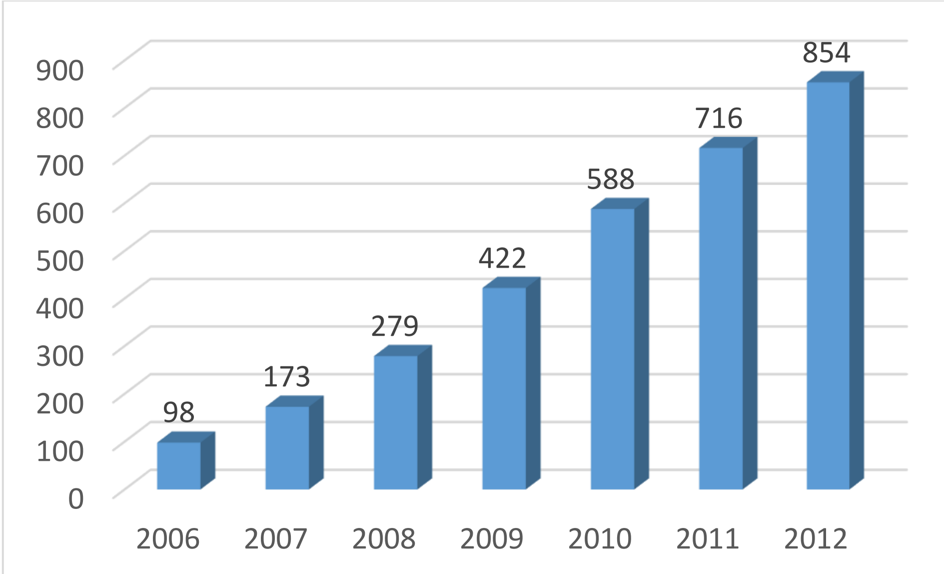



*Figure 1 – Sales of e-bikes in EU (1000 units) (10)*

As it is shown in Figure 2 the highest share of electric bicycles sales in the EU market belongs to Germany, followed by Netherlands with 44% and 21% respectively (as of 2012), other countries have 5% or less (10).

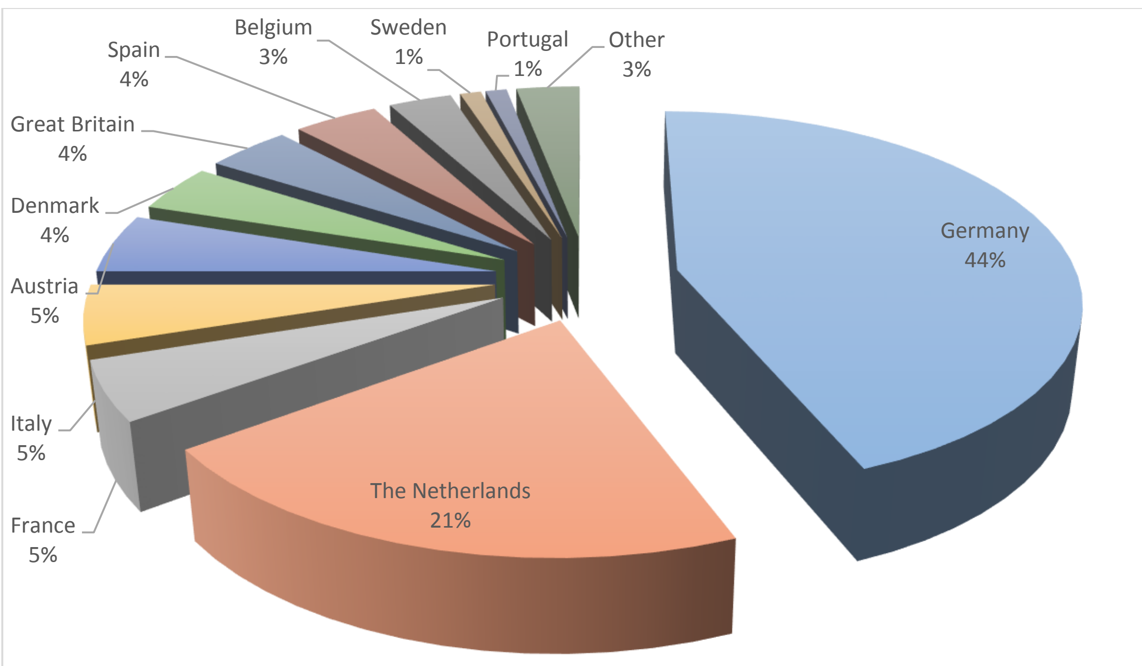



*Figure 2 – Sales of e-bikes in EU (2012) (10)*

The rising interest and market growth of electric bicycles can be explained by several factors, below are stated some of them according to Pike Research (9):

- In countries where regular bicycles are commonly used for transportation reasons electric ones are good alternatives and can be used for transportation as well
- Customers are looking for reliable vehicles with low operating costs
- Faster transportation system compared to regular bicycles
- Market is not occupied with high numbers of manufacturers and it has opportunities for new entrants
- Different options are available for meeting the specific needs of various markets
- Intention of using electric bicycles as a sport activity, especially in North America and Europe for aged people

The characteristics and demographics of electric bicycle users are different based on the country. It is also vital to mention that in countries where throttle-control or scooter-style electric bicycles (SSEB) are allowed, and customer can choose between them and pedelec (pedal-assist electric bicycle), they mostly prefer SSEB. The Asia Pacific market where throttle-control electric bicycles are the most popular ones is the best proof for that (9). This can also be explained by the fact that most of the users of electric bicycles in China ride it as an alternative to public transport, which is usually crowded and not convenient. Thus, they prefer electric bicycles because of high speed and use it for longer trips compared to regular bicycles (11).

Electric bicycle can be used as a commuter, as a tool for doing physical activities, as a tool for random trips (e.g. for shopping or just for the enjoyment) or any other reason. Nowadays our sociality tends to be friendlier to the environment and it also values sustainability everywhere. Therefore, considering the growing prices of fuels as well as the emissions caused by vehicles with an internal combustion engine, it is reasonable to suppose that in the nearest future people’s interest to the electric bicycles will only increase.

Furthermore, study done by Pike Research shows that in contrast with the reducing car sales and relatively stable numbers for the sales of regular bicycles during the same period, the growth in the market of electric bicycles is significant.  What is more, the study also predicts that the trend in Western Europe will continue and will reach $ 2.4 billion in 2016, which will account 12% from the global market revenue (12).

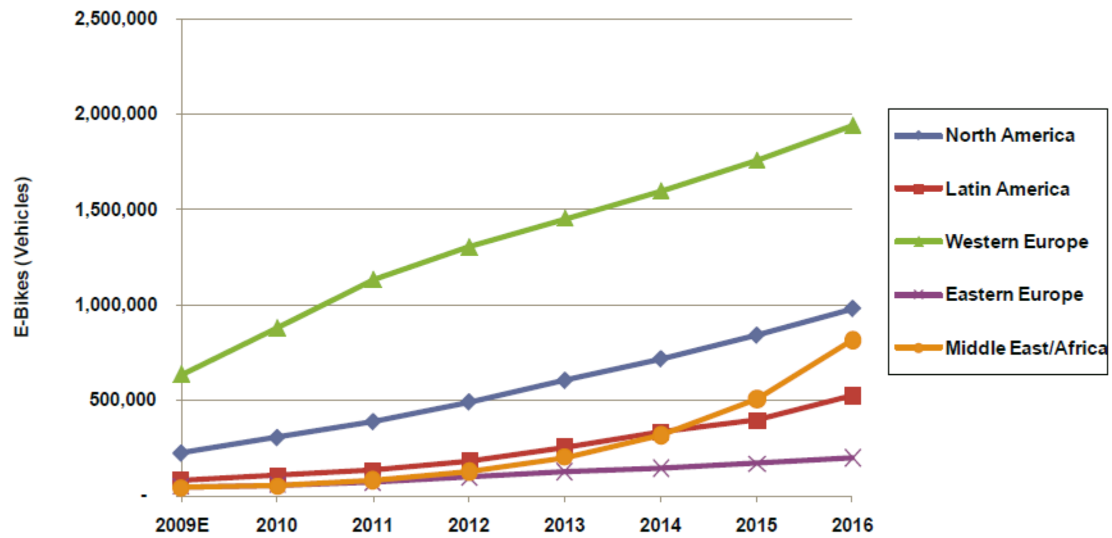



*Figure 3 – Annual sales of electric two-wheel vehicles, excluding Asia-Pacific. Source: Pike Research (12)*

Figure 3 shows that after Asia-Pacific Western Europe has and will have the largest market for electric two-wheel vehicles.

### 2.1.1 Bicycle sharing systems

The Mayor of Lyon once said “There are two types of mayors in the world: those who have bike-sharing and those who want bike-sharing” (13). Today bicycle sharing systems are one of the most important and interesting sections in the bicycle market. Its popularity can be explained by several reasons, for instance sustainability, environmentally friendly, healthy and also cheap transportation option for users; moreover, it can be solution for avoiding traffic congestions in crowded cities.

Nowadays there are more than 535 bicycle sharing systems in 49 different countries (14). Figure 4 shows bicycle sharing systems all over the world and it can be seen that in the USA, EU countries and China the density of these systems are particularly high.


*Figure 4 – Bicycle sharing systems worldwide. Source: www.bikesharingmap.com*

What is more, the organizations who operate bicycle sharing system normally have a supplier or partner which produces not only the bicycle, but the whole system for the sharing, i.e. bicycle, docking station, payment and self-care terminal, software solution, etc. In order to have a better understanding of this market a brief overview of "all-in-one" bicycle sharing system producers was done. It is worth to mention that even though the aim of all these companies is the same, i.e. bicycles for sharing, the solutions to which they came as well as the total products and services they are offering varies a lot in different companies.

A total of 8 different companies which produce "all-in-one" bicycle sharing systems were analyzed, out of them 3 companies have also shared electric bicycles.

## All-in-one bicycle sharing systems

### Nextbike

Nextbike is a German company with the headquarters in Leipzig and it has a very large international bike sharing network. It is present in more than 70 cities mostly in Europe but in 2015 the USA will also join the Nextbike network. The different products which the company produces for bicycle sharing system are summarized in Table 1 (15).

*Table 1 – Products by Nextbike*

| **Smart Bike** | **Smart Dock** |
|---|---|
| • Rental via mobile application, smart card or through the on-board computer<br>• GPS, GSM (2G) & WPAN modules<br>• Return is possible in docks or stand-alone via internal Smart Lock | • Electro-mechanic lock with integrated RFID return detection<br>• Wireless communication and internal power supply<br>• LED status signal |
| **Smart Box** | **Terminal Touch and Terminal Touch and Pay** |
| • Wireless communication WPAN return detection with range of +/- 40m<br>• Server connection via energy efficient GSM (2G) module<br>• Internal data storage for rental in offline modus<br>• Easy to install and can be attached street signs, trees or walls | • Integrated Smart Box<br>• 10" touch screen with 7" display<br>• Zoomable map with real-time information<br>• Operates with solar PV panels, so connection to the grid is not required<br>• Credit and debit card reader<br>• Contactless Reader (NFC) with LED and audio signal, and wake up function<br>• PinPad with monochrome 2,5" display |

### Gobike

Gobike is a company which produces electric bicycle sharing system; it operates in five different cities including Copenhagen with the system called Bycyklen. Through the tablet integrated on the bicycle frame users have access to different features. More details about Gobike are provided in Table 2 (16).

*Table 2 – Products and services by Gobike*

| The Bicycle and Docking | The Tablet |
|---|---|
| • Practical and stylish<br>• Aluminum frame and internal cable routing<br>• Integrated tablets with GPS<br>• An electrical motor (front hub) with four assistance levels<br>• Digital lock: stop anywhere and lock the bike via tablet<br>• Built in LED lights<br>• Front and rear luggage rack<br>• Belt drive instead of the traditional chain<br>• Docking by sliding the front wheel into the docking point<br>• The cost of trip is displayed on tablet | • Multiple language options<br>• Adjust the electric assistance level<br>• Login with a Travel Card<br>• Two navigation view options<br>• Points of Interest (attractions, restaurants, shopping destinations, etc…)<br>• Travel planner (options of public transportation)<br>• Using the digital lock<br>• Reporting problems<br>• Returning bicycle |

**Social Bicycles (Sobi)**

Social Bicycles is an American company which operates in 9 US cities. The system does not require any special docking station and bicycle can be locked at any bicycle rack which is within the area where system operates. The bicycle itself is a "smart bike" and has integrated necessary facilities for checking it in or out. Some details about Sobi can be found in Table 3 (17).

*Table 3 – Description of the system by Sobi*

| For Rider | For Operator |
|---|---|
| • Easy to find and reserve (web, mobile app or from key pad on the bicycle)<br>• Fast access: get a pin code and unlock<br>• Park anywhere: any bicycle rack in the system area<br>• Socialize: share mapped rides, traveled distance, CO2 reduced, etc… | • Smart Bikes instead of Smart Racks<br>• Affordable: it costs fraction of existing station-based bike sharing systems<br>• Scalable: already existing bicycle parking can be used, no need to build a special parking<br>• Real time management through the software |

**PBSC Urban Solutions**

PBSC Urban Solutions is a Canadian company which has bicycle sharing systems in different cities, mainly in Canada and the USA, as well as one system in London. Some information about its bicycle and the whole system is shown in Table 4 (18).

*Table 4 – PBSC system, station and bicycle*

| System/station | The Bike |
|---|---|
| • Portable and easy to install. No excavation is needed<br>• Powered with solar PV's<br>• Wireless communication – no need to hook the telecommunication grid<br>• Reliable software<br>• Uniform "Plug and Play" module - fits easily into technical platform<br>• Simple and easy-to-use interface<br>• RFID wireless real-time connection payment can be made by subscribers with their user key directly at bicycle dock<br>• Same base for pay station or bicycle dock<br>• Sturdy for any climate | • Aluminum frame - light, strong, durable.<br>• One-piece handlebar covers and protects all components<br>• All cables and derailleur covered for better protection<br>• Chain protector integrated into bike structure<br>• Active lighting - front and back, always on when riding<br>• Suitable for a wide range of riders<br>• Low center of gravity for greater stability<br>• Tires - made for the urban jungle |

**Motivate**

It is another American company with the bicycle sharing solutions, Motivate designs, deploys and manages the whole system. It has systems in different cities over the USA, as well as in Canada and Australia. Details about this company are given in Table 5. Some of the customers of Motivate are for instance City Bike in New York, Divvy in Chicago and Bike Share in Toronto (19).

*Table 5 – Motivate technology and services*

| The Technology | What they do? |
|---|---|
| • Modular, portable and solar powered station and components<br>• Cost-effective, easy to install and manage<br>• Durable for different climatic conditions<br>• Plug and Play: no need for excavation or preparatory works<br>• No need for external power source: solar power and wireless communication | • Data analysis and reporting<br>• Bicycle redistribution<br>• Bicycle maintenance<br>• Station maintenance<br>• Station cleaning<br>• Feasibility studies<br>• Business planning<br>• Siting<br>• Coordinating partnerships |

**CycleHop**

CycleHop is American company which offers complete bicycle sharing solutions, including electric bicycles. It plans, implements and operates the whole system. It provides different solutions for cities, universities, hotels or companies. In Table 6 is given some information about the technologies CycleHop has and the services which they offer (20).

*Table 6 – Technologies and services by CycleHop*

| Different Technologies | What they do? |
|---|---|
| • Smart dock systems<br>✓ Docking point with card, key fob or pin code<br>✓ Bicycle is picked up and returned to one of the docking stations<br>• Smart bike systems<br>✓ Locking system attached to the bicycle<br>✓ Direct wireless connection from bicycle to server<br>✓ Possibility to utilize any bicycle rack<br>• Electric bicycle systems<br>• Smart lock systems<br>✓ Nearly universal GPS-enabled locks<br>✓ Locks can be accessed and tracked via smartphones | • Feasibility studies<br>• Implementation plan<br>• Business models<br>• Risk management<br>• Equipment & technology development<br>• Network & location planning<br>• Staffing & customer relations<br>• Balancing stations<br>• Assembly & installation<br>• Branding, marketing & outreach<br>• Equipment maintenance |

**Sycube**

Sycube is an Austrian company which was founded in 1995 and it provides solutions in different fields including bicycle sharing systems. Sycube offers fully automated bicycle sharing system with both regular and electric bicycles (21). Table 7 collects some details about this system.

*Table 7 – Sycube technologies and services*

| Varity of Terminals and Docks | Software and Bike |
|---|---|
| • Integral Terminal (it has the terminal itself plus SAFE type docking station)<br>• Light Terminal (saving the space, can accept up to 12 bicycles)<br>• Eco Terminal (with Solar PV and extremely energy saving interior)<br>• All-in-one Terminal<br>• COMPACT docking station<br>• eCOMPACT docking station<br>• SAFE docking station (mainly for electric bicycles, because it protects its sensitive parts from vandalism) | • Tariff management<br>• Billing<br>• Customer management<br>• Fleet management<br>• Incident management<br>• Services for end user (web portal)<br>• i:SY bicycles and pedelecs |

**On Bike Share**

One Bike Share is an American company which has a bicycle sharing system with simple solution. The idea is to have a locked key-box; the key for unlocking the shared bicycle is inside that box. Each user receives a personal PIN code for opening the key-box and taking the key. After checking bicycle in the key should be returned as well. On Bike Share has customers among universities, hotels and resorts, as well as businesses and corporate campuses. Some details about the services and bicycle are shown in Table 8 and Figure 5 (22).

*Table 8 – On Bike Share Key Box and Bicycle*

| Key Box | Bicycle |
|---|---|
| • Security and simplicity<br>• Keys for the bikes inside Key Boxes<br>• PIN code to open Key Box and take the key<br>• No internet access required | • Shimano 7 speed internal gear with twist grip shifting<br>• Sussex shaft drive system (no chains)<br>• OnLock integrated to the bike frame |


*Figure 5 – Steps how to check out bicycle from On Bike Share. Source: www.onbikeshare.com*

Comparison of all these systems showing all their similarities and differences are summarized in Table 9

*Table 9 – Comparison of different bicycle sharing systems*

| | Next-bike | Cycle-Hop | Gobike | On Bike Share | Sycube | PBSC | Motivate | Sobi |
|---|---|---|---|---|---|---|---|---|
| Electric Bicycle | ✗ | ✓ | ✓ | ✗ | ✓ | ✗ | ✗ | ✗ |
| Return at docking stations | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✗ |
| Stand-alone return | ✓ | ✓ | ✗ | ✓ | ✗ | ✗ | ✗ | ✓ |
| GPS | ✓ | ✓ | ✓ | ✓ | ? | ? | ? | ✓ |
| Mobile App. | ✓ | ✓ | ✓ | ✗ | ✓ | ? | ? | ✓ |
| Payment Terminal | ✓ | ✗ | ✗ | ✓ | ✓ | ✓ | ? | ✗ |
| Integrated Tablet, Computer or Navigator | ✗ | ✗ | ✓ | ✗ | ✗ | ✗ | ✗ | ✓ |
| Stations With Solar PV | ✓ | ✗ | ✗ | ✓ | ✓ | ✓ | ✓ | ✗ |
| Business Planning and Feasibility Analysis | ✗ | ✓ | ✗ | ✗ | ? | ✗ | ✓ | ✗ |
| Operation of the System | ? | ✓ | ✓ | ✗ | ? | ✓ | ✓ | ✗ |

### 2.1.2 Business model for bicycle sharing systems

In general the asset ownership structure of bicycle sharing system can be characterized within three main groups (23):

- Publicity owned and operated
- Publicity owned and privately operated
- Privately owned and operated

Within the frames of the publicity owned and operated model, the government owns all the assets, and what is more, is in charge of the design, installation, operation and all the other services necessary for the system. This can be considered as a main advantage of this business model. Operation of the system may also be contracted out to a parastatal or some other governmental agency. The disadvantage of this approach is that sometimes a government-owned entity may work less enthusiastic and efficient compared to private ones (23).

An example of publicity owned and privately operated bicycle sharing system is Bicing in Barcelona. It can be a fee-for service model, when all the assets are owned by government but the service and operation of the system is done by private company. In this case, the operator is responsible for running the system, handling the logistic and maintenance, while the public owner has a control at the key phases of the project (23).

Privately owned and operated model suppose that a private company owns the assets and provides all the services necessary for the sharing system. In this model government may provide the land where stations should be located. Nevertheless, in some cases it can also charge the operator a fixed fee or share its revenue with the city (23).

### 2.1.3 Electric bicycle sharing systems

Despite the popularity of bicycle sharing systems, they are not ideal. Some of the challenges which are facing regular bicycle sharing systems can be solved by integrating electric bicycles. It is common for users to go more downhill and as a result causing absence of bicycles at higher stations and overload at stations which are located lower. For that reason, redistribution of bicycles is one of the most important aspects during the operation of bike sharing system and normally it values the third of the total operational expenses (24). However, in case of having electric bicycles it can be expected to have more equal distribution between stations, because with the electric bicycle going uphill does not require high effort from the cyclist and consequently the cost of bicycle redistribution will be lowered. Moreover, thanks to the same reason electric bicycles can also be used by older people or people with some health limitations. Therefore, the diversity and the total number of the users will be increased.

Another benefit of these system is the higher speed and acceleration of the electric bicycle compared with the regular one, which makes it an attractive alternative to public transportation systems or personal cars.

Already several European cities adopted the concept of sharing pedal-assist electric bicycles (pedelecs) together with the regular ones or even without them. One of the early adopters in this field was the electric bicycle sharing system in Copenhagen called Bycyklen. It was launched in 1th of April 2014 (25) and to date has already 1860 pedelecs in 100 different stations located in Copenhagen. It has a smart electric bicycle (Figure 6) with integrated GPS routing device and tablet through which user can check in or out the bike, select the route of the ride and use many other features (16).

*Figure 6 – Electric bicycle used in Bycyklen system in Copenhagen. Source: gobike.com*

Call a Bike is another company which has bicycle sharing systems in several cities over the Germany. Mainly it operates with regular bicycles, though; in Stuttgart it has both pedelecs and bicycles. Currently Call a Bike has a fleet of electric bicycles in 44 sharing stations in Stuttgart (Figure 7) (26).

*Figure 7 – Pedelec from e-Call a Bike in Stuttgart. Source: www.callabike-interaktiv.de*

One of the biggest bicycle sharing system in Europe operates in Barcelona, it is called Bicing and has a fleet of 6000 bicycles in more than 400 sharing stations (27). At the end of 2014 it started a pilot project of electric bicycle sharing and today has 300 electric bicycles in 46 different stations, with 2500 users (with access to electric bicycles) and many people in the waiting list for the access (28)(Figure 8).


*Figure 8 – Electric bicycle from Bicing in Barcelona. Source: Bicing.cat*

These are just some examples of electric bicycle sharing systems which are already operating and seem to be successful, with many users involved. It is reasonable to assume that in future the number of these kind of systems is going to increase, for instance BikeMi, the bicycle sharing system in Milan, which currently operates only with regular bicycles, during 2015 is going to launch 1000 pedal assist electric bicycles and will build 80 stations for them (29).

Comparison of the prices offered by the systems described above is done in Table 10. It is worth to mention that Call a Bike has discounts for students as well as for the ones who owns a train card; however only full prices without discounts are summarized in Table 10 (27), (30), (26).

*Table 10 – Cost comparison of different systems*

| | | Subscription fee | Price for the first 30 minutes |
|---|---|---|---|
| Bycyklen | Electric bicycle | 9.38 €/month[1] | Free |
| Call a Bike (Stuttgart) | Regular bicycle | 48 €/year | Free |
| | Electric bicycle | 54 €/year | 0.12 €/minute |
| Bicing | Regular bicycle | 47.16 €/year | Free |
| | Electric bicycle | 61.16 €/year | 0.45 € |

## 2.2 Case study: Bicing Barcelona

As it was mentioned earlier in the report, Bicing is a leading bicycle sharing system which operates in Barcelona and also has a small fleet of electric bicycles. In order to gather more information concerning Bicing and electric bicycle sharing systems in general, an interview was conducted with Raúl Ganzinelli Aguilera who works in the Municipality of Barcelona and is responsible for Bicing unit. This section summarizes the outcomes of that meeting.

For operating Bicing bicycle sharing system there is a 10 years contract (till 2017) between the Municipality of Barcelona and Clear Channel Company. What is more, for the next decade (i.e. 2017-2027) there is an idea of having mixed system with large number of regular and electric bicycles. However, before staring the large project it was decided to launch a pilot program for two years with 300 electric bicycles and 2500 users. Currently Bicing Electric has 46 stations out of which only 5 are outdoor and the rest are at indoor car parking for security reasons. During the pilot all the challenges and issues concerning the sharing of electric bicycles are going to be analyzed, only after that the feasibility of the large scale project can be estimated.

Clear Channel is the operator of the system and it has three main partners in Spain who are responsible for producing the electric bicycle and all the equipment necessary for the sharing system,

[1] Currency was converted from Danish Krone to Euro with the conversion rate DKK 1 = € 0.13

except the software which is was developed by Clear Channel. Table 11 shows some information about these partners.

*Table 11 – Partners of Clear Channel for Bicing Electric*

| Field | Name of the company | Production |
|---|---|---|
| Electric bicycle | Ecobike | Design, battery, motor, controller, etc… |
| Station and charging | Circontrol | Charging solution in bicycle |
| | Noval | Docking anchorage, charger at the docking slot |

Price of the Bicing electric bicycle is € 1500, out of which approximately € 600 belongs to the high quality Lithium-ion battery which has a performance of 3000 charging cycles and can run the bicycle for 20000 km. The bicycle is equipped with an electric motor of 250 W power and has three levels of assistance for the cyclist.

Unlike many other bicycle sharing systems, where the owner companies are provided with free advertisement space on bicycles and other sites in the city, Bicing is not working like that and Clear Channel does not have free advertisement spaces in Barcelona. Therefore, the annual expense of the system operation (€ 16 million), is partially covered by subscribers (€ 4 million) and Vodafone (€ 1.2 million) who is the sponsor of Bicing. The rest € 10.8 million/year is reimbursed the Municipality of Barcelona.

The structure of a company which operates a small scale (300 units) electric bicycle sharing system is presented in Figure 9, it also suggests the number of employees necessary for running the system.

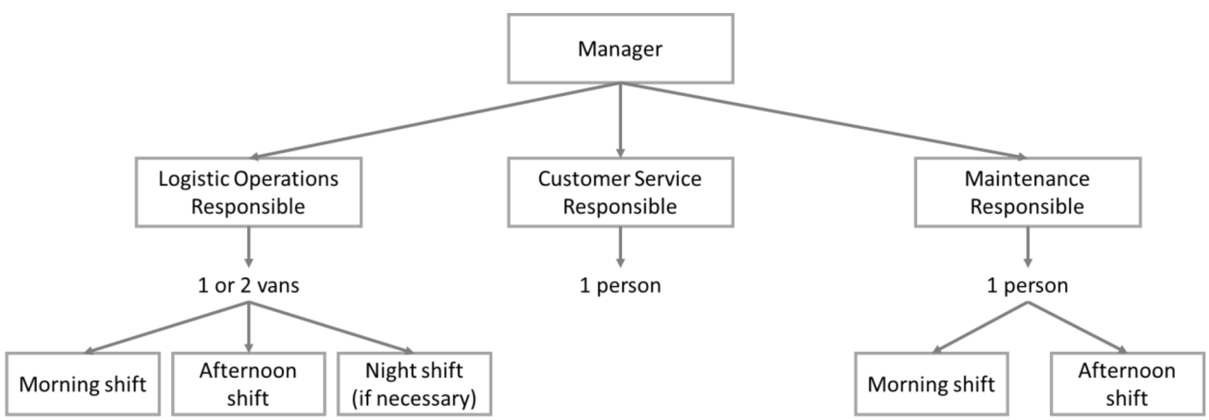



*Figure 9 – Structure of a small scale electric bicycle sharing company*

Furthermore, it is also necessary to consider working and no-working days and adjust the number of employees accordingly.

In addition, it is also worth to mention that the regular bicycle sharing system of Bicing is much larger and complicated compared to the electric one. For instance only for the maintenance of bicycles it has two stocks in different sides of Barcelona where bicycles are taken for reparation. The difference between regular and electric bicycle share is also reflected in the price of the subscription and usage fees. While for regular bicycles in Bicing user should pay 47.16 €/year and the first 30 minutes of each ride is free of charge, in case of electric bicycle user pays an additional 14 €/year and also 0.45 € for the first 30 minutes of each ride (27).

## 2.3 Cost comparison

In this section a cost analysis is carried out based on the data available on the web, the information which was provided by Raúl Ganzinelli Aguilera from the Municipality of Barcelona during the interview as well as some assumptions. For the regular bicycle sharing system the capital cost per bicycle varies from $ 3000 to $ 4500 based on the system, while the operations cost is between $ 1200 and $ 1950 (31). More details are available in Table 24 and Table 25in the **Appendix**.

An average number of $ 3700 and $ 1600 for capital cost per bicycle and operation cost respectively are taken for the regular bicycle system in order to conduct further calculations. Considering the fact that normally electric bicycles are more expensive than the regular ones, for instance the price of the electric bicycle used in Bicing is as high as € 1500, the capital cost for these systems is assumed to be 70 % more expensive than it is for regular system, namely $ 6290. Additionally, an amortization expenses equal to 10 % of the capital cost is also taken into account.

It was mentioned earlier that approximately 30% of the operation cost in bicycle sharing systems comes from the redistribution of bicycles between stations (24) and it was also confirmed by the contact person from the Municipality of Barcelona during the interview. However, it is also vital to take into consideration the fact that with electric bicycles it is significantly easier to go uphill compared to the regular ones. For that reason, it is expected that the sharing system with electric bicycles will have more equal bicycle distribution by users, and therefore the operation cost related to redistribution of bicycles will be lower compared to the regular system. Nonetheless, it is also necessary to remember that electric bicycle sharing systems are also using electricity for charging batteries which requires some additional expenses. A simple sensitivity analysis was done for 10 years of the system operation with a fleet of 6000 electric bicycles to check outcomes based on the different amounts of the reduced costs of operation as well as the capital cost. Details of the calculation are given in Table 12. The fleet of 6000 was chosen because it is similar to the number of regular bicycles in Bicing system (27), but in case of other number of electric bicycles in the system the ratio between the costs of both systems will still remain unchanged.

*Table 12 - Cost comparison between regular and electric sharing systems*

| | Expenses | Costs in euros* | Total cost for 10 years of operation |
|---|---|---|---|
| Regular bicycle sharing system | Capital cost | € 3367 | **€ 109,582,200** |
| | Amortization cost | € 337 | |
| | Operation cost | € 1456 | |
| Electric bicycle sharing system | Capital cost | € 5724 | - |
| | Amortization cost | € 572 | |
| | 10% less operation cost | € 1310 | **€ 116,401,740** |
| | 15% less operation cost | € 1238 | **€ 112,033,740** |
| | 20% less operation cost | € 1165 | **€ 107,665,740** |

*Currency was converted from USD to Euro with the conversion rate $ 1 = € 0.91

Table 12 shows that if operation expenses in electric bicycle sharing system are reduced by 10% or 15% compared to the system with regular bicycles, the total cost for 10 years of operation is still more expensive. However, the difference is not big; what is more, if the savings in operation costs are considered up to 20%, then the total cost after 10 years of operation for electric bicycle sharing system is cheaper than for the regular one. Therefore, it is believed that this kind of systems can cost competitive to regular bicycle sharing systems.

## Conclusion of market analysis

Different market trends and directions concerning electric bicycles were discussed in this chapter. Overall there can be no doubts that it has a promising future and will continue gaining popularity all over the world. However, it was also highlighted that based on the country, continent, legal regulations and several other factors the types and prices of electric bicycles can vary significantly.

Additionally it was identified that in the huge market of bicycle sharing system there is a rising interest for electric bicycles. Therefore, taking into consideration the attractiveness of this market, the fact that it is considerably new and has a trend of growing, as well as the potential which it has in Europe, it has been decided to select the market of electric bicycle sharing systems as a target market for this project. The analysis done in sections 2.1.1 and 2.1.3 showed that in case of targeting the market of shared bicycles and in particular electric bicycles, it is necessary to produce not only the bicycle itself, but also the complete solution for the sharing system. Moreover, in some cases business planning and feasibility analysis, as well as, the further operation of the system including relocation and maintenance of bicycles is done by the producer company.

Overall the market of electric bicycle sharing systems is topical already now and is believed to be even more promising in the nearest future. Some of the concerns related to the sharing of electric bicycles are the higher price of the subscription and usage compared to the regular bicycle sharing, as well as the total cost of the sharing systems itself. Nonetheless, as it was shown in the last section of this chapter, sharing systems with electric bicycle can be cost-competitive with regular bicycle sharing systems.

Therefore, further technical analysis and selection of the components for the electric bicycle will be done in the way to meet the specific requirements of the shared electric bicycles market.

# 3 Technical Analysis

Pedal-assist electric bicycle consist of many different components, for instance motor and its controller, different types of sensors and the battery, etc. Therefore, further in this chapter a detailed study of the types, working characteristic, advantages and drawbacks of these components was conducted.

## 3.1 Motors

Motor is the essential part of electric bicycle as it is responsible for propulsion of the bicycle. The motor of electric bicycle can be integrated to the front or rear wheel, using the hub motor technology or it can be located directly under its pedals and that will be an electric bicycle with mid-drive motor. Additionally the electric power assist system can be added to bicycles using chain, belt or friction drives (1). Regardless the type of the motor, in the European market according to the legal regulations its power cannot be higher than 250 W (3).

Out of many different types of electric motors Brushed and Brushless DC motors (BDC and BLDC respectively) are the common ones used in electric bicycles. Even though, nowadays BLDC accounts up to 90% of all the electric bicycle conversion kits worldwide (32). Compared to the brushed motors the brushless ones are faster, cleaner, more efficient, more reliable and less noisy. However, instead they require a control electronics which replace the function of commutation in brushed motor and energize appropriate winding (33).

### 3.1.1 Brushless DC Motor

Brushless DC Motor (BLDC) is a type of synchronous motor, which means that the magnetic field generated by stator rotates at the same frequency as the rotor. Thus, there is no “slip” as it is for induction motors. BLDC motor has rotor made from permanent magnet and stator with windings. This construction allows to avoid brushes and commutator in the system, instead it requires a control electronics which will energize the proper winding (33). For that reason it is necessary to determinate the position of the rotor, which can be done through Hall sensors or optical sensors used as a position detectors (34).

Figure 10 shows the transverse section of Brushless DC Motor. Hall sensors are integrated to the stator and in order to make the installment of these sensors easier some motors have Hall sensor magnets. These, simply are small duplicates of the rotor and as a result, whenever rotor rotates Hall sensor magnets give the same effect as the main magnets. When the magnetic poles pass near the Hall sensors, they give either high or low signal and thus, indicating if the N or S pole passes near the sensors. Usually motors are equipped with three Hall sensors (35).

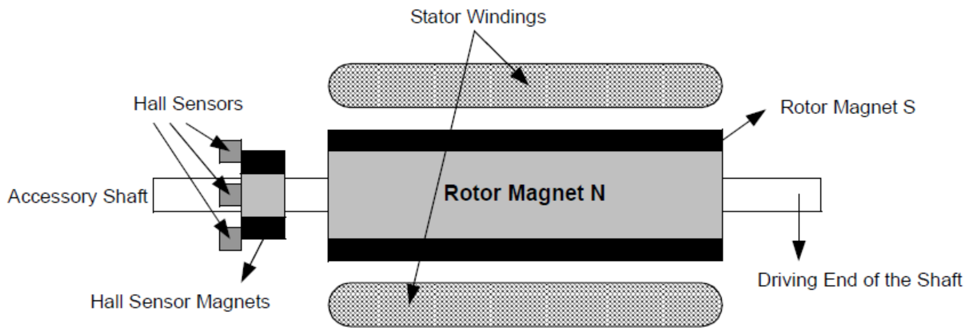



*Figure 10 – Transverse section of BLDC motor (35)*

Furthermore, the signals from Hall sensors are sent to the motor controller which decides the sequence of energizing the appropriate windings of stator through power switches (35). Figure 11 shows an example of such control system.

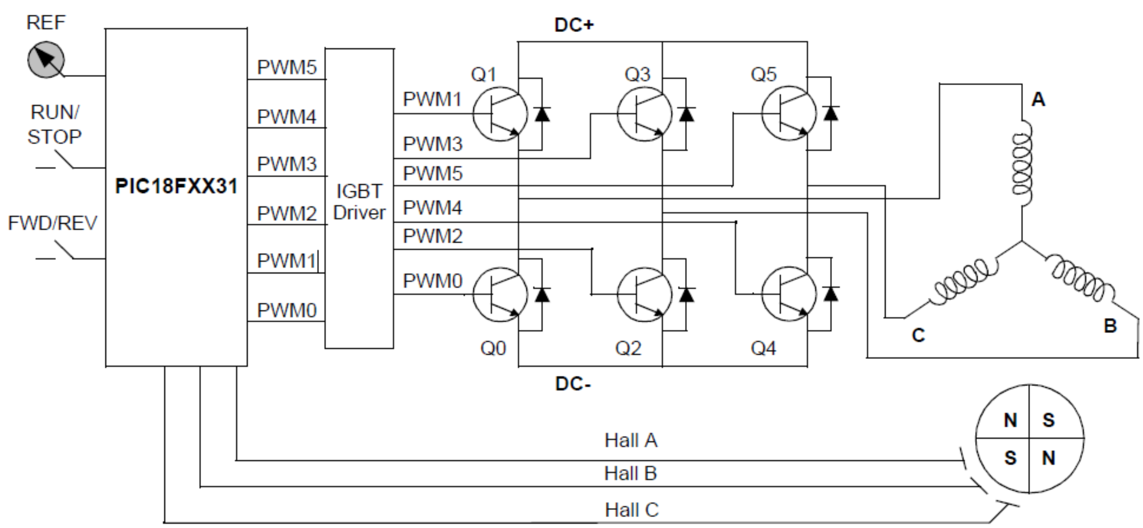



*Figure 11 – Control diagram of BLDC motor (35)*

Comparison of the main characteristics and features of BLDC motor with the brushed one is summarized in Table 13 (35). These are some characteristics of BLDC motor because of which it is widely accepted in the market of electric bicycles.

*Table 13 – Comparison of Brushless and Brushed DC motors*

| Feature | Brushless DC motor | Brushed DC motor |
|---|---|---|
| Communication | Electronic | Brushed |
| Life time and maintenance | Longer life time, low or not maintenance | Lower lifetime, periodic maintenance |
| Efficiency | High | Moderate |
| Rotor inertia | Low inertia which improves the dynamic response | High inertia which limits the dynamic characteristics |
| Cost | High | Low |
| Control | Complex and expensive | Not expensive and simple |
| Controller | Always required | Required only if variable speed is necessary |

### 3.1.2 Mid-drive motors

Mid-drive motor, which can also be called crank motor is mounted in the crank and pedal area of the bicycle, normally at the bottom of the frame. Figure 12 shows an example of approximately where the motor can be located in mid-drive electric bicycles. Placing the motor between the pedals allows using bicycle's transmission system as a gears for the motor, so it can be lighter and will always operate within the optimum RPM range. Therefore, electric bicycles with mid-drive motor technology have good performance at steep hills conditions and mountain biking.


*Figure 12 – Position of the motor and the battery for mid-drive electric bicycle*

Crank motors can different appearance and can be designed in a way to fit the bicycle in the most natural way. Even though, the standard mid-drive motor is not possible to hide and it will be seen as an additional component added in the regular bicycle. Figure 13 shows two different designs of mid-drive motors for electric bicycles.


*Figure 13 – Different designs of crank motor. Source: www.szbaf.com*

The main benefits and drawbacks of mid-drive technology for electric bicycles are summarized below (2):

**Advantages**

- Possibility of using a bicycle transmission as a gearbox for the motor
- Operating the motor at optimal torque. Good torque characteristics
- High performance at steep hills
- Good weight distribution. Motor is located low and in the center
- No extra weight in tires
- Longer battery running time(compared to hub motors) due thanks to optimal performance of the motor

**Disadvantages**

- Usually have a high cost
- Noisy operation due to the chain drive system
- Implementation is difficult
- Have many moving parts, therefore the reliability is not very high

### 3.1.3 Hub motors

In opposite to the mid-drive technology hub motor is located in the wheel of bicycle and in fact it replaces the traditional hub of the wheel (36). Figure 14 shows an example of 250 W hub motor for electric bicycle.


*Figure 14 – Hub motor for electric bicycle. Source: www.szbaf.com*

It is possible to have geared or direct drive hub motors and both technologies are used in electric bicycles (32). In addition it is worth to mention that even if hub motor is geared, it still has only one transmission ratio.

**Direct Drive Hub Motors**

Typically direct drive hub motors are heavy and large. It is explained by fact that the wheel speed in this type of motors is slow, around 200 rpm in contrast with over 3000 rpm for geared motor (37). The power density of electric motor is directly proportional to the speed between the magnets and windings, therefore in order to have an adequate power and torque motor has to be large. Some producers try to solve this problem by increasing the diameter of the motor, as it will cause to the higher relative speed between the rotor and windings. However, there are some mechanical complications for making motors with too big diameter. One of the important features of direct drive hub motors is that they are always mechanically engaged which gives possibility to apply regenerative braking system. Nevertheless, it also means that cyclist always has to overcome the resistance of the motor even if it is not working (37). Figure 15 shows an example of direct drive hub motor.

*Figure 15 – Direct drive hub motor. Source: www.ebikes.ca*

**Geared Hub Motors**

These types of hub motors have a gearing system inside which allows to reduce the speed of fast and efficient motor to the speed required for the bicycle wheel. Geared hub motors are normally smaller and have about 50% less weight than the direct-drive motors with an equivalent power. Although different options of the gearbox configurations are possible, the most common is the outrunner motor which drives the center of a planetary gear set linked to the motor (37). The great majority of geared hub motors available in the market have a free-wheel inside, and consequently when motor is not used the rolling friction for spinning motor is very small. However, with this technology it is not possible to apply regenerative braking (37). Figure 16 shows an example of geared hub motor.

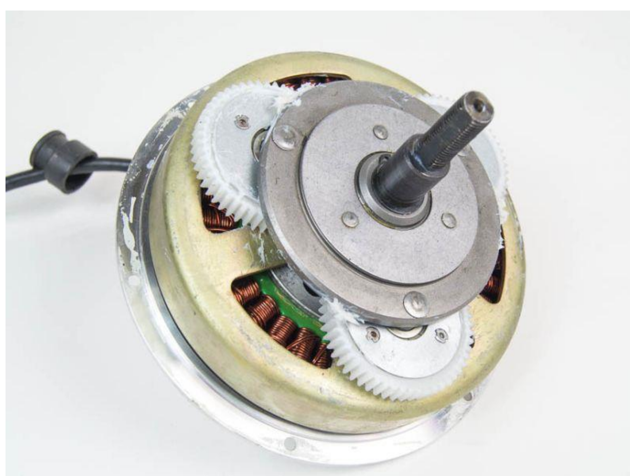


*Figure 16 – Geared hub motor. Source: www.ebikes.ca*

The comparison of geared and direct-drive hub motors is summarized in Table 14.

*Table 14 – Geared and direct-drive hub motors*

| | **Direct Drive Hub Motor** | **Geared Hub Motor** |
|---|---|---|
| Size/weight | Large/heavy | Small/light |
| Rotating speed | Low, ~200 rpm | High, ~3000 rpm |
| Possibility of regenerative brake | Yes | No |
| Motor resistance | Yes | No |
| Moving parts | Few. Reliability is high | Many. Prone to wear out |

The hub motor of an electric bicycle can be located either in the front or in rear wheel as it is shown in Figure 17.

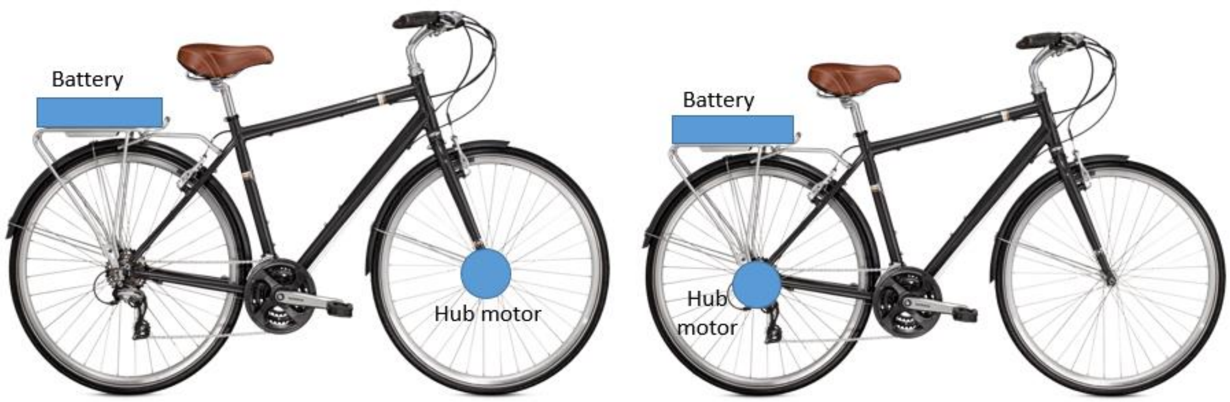



*Figure 17 – Possible locations of hub motor for electric bicycles*

In the current market of shared electric bicycles both options of motor location are used. For instance as it is shown in Figure 6, the electric bicycle of Bycyklen has the hub motor built in the front wheel, while Call a Bike and Bicing (Figure 7 and Figure 8 respectively) have rear wheel hub motor. Although the difference between these two options is not very significant, each of them has some specific characteristics which are necessary to take into consideration before designing an electric bicycle.


*Figure 18 – Bicycle frame. Source: www.electricbikereview.com*

Hub motor adds an additional weight to the wheel and also such called "unsprung" weight to the bicycle, which reduces its balance (38). Furthermore, as it can be seen in Figure 18, the rear fork of bicycles is normally reinforced while front fork is weaker. For that reason if the hub motor is designed to be located on the front wheel, then it is recommended to use a steel front fork instead of the traditional aluminum one (39).

The general comparison of electric bicycles with front and rear hub motors is done in Table 15 (39) (40)

*Table 15 – Comparison of electric bicycles with rear and front wheel hub motors*

| Rear wheel | Front Wheel |
|---|---|
| Aluminum rear forks are can be used | Higher pressure on front forks, not suitable for aluminum ones |
| Better traction when climbing up hills off-road | Practically two wheel drive |
| Limitations of bicycle gearing. Up to 7 speed freewheels | Rear gearing system of bicycle remains unchanged |
| Not equal weight distribution, the rear of bicycle becomes heavier especially if battery is rear mounted | Better weight distribution if battery is located at the rear |
| Higher stress on the rear wheel | Additional weight on front wheel and more force on the handlebars |

## 3.2 Sensors and controllers

Sensors are very important components of any electric bicycle since they are collecting information regarding the current characteristics of the bicycle and sending it to the controller. The controller analysis received data and sends further commands to the motor and battery of the bicycle. Therefore, careful selection and correct operation of sensors are vital for the good performance of electric bicycle.

As it was mentioned earlier in this report, according to the legal regulations in European Union motor of electric bicycle can operate only during pedaling (3). To detect if cadence or torque sensors can be used, and while both of these sensors are able to detect if pedals are rotating or not, they have a huge difference in functionality and in the available features (41).

### 3.2.1 Cadence sensor

The most popular type of cadence sensor is in fact a combined cadence and speed sensor which allows to measure both of these characteristics. Garmin GSC10 is an example of such sensor, as it is marked in Figure 19 it only has three parts, namely spoke magnet, cadence magnet and the electronics pod mounted in between of these two magnets in a way to capture both speed and cadence (42).

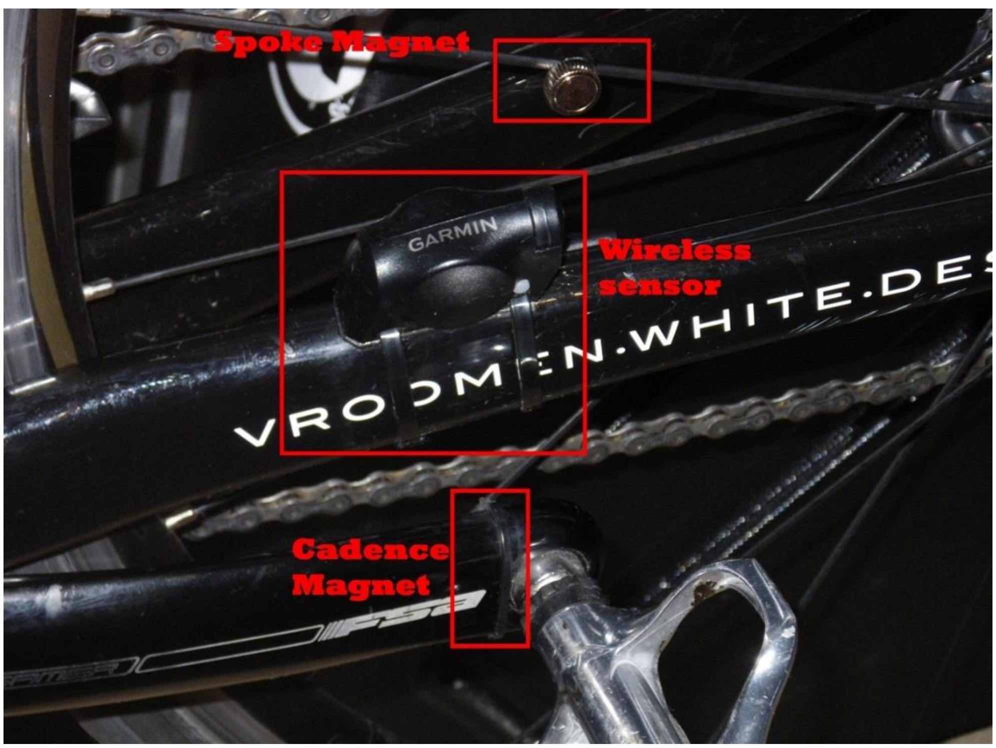



*Figure 19 – Garmin GSC10 cadence and speed combined sensor. Source: www.dcrainmaker.com*

Although cadence sensors are able to detect if the cyclist is pedaling or not at any exact moment and can be used in electric bicycles for that purpose, still they are not very intuitive and far not the best solution for a good electric bicycle. One of the problems which can be faced in case of using this sensor is that when the cyclist starts pedaling the motor wants to turn on with the full power. However, while going up to hill the pedaling slows down and cadence sensor sends an information to the motor for giving less power, while in fact more power is necessary for going up to the hill (41).

Yet, this type of sensor is widely used by manufactures of pedal assist electric bicycles because of their affordable price. Price for the Garmin GSC10, the most popular cadence and speed combined sensor, is $ 60 on official website of the producer (43), but it is possible to find sensors of other brands with even cheaper price.

### 3.2.2 Torque sensor

In order to have better riding experience and high intuitive control, in expensive electric bicycles torque sensors are used (44). Torque sensor basically measures how hard cyclist is pressing on the pedals and based on that informs motor how much power is necessary to provide. Thus, torque sensor applies power much smoother compared to the cadence one (41). In other words, if cyclist is pedaling hard then less power will be applied by the motor and in case of slow pedaling motor will provide more power to complement the shortage.

There are several types of torque sensors available in the market, namely bottom bracket sensor, idler wheel on chain sensor, strain gauge on rear axle, crank sensor and spring gauge technology (44).

**Bottom bracket sensor**

These types of sensors are integrated to the bottom bracket of bicycle and are invisible components (Figure 20). There are several manufacturers of this type of sensors for electric bicycles such as Thun, NCTE or Bafang and for each of them the technology used can be slightly different. Nevertheless, they are usually protected from water and dirt, are able to operate at low and high temperatures, do not require any maintenance and re-calibration (45) (46) (47).

*Figure 20 – X-Cell RT bottom bracket sensor. Source: www.thun.de*

In order to measure cadence, rotational direction and torque X-Cell RT sensor by Thun uses a system composed from 2 hall sensors and a PCME sensor. Furthermore, the collected information can be sent to the controller as an analog (sinusoidal) or digital signal (48).

Although these types of sensors have many advantages and they are beneficial for a good electric bicycle, the biggest disadvantage which they have is probably the high price; it can be up to € 245 (45).

**Idler wheel on chain sensor**

An example of idler wheel on chain sensor is TMM4 produced by IDbike Company. It is designed in a way to feel the tension on the chain, and thus to measure the crank torque of the cyclist. Figure 21 shows that the sensor itself can be fully covered by a plate, which protects it from external factors and makes an improved appearance (49).

a b

*Figure 21 – a. TTM4 sensor, b. TTM4 sensor installed in bicycle. Source: www.idbike.com*

The working principle of this sensor is based on the sensor plate, i.e. the deflection of the plate caused by the chain force is being measured, which allows to calculate the torque of the cyclist. The sensor itself consists of a case from engineering plastic where a printed circuit board, a magnet and a small set screw are mounted (49).

**Strain gauge on rear axle**

This sensor is used by BionX, which is a company who produces electric bicycle conversion kits, as well as separate products for converting regular bicycle into an electric one. They are using Proven Strain Gauge (PSG) technology, where the sensor is integrated in the motor itself. Thus, it provides smooth operation and remains seamless (50). As the sensor is a part of the motor it is not possible to purchase it separately, Figure *22* shows an example of such hub motor for electric bicycle.


*Figure 22 – BionX D series motor. Source: ridebionx.com*

**Crank sensor**

Combined torque and rotation sensor integrated into the bicycle crank-arm is another type of solution for pedal assist electric bicycle (51). HESC Twin Sensor shown in Figure 23 is an example of this type of sensors produced by ST Suntour.

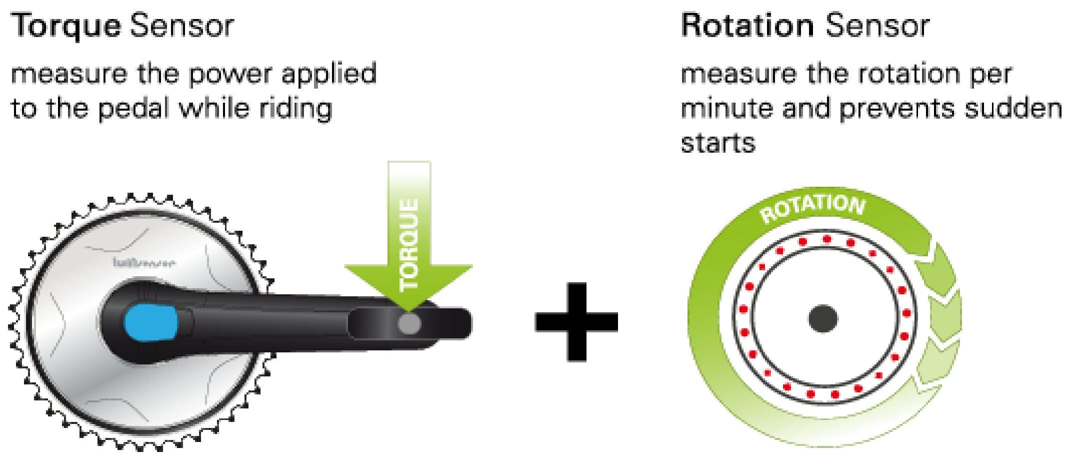



*Figure 23 – Twin Sensor technology by ST Suntour. Source: www.dev.srsuntour-electric.com*

The centerpiece of the crank set forms a state-of-the-art torque sensor which continuously monitors pressure on the pedal. What is more, with this information controller is able to calculate the exact amount of the power at which motor has to work for maintaining the desired wheel speed. Combination of torque and rotation sensors causes smooth and natural operation; moreover, as the torque is measured at the spot where it first impacts, the high accuracy of the measurement is achieved (51).

**Spring Gauge**

This type of torque sensor is used in electric bicycles produced by Stromer Company. As it is shown in Figure 24 the construction is very simple, it consists of a spring and a sensor itself which should be mounted on the rear dropout of the bicycle (44).

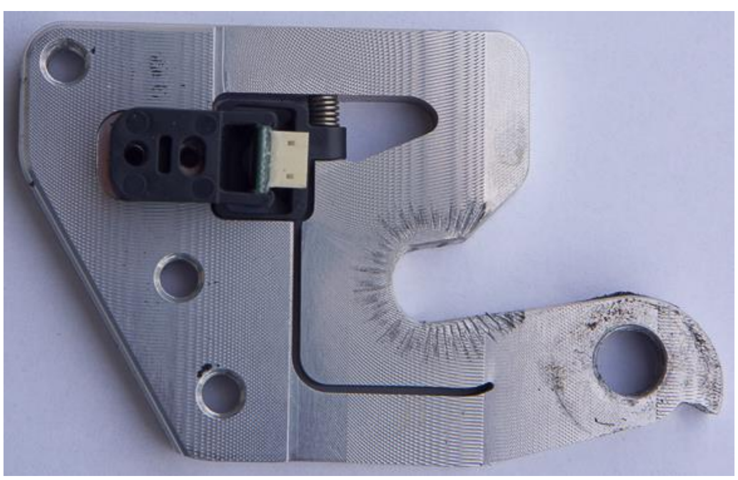
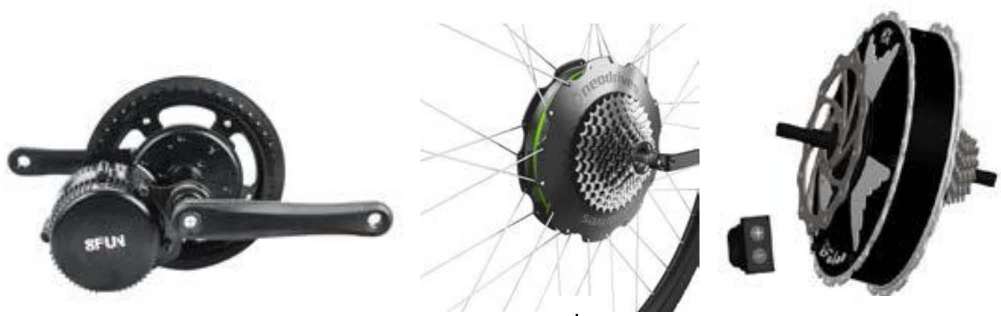


*Figure 24 – Spring gauge by Stromer. Source: www.electricbike.com*

For one of the sensor types mentioned above, namely the one produced by BionX the sensor is integrated to the motor, which brings to smooth and decent operation. Figure 25 shows that there are some other companies, which adopted similar solution and integrated either speed or torque sensor into the motor (52). Considering the fact that the company producing an electric bicycle for sharing system most likely will purchase the motor from an external partner instead of producing an own motor, the option of motor with integrated sensor might be a suitable and elegant solution.




a b c

*Figure 25 – Electric bicycle motors with integrated sensors. a. 8Fun, b. Neodrives, c. Falco (52)*

### 3.2.3 Controllers

Controller can be considered as a brain of electric bicycle, it receives information from hall sensors concerning the rotor position in order to energize the brushless DC motor in an appropriate way. Moreover, the data from all the other sources, such as speed, cadence or torque sensors are received and analyzed by controller. Based on the provided information controller regulates the power of the motor. What is more over-voltage, over-current and thermal protections are also handled through the controller of the electric bicycle (1).

In general the controller of electric vehicles operates between the battery and the motor; it converts DC from the batteries into AC for the motor. Some controllers are also able to convert the motor into a generator, so that the regenerative braking technology can be applied. Modern controllers regulate the power of the motor, and thus adjust speed and acceleration of the vehicle through pulse width modulation process. This technique is based on switching devices, for instance silicon-controlled rectifiers, which rapidly interrupt the flow of electricity to the motor. When intervals are short high power is achieved and in case of long intervals the power is lower (53).

Based on the type of the electric bicycle, i.e. pedal assist or throttle based, as well as the specific features which the bicycle may or may not have, its controller can vary a lot. Figure 26 shows an example of the working diagram of controller for an electric bicycle with Brushless DC motor (54).

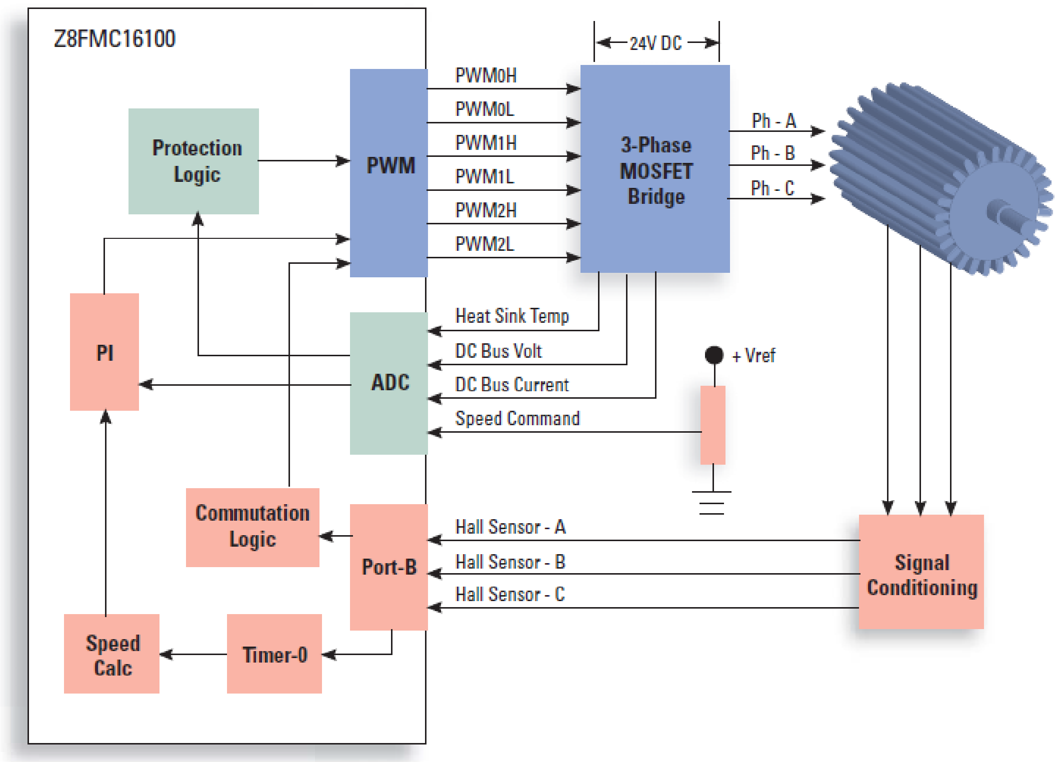



*Figure 26 – Controller block diagram of an electric bicycle with BLDC motor (54)*

Some of the companies which produce motors for electric bicycles, for instance Bafang (Figure 27) (55) is also producing controllers which suit their motors in the best way. What is more, there are also motors for electric bicycles which are produced with already integrated controller (52).

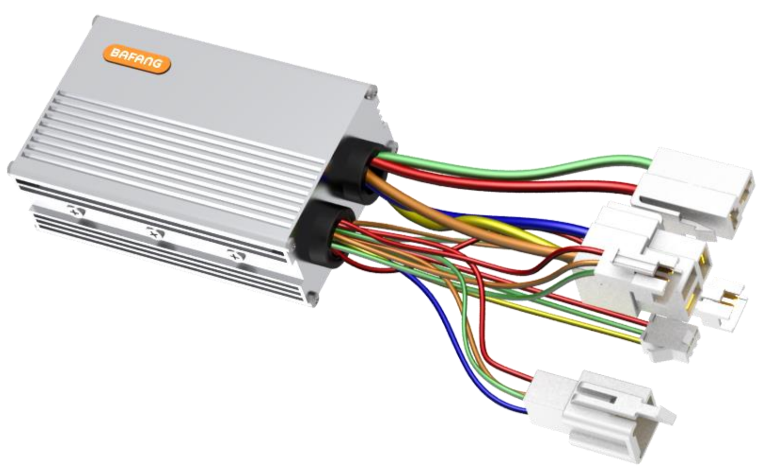



*Figure 27 – Electric bicycle controller by Bafang. Source: www.szbaf.com*

Table 16 provides an overview of several motor and controller manufactures for electric bicycle and compares their products.

*Table 16 – Comparison of different manufacturers of electric bicycle motors and controllers*

| | Bafang | BionX | Bosch | Ananda | ETM Power | Falco | Heinzmann |
|---|---|---|---|---|---|---|---|
| Motors | Hub and mid-drive | Hub | Mid-drive | Hub | Hub | Hub | Hub |
| Separate controllers | Yes | No | No | Yes | No | No | Yes |
| Integrated controllers | No | Yes | Yes | Yes | No | Yes | No |
| Integrated torque, cadence or speed sensors | No | Torque | Torque, cadence and speed | Speed or torque | No | Torque and/or crank | No |
| Separate sensors | Yes | No | No | Yes | No | No | Yes |

Taking into consideration the fact, that the company which assembles an electric bicycle for sharing systems will most likely buy a motor from some external partner, it is also recommended to purchase a controller from the same manufacturer. That will help to avoid problems with the incompatibility of motor and controller.

## 3.3 Batteries

The first rechargeable battery was invented by French physicist Gaston Planté in 1859, it was based on lead acid, the technology which is widely used even today (56). Although nowadays there is a huge variety of different technologies for rechargeable batteries in practice only four of them are suitable for electric bicycle. These batteries are Lead Acid, Nickel Cadmium, Nickel Metal Hydride and Lithium-ion or Lithium Polymer (57). In the following sections a closer look to these technologies will be done.

### 3.3.1 Lead Acid (PbA)

Based on the purpose of the usage there are two types of Lead Acid batteries, namely Starter and Deep-Cycle. While both types of batteries can look identical, they have different construction and purpose. Starter battery is designed for cranking an engine of vehicles by providing momentary high power burst, but it is not suitable for long term and constant power supply (58). In opposite, Deep-Cycle battery is designed to meet this purpose; hence, for electric vehicles and particularly for electric bicycles this type of Lead Acid battery should be considered. Performance of Deep-Cycle battery is shown in Table 17, where Depth of Discharge (DOD) is a method to indicate the state of charge of the battery (DOD = 100% means battery is empty, DOD = 0% means battery is full) and cycles represent the lifetime of the battery, i.e. how many times it can be discharged and charged until it degrades irreversibly (59) (60).

*Table 17 – Cycle performance of Deep-Cycle Lead Acid battery (58)*

| Depth of Discharge | Cycles |
|---|---|
| 100% | 150-200 |
| 50% | 400-500 |
| 30% | 1000 and more |

Lead is a toxic substance and from the environmental point of view it would be better to replace all these types of batteries based on lead with some other configuration. Nevertheless, currently the alternatives and in particular the Li-ion batteries are not able to offer competitive price.
Advantages and disadvantages of Lead Acid batteries are described below (58)

**Advantages**

- Cheap technology and easy to produce
- Lowest self-discharge
- Good performance at low and high temperatures

**Disadvantages**

- Low energy density, poor weight-to-energy ratio
- Long charging time (can be up to 14 hours)
- Repeated deep-cycling reduces battery life time
- It is not environmentally friendly

Valve-regulated Lead-Acid (VRLA) battery is another type of Lead Acid battery and Absorbent Glass Mat (AGM) is a type of VRLA battery. In these types of batteries the plates can be flat to fit the standard rectangular case of flooded Lead Acid battery or they can be in cylindrical cell (61).

**Advantages**

- It is maintenance free
- Up to 5 times faster charge time compared to flooded technology
- Better cycle life than flooded technology
- Resistant to vibrations
- Works well at cold temperatures

**Disadvantages**

- Higher manufacturing cost than flooded technology
- Sensitive to overcharging
- Its capacity has a gradual decline
- Low energy density
- It is not environmentally friendly

### 3.3.2 Nickel-Cadmium (NiCd)

For a long time Nickel-Cadmium was the technology preferred to be used for two-way radios, medical equipment, professional video cameras and many other tools (62). The biggest disadvantage which it has, is the environmental impact, it contains a toxic material and cannot be disposed of in landfills. Advantages and disadvantages of these types of rechargeable batteries are provided below (62):

**Advantages**

- Fast and simple charging
- High number of charging and discharging cycles (over 1000)
- Good load performance
- It can be stored in a discharged state
- Good performance at low temperatures
- Not expensive
- Available in a wide range of size and performance options

**Disadvantages**

- Relatively low energy density
- It needs periodic full discharges
- High self-discharge
- It is not environmentally friendly, cadmium is a toxic material

### 3.3.3 Nickel-Metal-Hydride (NiMH)

Modern Nickel-Metal-Hydride rechargeable battery provides 40% higher energy density than Nickel-Cadmium, but probably the most important advantage which it has, is the environmental compatibility as it contains only mild toxins. It is a good competitor for Li-ion batteries in the market of Hybrid Electric Vehicles, with two beneficial advantages, namely price and safety (62).

More details about the advantages and disadvantages of NiMH technology are given below (62):

**Advantages**

- Environmentally friendly, contains only mild toxins
- Has 30-40% higher capacity than standard NiCd
- It is less prone to memory
- Recycling is profitable, because it contains nickel

**Disadvantages**

- Limited service life, deep discharge reduces service life
- Complex charging algorithms
- Does not absorb overcharge well
- Generates heat during fast charge or high load discharge
- High self-discharge, 20% during the first 24 hours
- Performance degrades at high temperature

### 3.3.4 Lithium-ion or Lithium Polymer

Lithium is the lightest of all metals, it has great electrochemical potential and provides the highest energy density per weight. Although rechargeable batteries with lithium metal on anode can provide extremely high energy density, it is not safe to use. Due to the unwanted dendrites it is possible to have a thermal runaway which is also called "venting with flame" (63).

In contrast with dangerous Lithium-metal, the Lithium-ion rechargeable battery is safe and does not have the problem mentioned above. Even though, Li-ion has lower energy density then the Lithium-metal it is still the twice of NiCd rechargeable battery and has high nominal voltage of 3.6 V in contrast with 1.2 V of nickel based system (63).

Li-ion battery is widely accepted for portable devices and consumer industry thanks to its high energy density and absence of toxic materials. Due to these characteristics, as well as, gradually reducing cost it gains popularity also in the market of electric vehicles (63).
Advantages and disadvantages of Li-ion rechargeable battery are described below (63).

**Advantages**

- High energy density
- Capability of rapid charge and high load
- Sealed cells
- Long cycle

- No maintenance is required
- Environmentally friendly
- Good energy efficiency
- Low self-discharge

**Disadvantages**

- High cost
- Protection circuit is required for limiting the voltage and current
- Possibility of venting and thermal runaway in case of stress
- It degrades at high temperatures
- No rapid charge is possible at temperatures below 0 °C

It is vital to know that there are different types of Li-ion batteries, mainly based on the material of the cathode. Some of them are suitable for electric vehicles and are used in electric bicycles or cars.

**Lithium Manganese Oxide ($LiMn_2O_4$)**

Lithium Manganese Oxide (LMO) has around 50% higher specific energy compared with the nickel based batteries. Mostly Li-manganese can be combined with Lithium Nickel Manganese Cobalt Oxide (NMC), which improves the specific energy and also makes life span longer. The combination of these two technologies takes the best characteristics form each system. For that reason it is used in many electric vehicles (64).

**Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$)**

This battery is based on nickel-manganese-cobalt technology for a cathode and it can be tailored either for high specific energy or high specific power. It is widely used in electric bicycles and other powertrains with a cathode combination of one-third cobalt, one-third manganese and one-third nickel (64).

**Lithium Nickel Cobalt Aluminum Oxide ($LiNiCoAlO_2$)**

Lithium Nickel Cobalt Aluminum Oxide or NCA has high energy density, good specific power and long life span. However, its cost and safety are less attractive. This type of battery is used in Tesla Electric Vehicles (64).

**Lithium Titanate ($Li_4Ti_5O_{12}$)**

In this type of battery the graphite of anode of the usual Li-ion is replaced with Li-titanate. The cathode is graphite and it resembles the standard architecture of the Li-metal battery. It has several advantages such as safety and excellent low temperature discharge characteristics. Nevertheless, it is expensive and has low energy density (64).

There overall characteristic of the above mentioned types of Li-ion batteries are summarized in Table 18.

*Table 18 – Characteristics of different Li-ion batteries (64)*

| | Lithium Manganese Oxide ($LiMn_2O_4$) | Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$) | Lithium Nickel Cobalt Aluminum Oxide ($LiNiCoAlO_2$) | Lithium Titanate ($Li_4Ti_5O_{12}$) |
|---|---|---|---|---|
| Nominal Voltage | 3.7 V | 3.6 - 3.7 V | 3.6 V | 2.4 V |
| Specific Energy | 100-150 Wh/kg | 150-220 Wh/kg | 200-260 Wh/kg | 70-80 Wh/kg |
| Cycle Life | 300-700 | 1000-2000 | 500 | 3000-7000 |

Comparison of the specific energy for different types of batteries are presented in Figure 28 (65).

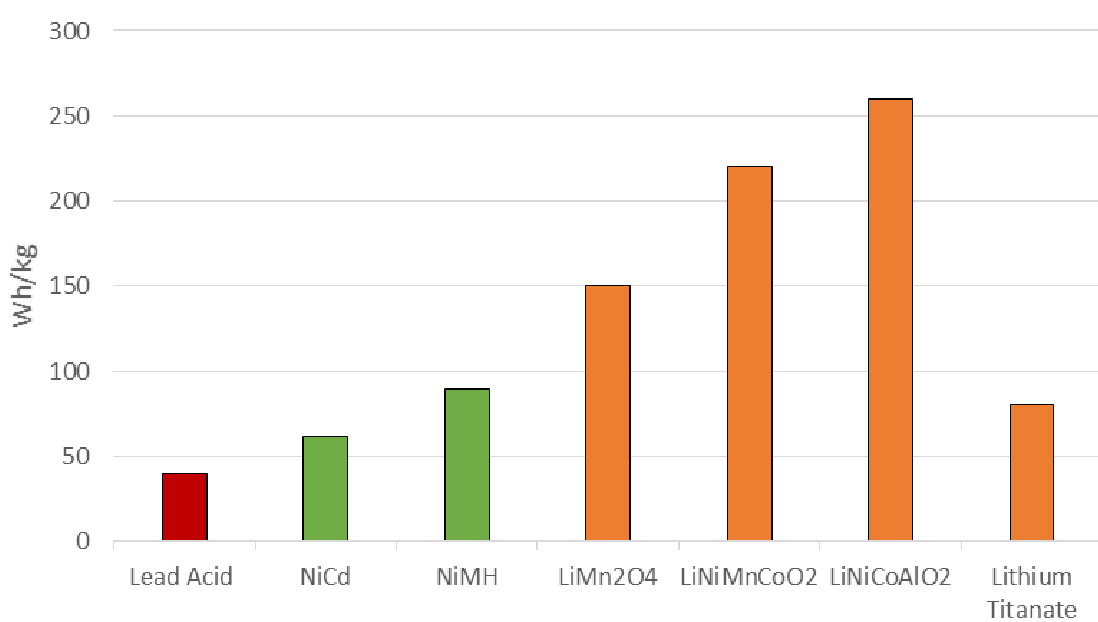



*Figure 28 - Specific energies of different batteries*

### Lithium Polymer

Lithium Polymer is not considered as a unique chemistry, it can be built in many different battery systems, for instance Li-Cobalt, NMC, Li-Manganese, etc. In order to make the modern Li-polymer batteries conductive at room temperature, gelled electrolyte is added. It is basically the same Li-ion, with the same cathode and anode material, and with similar amount of electrolyte. All the Li-polymers today have a micro porous separator with some moisture. Thus, the only difference from Li-ion is that traditional porous separator is replaced by micro porous electrolyte. Li-polymer has slightly higher energy density and can be a bit thinner from Li-ion, but the cost of its production is approximately 30% higher.

## 3.3.5 Costs and capacities of e-bikes batteries

Capacity of the battery for electric bicycles varies a lot based on the producer of the bicycle and its type. Battery with higher capacity can run the electric motor for longer time, but it also leads to more expensive cost and heavier weight of battery. Therefore, in order to select correct battery for electric bicycle it is necessary to take into consideration requirements of the target market. Typically the energy capacity of the batteries for electric bicycles vary between 240 Wh and 550 Wh, however, higher capacities are possible as well.

Different battery packs can come in different capacity (Ah) and rated voltage (V). Typically these characteristics can vary between 9 - 12 Ah and 12 - 48 V for the capacity and rated voltage respectively, although again, these ranges are not critical and it is possible to find batteries within other capacity and rated voltage ranges.

Cost comparison for different types of batteries is done according to the prices available at Battery Space website (66), which is an online shop specialized on batteries and charging solutions. Results are provided in the Table 19.

*Table 19 – Cost comparison of different rechargeable batteries*

| | Lead-Acid | NiCd | NiMH | Li-ion/Li-polymer |
|---|---|---|---|---|
| Capacity | 480-600 Wh | ~500 Wh | 400-600 Wh | 400-600 Wh |
| Price* | € 77-118 | € ~360 | € 410-550 | € 450-730 |
| Weight | 15-18 kg | ~12 kg | 7-12 kg | 2.3-3 kg |

*Currency was converted from USD to Euro with the conversion rate $ 1 = € 0.91

## 3.4 Bosch example

In this section an overview of commercially available electric bicycle conversion kit produced by one of the big companies will be done in order to see all the similarities and differences between the needs of the electric bicycle in sharing system and for the private use.

Bosch company has several electric bicycle conversion kits and all of them are based on the mid drive technology. Figure 29 shows a system which consists of a drive unit, power pack, eShift gear shifting system and a clever control center (67).


*Figure 29 – Active Line eBike system by Bosch. Source: www.bosch-ebike.de*

As it was mentioned earlier that the kit is based on mid-drive technology. Therefore, the drive unit should be located on the middle of the bicycle and cranks with pedals should be attached to the motor instead of the crank freewheel. The motor is equipped with a 3-sensor concept which takes measurements 1000 times per second and powerful electronics to perform the necessary control (67).

Battery is offered by Bosch is based on the Lithium-ion technology with an output voltage of 36 V and capacity of 8.2 Ah or 11 Ah, based on the pack type. What is more, the pack can be installed either on the rear carrier or on the down tube of the bicycle. The kit also includes an innovative electronic gear shifting solution which was designed together with the leading manufacturers such as Fallbrook, Shimano and SRAM. Lastly, the Intuvia clever bike control center completes the conversion kit, it suggests five different motor assistance levels and a user friendly menu provides information concerning speed, battery level, distance, etc… It also can be removed from the bicycle and information concerning all the trips can be extracted. In addition the device is equipped with a USP port giving possibility to charge a cellphone or some other portable device (67).

*Figure 30 - Ortler Bozen bicycle with Bosch eBike conversion kit. Source: www.bikester.es*

Figure 30 shows an example of such a system installed on the Ortler bicycle which can be purchased by around € 2100 (68).

## 3.5 Selection of components and design of the electric bicycle

In this section all the components for the electric bicycle will be selected taking into consideration the analysis which was done above, as well as the fact that the bicycles will be used in a sharing system, and therefore the choices of the components should be justified by the needs of the electric bicycle sharing system. For that reason, it is preferable to select simple and not very expensive solutions which are reliable and suitable for the use in an urban environment. Therefore, hub motor technology will be used instead of mid-drive, which is more complicated and also expensive (2). Moreover, all three electric bicycle sharing systems which have been analyzed in this report are using hub motor technology, thus the choice of this powertrain type is also based on the experience of these systems.

Furthermore, it is necessary to choose between rear and front wheel hub motors. As it was discussed earlier there is no big difference between these two options and both types are used in shared electric bicycle systems. However, the preference in this project will be given to the front wheel hub motor technology in order to have a better weight distribution and more accurate design.

Considering that the power of the motor is limited by legal regulations (3), a motor with 250 W power will be selected for the bicycle. Moreover, based on the analysis concerning different types of sensors which was done earlier it is reasonable to choose a motor with integrated torque sensor in order to have smooth performance and reasonable price. As for the geared and gearless technologies, the preference will be given to the first option because of its compact size and light weight, as well as the availability of the free wheel which eliminates the motor resistance. Therefore, Ananda M130 V motor with integrated controller and torque sensor is selected (52), more technical details of the chosen motor are available in Table 26 in **Appendix**.

Out of all the battery types which were discussed, the lithium-ion technology is believed to be the most preferable for the electric bicycles in this project. Although it is more expensive than Lead-acid and Nickel based batteries, it has high energy density, long lifetime and light weight which are vital aspects for the good user experience. The output voltage of the battery should correspond the need of the motor, i.e. it should be 36 V. Taking into account the experience of the Prismattery concerning battery technologies, it is decided that the battery pack with a battery management systems will be produced in-house using the externally purchased $LiNiMnCoO_2$ cells and other necessary components. The choice of this exact cell is based on its high energy density and long lifetime.

Knowing that the capacity of one cell is 2200 mAh (69) they will be connected in a way to have a total capacity 11 Ah and voltage 36 V as it is required for the motor. Therefore the energy capacity of the pack will be 396 Wh. In order to have the desired output the pack will be formed from 5 parallel lines and each line will have 10 cells in series as it is shown in Figure 31.

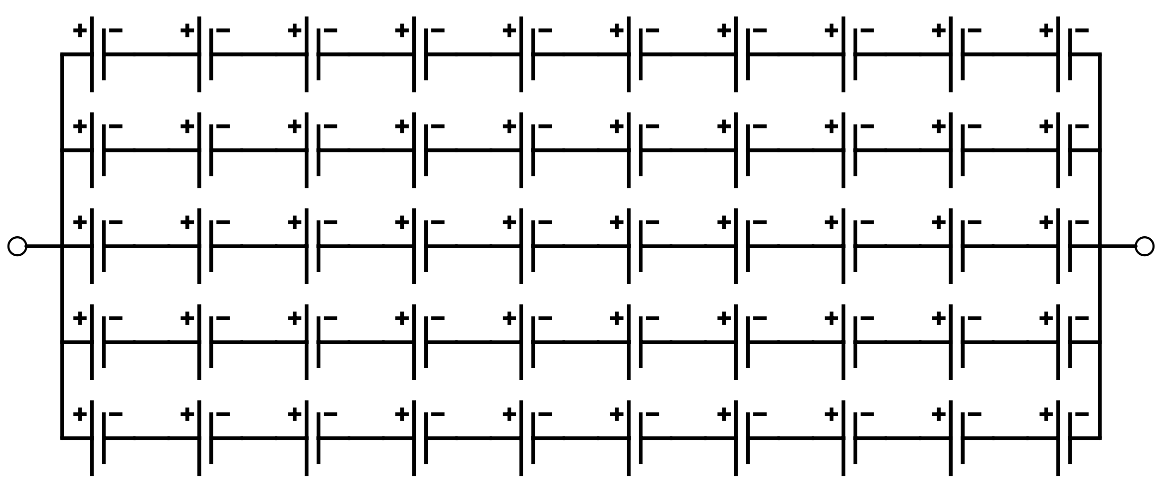


*Figure 31 – Connection of $LiNiMnCoO_2$ battery pack*

As it can be seen in Table 27 in the **Appendix**, 36 V and 3 A are recommended parameters of the charger for the selected battery pack. What is more, 3 A is the current for quick charging rate, while in a slow rate it is 1.5 A (70). More details about charging solutions and circuit will be discussed in the following section. However, it is vital to mention that chargers will be connected to the circuit already on the low voltage DC side and similarly to the battery packs, they will be produced "in-house".

Bicycle will also be equipped with inexpensive and simple console only for selecting the assistance level of the motor and showing the battery status. Remembering that the electric bicycle will be used in a sharing system and will be ridden by many different users, it is not reasonable to choose more expensive device.

Furthermore, the bicycle will be equipped with GPS device, in order to be able to track and know its location and an LED light with daylight sensor in a way that it will be switched on automatically if bicycle is used in darkness.

Finally, it is worth to mention that the software solution which is necessary for controlling the electric bicycle sharing system will be produced "in-house" by Prismattery.

The vector diagram of the electric bicycle showing the locations of the devices discussed above is shown in Figure 32.

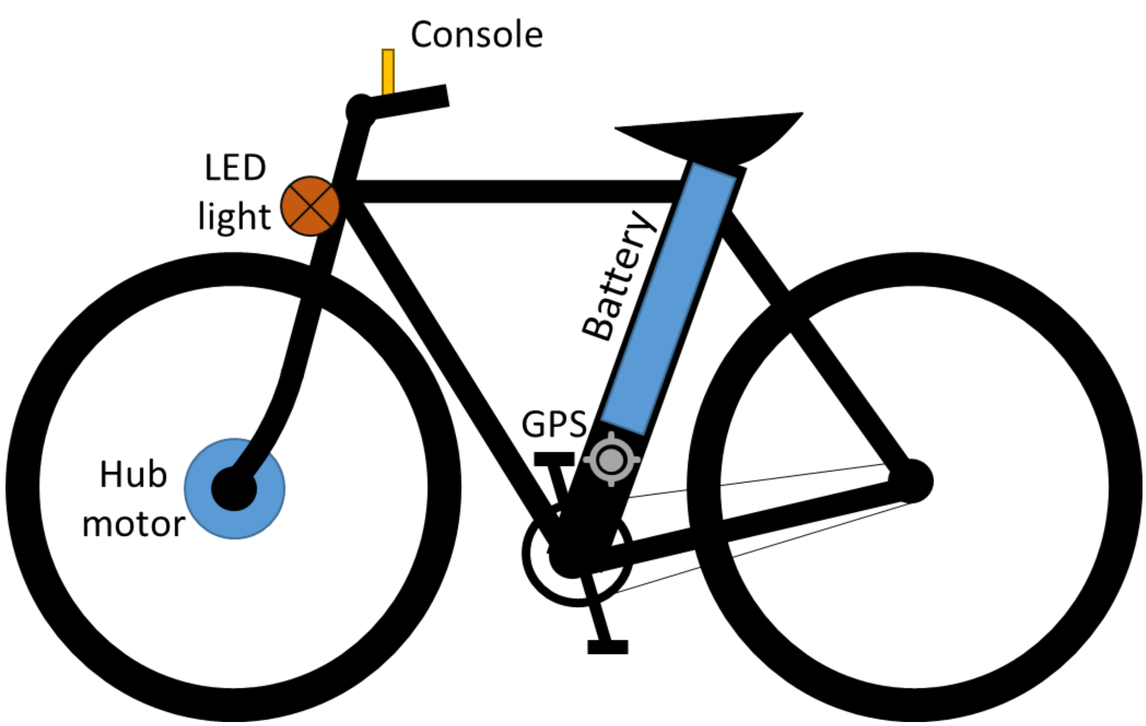



*Figure 32 – Vector diagram of the electric bicycle*

All the important components of the electric bicycle designed in this project, their characteristics and prices are summarized in Table 20 (71), (72). Prices for the console, GPS and LED light are assumed values.

*Table 20 – Technical specifications and costs of the components of the electric bicycle*

| Type of the electric bicycle | Pedal-assist | Cost |
|---|---|---|
| Motor type and power | Brushless DC, 250 W | € 150* |
| Controller | Integrated to the motor | |
| Sensors | Integrated torque sensor | |
| Power-train type | Frond wheel hub motor | - |
| Battery | $LiNiMnCoO_2$ : 11 Ah – 36 V | € 5.7* for one cell<br>€ 285 for the pack of 50 cells |
| Console | Simple, without display | € 15 |
| GPS | Available | € 50 |
| LED light | Available with daylight sensor | € 20 |

*Currency was converted from USD to Euro with the conversion rate $ 1 = € 0.91

Furthermore, it is also reasonable to assume that the price of the bicycle itself excluding the above mentioned components is approximately € 500. This assumption can be justified by looking on the cost of the electric bicycle in Bicing system, which, as it was mentioned earlier is € 1500, where 40 % of the price belongs to the battery. Therefore, the total cost of the electric bicycle is evaluated to be € 1020.

## 3.6 Charging solutions

### 3.6.1 Battery Management System and charging protocols

Battery Management System (BMS) is necessary for controlling the battery and securing its safe operation. BMS is responsible for monitoring the currents which are going into and out of battery during the charge and discharge respectively. Moreover, it is limiting overcharge and undercharge in the cells, ensuring the cells balancing and safe operation of the battery pack (73).

Batteries in many applications, for instance laptops or mobile phones, are being slowly discharged during the time and periodically recharged. For such batteries the primary role of the Battery Management System is to ensure the short time full recharging without damaging the battery and reducing its lifetime. Furthermore, if the device if plugged in BMS should decide whether maintain the full charge and draw outlet power, run off the battery without drawing outlet power or somehow combine these two options. For more complex systems, such as Hybrid Electric Vehicles which are being charge and discharged continuously BMS should be more advanced and be able to decide whether to dedicate full or partial current going into or out of battery for respectively charging or discharging it at any instant moment (73). The battery of an electric bicycle which does not have a regenerative braking operates more or less in a similar way as laptop battery. Therefore, it will belong to the first type of applications which does not require very complex BMS.

The objectives of battery charging are restoring the full state of charge in the most efficient way and in a shortest possible time. There are three main charging protocols for reaching these objectives (73):

- Constant Voltage (CV)
- Constant Current (CC)
- Combination of constant voltage and constant current (CV-CC)

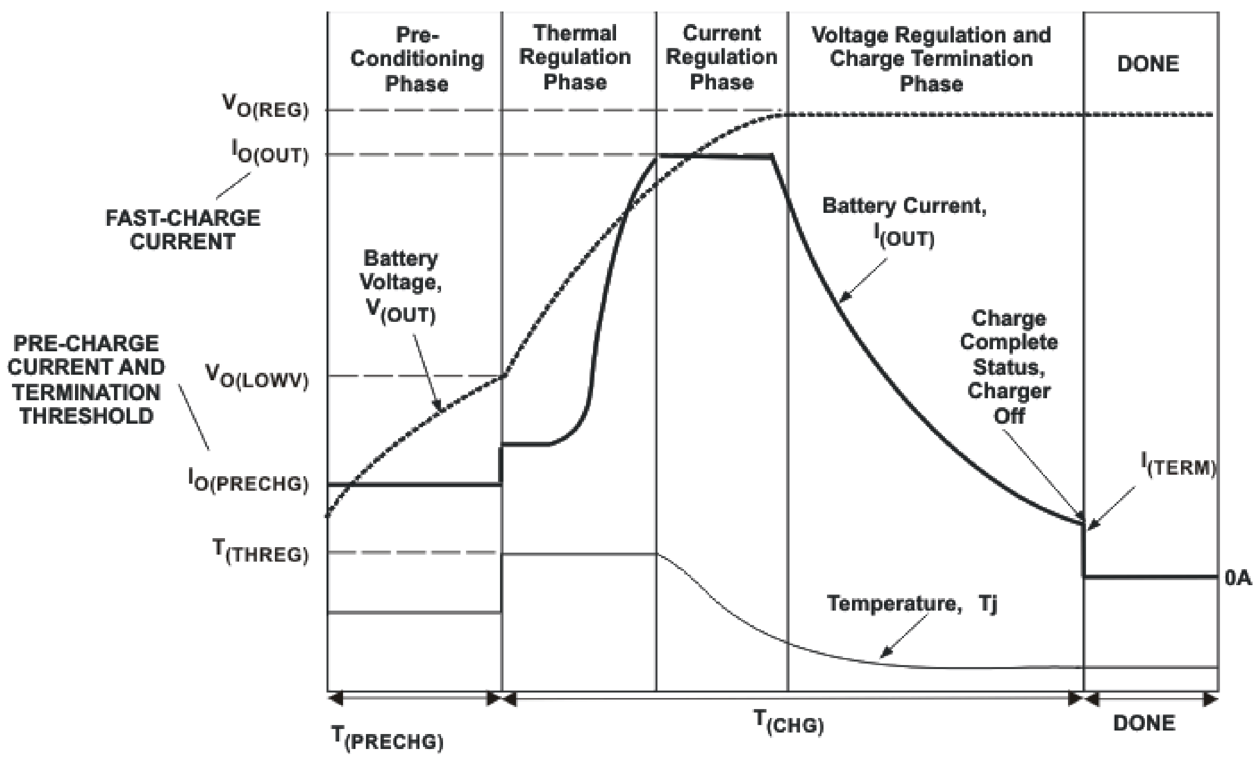



*Figure 33 – CV-CC charging profile with thermal regulation. Source: Texas Instruments, www.ti.com*

Figure 33 shows an example of CV-CC charging profile for Li-ion battery with a thermal regulator. When the battery voltage is below $V_{O(LOWV)}$ level which can be seen in the figure, the battery is assumed to be discharged, and therefore a pre-charge current $I_{O(PRECHG)}$ is applied until the voltage reaches $V_{O(LOWV)}$ level. This charging phase is called pre-conditioning and is followed by thermal regulation phase, where the current rises until temperature of the cell or the charger reaches $T_{THREG}$. In case the temperature remains below of the mentioned level, the fast-charge current $I_{(OUT)}$ is applied until reaching the $V_{O(REG)}$ voltage level. Furthermore, current is gradually reduced in order to maintain the voltage level of the cell and when it gets to $I_{(TERM)}$ the charge is complete and the charger is switched off (73).

### 3.6.2 Charging circuit

Based on the time necessary for the full charge of a battery it is possible to classify fast-charging and slow-charging technologies. If the circuits for slow-charging are relatively simple, fast-changing circuits should take into consideration the chemistry of the battery as well as provide reliable charging and charge termination (74).

Figure 34 shows an example of a battery charging circuit which is normally used for fast-charging technology. This circuit provides Constant Current charging, which is being maintained through $R_{SENSE}$ resistor. During the whole operation the voltage is monitored with a microcontroller. Sometimes temperature monitoring is also required for determining the state of the battery and the end of the charge (74).

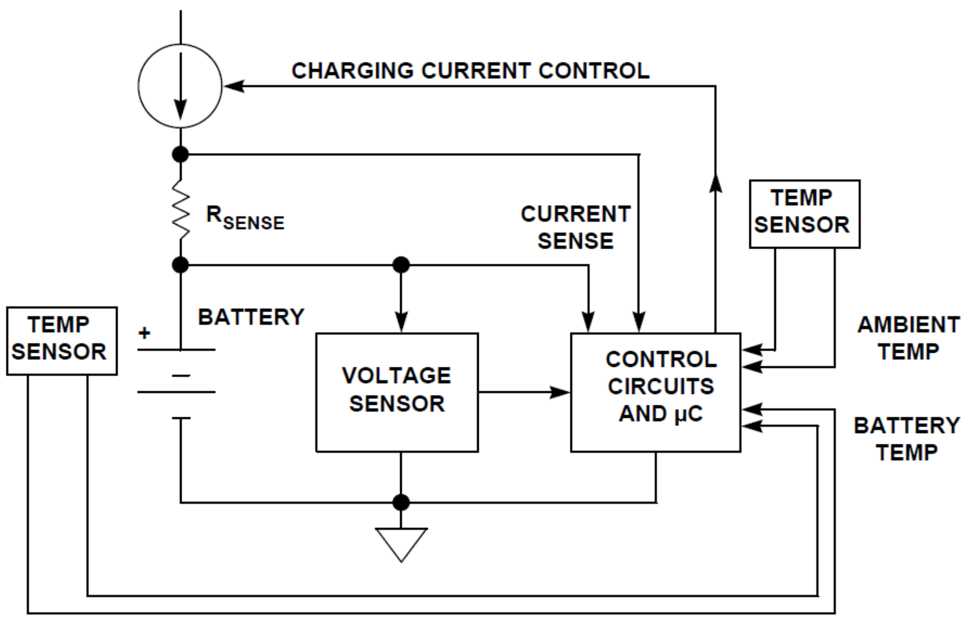



*Figure 34 – Generalized battery charging circuit. Source: Analog Devices (74)*

Figure 35 shows the circuit for charging several electric bicycles at the stations. In the scheme is shown that the power source is the electrical grid which operates under 230 V AC voltage. The circuit includes AC step down transformer which delivers 36 V AC voltages in the exit, AC-DC rectifier and capacitor for smoothing the voltage drop. Further the outcome goes to the DC bus to which special sockets for charging electric bicycles are attached, and thus when batteries are connected they will react as a load and will be charged with DC current.

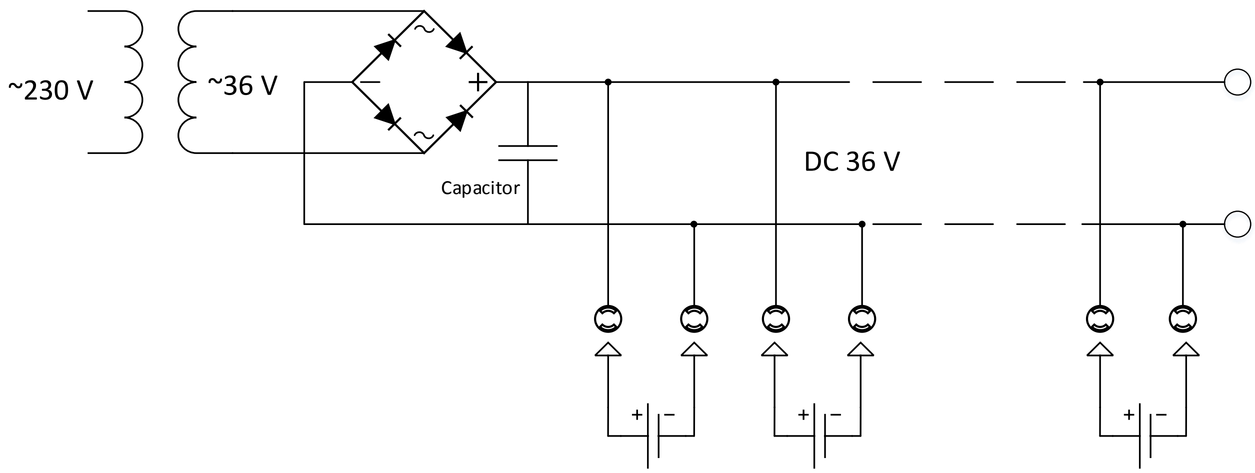



*Figure 35 – Charging circuit of electric bicycles station*

As in the DC side all the sockets and consequently batteries are connected in parallel the voltage for charging is the same, i.e. 36 V at all of the sockets.

### 3.6.3 Load analysis and sizing

In order to fulfill an accurate charging of the batteries it is necessary to design the charging circuit accurately, select correct source of power and calculate the cross sections of the connecting cables, wires and/or buses. Thus, the load on the network in case of charging several batteries simultaneously should be taken into consideration.

As it was mentioned earlier the output current from the charger in case of fast charging mode is 3 A. Therefore, the current which will flow in the circuit in case of connecting several electric bicycles at the same time can be high. Additionally, for more precise calculations it is assumed that the station has 10 docking spots which are connected in parallel, i.e. the maximum current which flows in the low voltage side when batteries of all 10 bicycles are being charged simultaneously can be calculated as follows:

$$I_{LV.Bat}^{DC} = N * I_{Ch} = 10 * 3 = 30\ A,$$

where $N$ is the number of bicycles simultaneously charging under the constant current and $I_{Ch}$ is the current of the charger under constant current charging mode. For accurate sizing an additional 20%

current was considered which may occur if in future an additional charging sockets or some other auxiliary equipment will be necessary to install at the station.

$$I_{LV}^{DC} = 1.2 * I_{LV.Bat}^{DC} = 1.2 * 30 = 36\ A$$

Therefore, the total maximum load can also be calculated:

$$P_{Total} = I_{LV}^{DC} * U_{LV} = 36 * 36 = 1296\ W,$$

where $U_{LV}$ is the voltage on low voltage side.

Having this value, it is now possible to calculate the maximum current which can flow on the high voltage side, which is necessary to know for selecting a correct cable. Taking into consideration the fact that the charging station is powered through a single phase circuit, the current can be calculated as flows:

$$I_{HV}^{AC} = \frac{P_{Total}}{U_{AC}} = \frac{1296}{230} = 5.63\ A, \text{ which can be rounded up to } I_{HV}^{AC} = 6\ A,$$

where, $U_{AC}$ is the AC voltage at the grid.

Furthermore, taking into account the fact that the charging station is powered from the grid, it is assumed that the circuit connects to the grid at the 400/230 V box which is located not more than 50 meters far. Table 21 shows the currents which will flow in the cables or buses of the circuit and the corresponding voltages.

*Table 21 – Currents and voltages in the circuit*

| AC side | | DC side | | |
|---|---|---|---|---|
| Grid to transformer | Transformer to AC-DC | Rectifier to bus | DC bus | Cables of sockets |
| 230 V | 36 V | 36 V | 36 V | 36 V |
| 6 A | 36 A | 36 A | 36 A | 3 A |

The other important criteria for sizing is the voltage drop, which according to the rule by the Institute of Electrical and Electronics Engineers (IEEE) should not increase 2.5 % of provided voltage (75).

Overall it is necessary to size accurately four cables and one bus. Calculation is provided below:

**AC cable which connects grid box to the step down AC-AC transformer**

Assuming that the cable is clipped to the wall directly, from Table 28 in **Appendix** can be seen that a cable with 1 mm$^2$ area corresponds for the mention current. However, it is also necessary to calculate if the voltage drop with the mentioned cable is within the acceptable range or not. As the acceptable range of voltage drop is 2.5% of the nominal voltage, it can be calculated as follows:

$$\Delta U_{AC}^{Acc} = \frac{2.5\%}{100} * U_{AC}^{HV} = \frac{2.5\%}{100} * 230 = 5.75\,V$$

Table 29 in **Appendix** shows that for the mentioned cable the voltage drop per meter is $\Delta U_{Cable} = 44\,\frac{mV}{A*m}$ and the drop for 50 m ($L_{Cable} = 50\,m$) cable will be:

$$\Delta U_{AC} = \Delta U_{Cable} * L_{Cable} * I_{Cable} = \frac{44}{1000} * 50 * 6 = 13.2\,V\ > 5.75\,V,$$

where $I_{Cable}$ is a current which flow in the cable.

As the voltage drop is higher than the acceptable one it is necessary to increase the cable area until it will be within the range.

Cross section: 1.5 mm$^2$, Voltage drop: 29 mV/(A*m)

$$\Delta U_{AC} = \Delta U_{Cable} * L_{Cable} * I_{Cable} = \frac{29}{1000} * 50 * 6 = 8.7\,V\ > 5.75\,V$$

Cross section: 2.5 mm$^2$, Voltage drop: 18 mV/(A*m)

$$\Delta U_{AC} = \Delta U_{Cable} * L_{Cable} * I_{Cable} = \frac{18}{1000} * 50 * 6 = 5.4\,V\ > 5.75\,V$$

Therefore, the cable with area **2.5 mm$^2$** is selected on 230 V AC side.

**Cables which connect transformer to AC-DC rectifier and rectifier to the DC bus**

Step down transformer and AC-DC rectifier are assumed to be located next to each other, and consequently the length of the cable which connects these two devices is not more than 2 meters. The cable which connects the rectifier to the DC bus is short as well and again is less than 2 meters. Seeing that the low voltage $U_{AC}^{LV} = 36\,V$, the maximum acceptable voltage drop can be calculated as follows:

$$\Delta U_{LV}^{Acc} = \frac{2.5\%}{100} * U_{AC}^{LV} = \frac{2.5\%}{100} * 36 = 0.9\ V$$

Assuming that the cable is clipped to the wall directly, from Table 28 in **Appendix** a cable with 6 mm$^2$ area should be chosen. The drop of voltage for the mention cable is 7.3 mV/(A*m) and the total voltage drop in the cable is:

$$\Delta U_{LV} = \Delta U_{Cable} * L_{Cable} * I_{Cable} = \frac{7.3}{1000} * 2 * 36 = 0.53\ V\ < 1.2\ V$$

Therefore, cable with **6 mm$^2$** area is suitable for the low voltage side of the circuit.

**DC bus to which charging sockets are attached**

The DC bus will go through all the length of the docking station so that special sockets for charging electric bicycles can be connected to it. For that reason a bus-bar with a rectangular section will be selected from Table 30 in **Appendix**. Considering the total current of 36 A, a bus with 15x3 mm should be selected.

**DC cables which connect each socket to the DC bus**

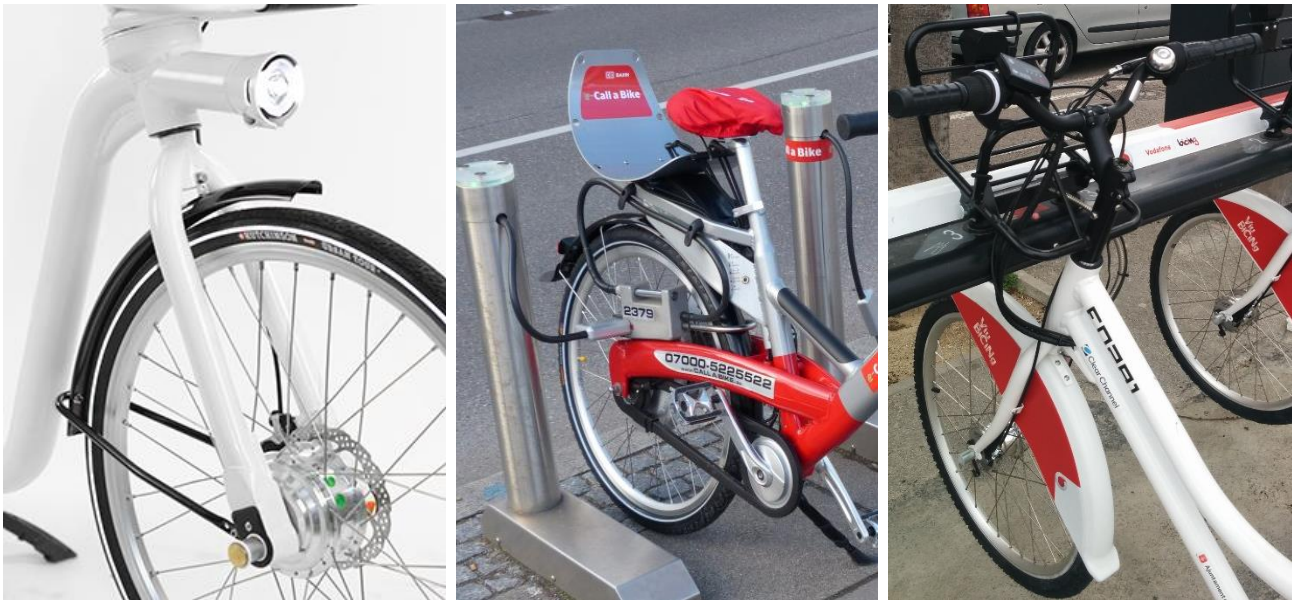
The length of these cables is very short and that is why the voltage drop is very low and can be neglected during the sizing.

The total current in the cable is 3 A, hence from Table 29 in **Appendix** a cable with **1 mm$^2$** is chosen.

Finally, as the maximum load in the network was calculated to be 1296 W, the capacity of the step down transformer which is necessary in the network for converting 230 V to 36 V, should be 1.5 kVA.

### 3.6.4 Charging with the automatic lock

Users of the shared electric bicycle should not worry about its charging. What is more, the process of checking bicycle in and out should be similar to regular bicycle sharing systems. Therefore, the electric connections for charging the battery need to be integrated to the locking system in a way to close the electric circuit and start charging when the bicycle is locked at the docking station. Although all three electric bicycle sharing systems which were discussed earlier in this report, namely Bycyklen, e-Call a Bike and Bicing have different approaches for solving the mentioned problem, all of them found a system which starts charging when the bicycle is locked.




a b c

*Figure 36 – Charging solutions of different electric bicycle sharing systems. a. Bycyklen, b. e-Call a Bike, c. Bicing*

As it can be seen in Figure 36 a. the electric bicycle of Bycyklen system has special contacts on the outer side of the bicycle's front fork. Bike is being locked simply by sliding the front wheel into the special docking spot, in that way the bicycle is being locked, the front wheel with the hub motor are protected from vandalism and the electric circuit is closed through the contacts on the front fork and the ones which are inside the docking spot.

E-call a Bike system uses metallic cable as it is shown in Figure 36 b., which ensures the secure locking of the bicycle and also has an integrated plug. Thus, it performs the role of the electric contact for closing the circuit. The locking system is similar to the one used in Call a Bike systems with regular bicycles and only the part with electric plug was added and the docking station is connected to the electric grid via subterranean serial bus (76).

The last system belongs to Bicing, locking of the electric bicycle is done through the special equipment which is connected to the bicycle handlebars and can be used also as a front basket. Although the locking mechanism is similar to the one used in the regular bicycle sharing system by Bicing, the endings of its anchors are also an electric contacts and by locking the bicycle the electric circuit is being closed. Thus, power is supplied to the battery of the electric bicycle through the wires which can be seen in Figure 36 c.

Taking into consideration the fact that the electric bicycle for the sharing system discussed in this project will have a front wheel hub motor, the most suitable charging solution out of the ones described above is the option with contacts on the front fork. It can be locked by sliding into the special docking slot as it is shown in Figure 37 and as it was mentioned earlier this kind of systems solve two problems, namely charging and securing the hub motor from vandalism.


*Figure 37 – Docking point for GoBike electric bicycle. Source: www.gobike.dk*

Therefore, similar solution will be applied for the electric bicycle sharing system discussed in this project. It is also worth to mention that for safety reasons the electric contacts inside the docking slot should be appropriately insulated from its frame with rubber gaskets and they should be able to work under different climatic conditions.

## 3.7 Cost of the design

Already knowing the cost of the bicycle, it is also vital to estimate the price of the whole system. For that reason a cost calculation for one station with 10 electric bicycles was performed and presented in Table 22, where prices of the equipment are based on different on-line sources (77) (78). Unfortunately, it was not possible to find a reliable information concerning the price of the AC-DC converter. Therefore, it was assumed to be equal to the price of the transformer.

What is more, an extra 30 % is added as a cost of cables and additional equipment, such as plugs, bus-bars, lights, rubber gaskets, etc…

*Table 22 – Prices of the components of the electric bicycle sharing station*

| Equipment | Price per unit/meter* | Units/meters | Total Price |
|---|---|---|---|
| 230/36V AC transformer 1.5 kVA | € 250 | 1 | € 250 |
| AC-DC converter | € 250 | 1 | € 250 |
| Payment terminal | € 1274 | 1 | € 1274 |
| Cables and additional components | Extra 30 % | | € 532 |
| **Total** | | | **€ 2306** |

*Currency was converted from USD to Euro with the conversion rate $ 1 = € 0.91.

The cost of the installation and construction works are not considered in this calculation, because they will vary in different countries and are considered to be as an additional service.

Remembering that the price of the electric bicycle was estimated to be € 1020 per unit, the cost of the one sharing station with 10 bicycles can be calculated as follows:

$$P_{sys} = P_{st} + N_{e.b.} * P_{e.b.} = 2306 + 10 * 1020 = € 12506$$

where $P_{sys}$ , $P_{st}$ and $P_{e.b.}$ are prices of the system, station and the electric bicycle respectively. $N_{e.b.}$ is the number of electric bicycles in the station.

## Conclusion of technical analysis

In this chapter various technical solutions concerning the components and drive-train types of electric bicycles were discussed and taking into considerations advantages and disadvantages of different solutions, as well as their suitability for the electric bicycle in sharing system all the necessary components for the bicycle were selected. Thus, an electric bicycle with Li-ion battery pack and front wheel geared BLDC motor which has integrated controller and torque sensor was designed. Moreover, the review of a bicycle with Bosch conversion kit highlighted the contrast between solutions applied for shared and private electric bicycles.

Further, the analysis which was done concerning charging problems showed that for electric bicycles in sharing systems it is necessary to have some solution which will allow automatic charging of the bicycle when it is locked at the docking station. Therefore, the working principle of a system which should be applied to the electric bicycle to allow automatic charging was explained.

And lastly considering the fact that electric bicycle need to be charged at docking stations, the electric circuit for providing necessary power to the station was designed and an appropriate sizing for supply cables was done.

# 4 Environmental analysis

## 4.1 Urban transportation

Both public and personal transportation are important components of urban commutation. Therefore, they should be managed and controlled accurately in order to avoid economic, social and environmental problems which can be caused by inappropriate management of the transportation system. Normally public transportation in cities can include city buses, trolleybuses, trams, metro systems and passenger trains (79).

In the segment of personal transportation one of the reasons of increasing number of traffic congestions in cities is that more people want to own a personal vehicle. Although increasing motorization is supposed to lead to faster and more comfortable journeys, it also causes traffic jamming which not only aggravate commuters, but also make trips time-consuming and not reliable. According to the Harvard Center for Risk Analysis the traffic congestions in the 83 largest urban areas of the USA caused more than 2200 premature death and added $ 18 billion to the public health cost in 2010 (80)(Figure 38).

*Figure 38 – New York, rush hour. Source: www.shutterstock.com*

As it was mentioned earlier in this report, many cities over the world have adopted bicycle sharing system and using it as a part of public transport system (31). Therefore, it is believed that these systems are not only decreasing the traffic load, but also have a valuable contribution in reducing emissions of pollutants such as $SO_x$, $NO_x$ and particulate matters (PM's) as well as greenhouse gases.

The importance and the topical role of shared bicycle systems in urban mobility is also represented in Figure 39, according to which most of the short and some part of mid-distance trips can be coved by shared bicycles instead of other public transportation systems. What is more, with electric bicycle sharing system the trip distance can be increased.

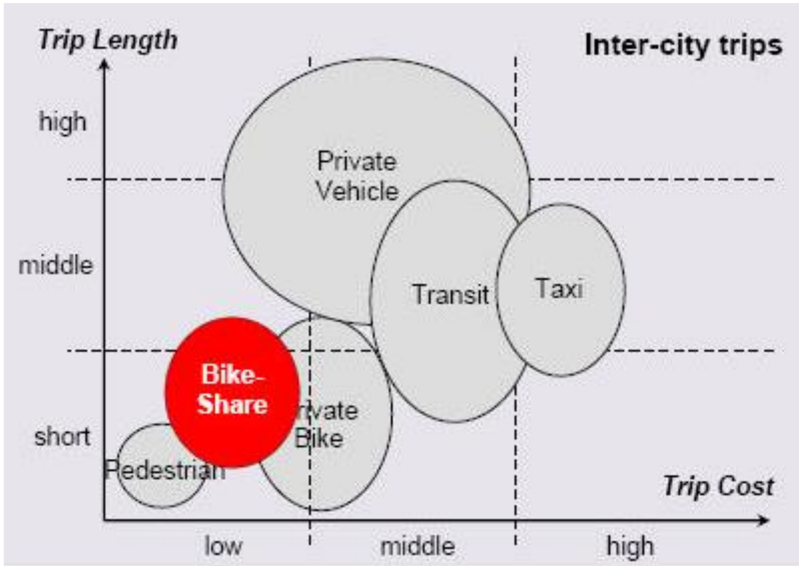



*Figure 39 – The role of bike sharing systems in urban mobility. Source: Quay Communications Inc. 2008.Trans Link Public Bike System Feasibility Study. Vancouver*

In contrast with more conventional urban transportation systems bicycles as well as electric bicycles sharing systems can have a valuable contribution in users' health. The study conducted by BMJ (British Medical Journal) which includes factors such as health benefit, air pollution and risks of road traffic crashes, shows that thanks to Bicing bicycle sharing system which operates in Barcelona, 12.46 deaths are avoided every year (81). Furthermore, health benefits for riding a pedal assist electric bicycle were also studied and it was proved that they provide certain level of physical activity and hence have positive input for the cyclist's health (4).

## 4.2 Emissions

Both regular and electric bicycles do not produce any emissions during the utilization; however, for electric ones it is required to have a battery which in some cases can be harmful for the environment. Moreover, a source of electrical energy is necessary in order to recharge the battery and that can be engaged with some emission; yet electric bicycles are considered to be Zero-Emissions Vehicles (82). Although it is not considered for the system in this project, but seeing that the energy demand of the electric bicycle sharing system is not very high, it is possible to power the whole system only using solar energy and avoid emissions from fossil fuels for electricity production depending on the electrical mix of the country. Moreover, there are several successful examples of docking and charging stations for electric bicycles which operate only with solar energy. For instance cycleUshare the pilot project in University of Tennessee (Figure 40) or the solar parking station for shared electric bicycles in Tokyo construed by Sanyo Electric (Figure 41) (83), (84).

*Figure 40 – CycleUshare electric bicycle station on AG Campus at University of Tennessee. Source: www.cycleushare.com*

*Figure 41 - Solar parking lots for electric bicycles in Tokyo. Source: www.treehugger.com*

In order calculate potential emissions avoided in case of using electric bicycle sharing system, some statistical data were taken from Bicing service which operates in Barcelona. According to numbers available on the website of the company for the regular bicycle sharing system monthly each bicycle makes a trip of 477.9 km (27). What is more, it is also measured that the average trips of electric bicycles used in the system are 1.42 times longer than it is for regular bicycles (85). Hence, it can be estimated that in case of full scale and normally operating electric bicycle sharing systems the monthly trip distance per bicycle will be:

$$Total\ distance\ per\ elecric\ bicycle = 1.42 * 477.9 \approx 679\ km/month$$

Furthermore it can be assumed that at least for the half of the mentioned distance electric bicycles replace car or public transport trips which are based on fossil fuel. Therefore, the distance of car trips which reduced each electric bicycle will be:

$$Reduced\ card\ trips\ per\ electric\ bicycle = \frac{679}{2} = 339.5\ km/month = 4074\ km/year$$

An average fuel consumption of cars with gasoline and diesel engines are assumed to be 8 and 6 litters respectively for 100 km. Emissions of $CO_2$ from burning 1 litter of gasoline or diesel are 2.32 or 2.66 kg[2] correspondingly (86). Moreover, according to Spanish traffic department 66 % of vehicles in Barcelona are based on gasoline while 44 % come with diesel engines (81) and it should be taken into consideration for the calculation of emissions.

Furthermore, for precise calculation of the carbon footprint of the system it is also necessary to take into account $CO_2$ which will be emitted from vans during redistribution of bicycles. Assuming 10 vans with gasoline engine for the system with 6000 electric bicycles and also estimating the daily trip of 100 km for each van the yearly emission of $CO_2$ can be calculated as follows:

$$CO_2\ from\ vans = 10 * 100 * 365 * \frac{8}{100} * 2.32 = 67744\ kg\ of\ CO_2/year$$

Emissions that will be reduced because of the system with 6000 electric bicycles are:

$$Reduced\ CO_2\ (gasoline) = 6000 * 0.66 * 4074 * \frac{8}{100} * 2.32 = 2994292.2\ kg\ of\ CO_2/year$$

$$Reduced\ CO_2\ (diesel) = 6000 * 0.44 * 4074 * \frac{6}{100} * 2.32 = 1497146.1\ kg\ of\ CO_2/year$$

$$Reduced\ CO_2\ emissions\ = 2994292.2 + 1497146.1 = 4491438.3\ kg\ of\ CO_2/year$$

Therefore, the total reduction of $CO_2$ emission will be:

$$Total\ CO_2\ emission\ reduction = 4491438.3 - 67744 = 4423694.3\ kg\ of\ CO_2/year$$

[2] Unit conversion from pounds/gallon to kg/litter was done

Ideally it would be better to use electric vans for redistribution of bicycles, but as calculations done above show even in case of using conventional vans the electric bicycle sharing system with a fleet of 6000 bicycle will reduce yearly emissions of $CO_2$ by **4423.7 tons**.

Although $CO_2$ is a greenhouse gas and is harmful for the climate, vehicles based on internal combustion engine also emit air pollutants which are more damaging for the human health. Some of these pollutants are particulates, sulfur and nitrogen oxides (PM's, $SO_x$ and $NO_x$ respectively) (87).

Using the same logic and the method of calculation as earlier, it can be evaluated the amount of the reduced pollutants. By the Euro 6 European emissions standards the $NO_x$ emissions for gasoline and diesel cars are regulated to be 0.06 and 0.08 g/km respectively; additionally according to the same regulation the emissions of PM's should not increase 0.005 g/km for both types of fuels (88). What is more, emission of $SO_x$ and particularity $SO_2$ is measured to be 0.031 and 0.1249 g/km[3] for gasoline and diesel respectively (89).

Reduction of $NO_x$ emissions can be calculated as follows:

$$Reduced\ NO_x\ (gasoline) = 0.06 * 6000 * 0.66 * 4074 = 967982.4\ g\ of\ NO_x/year$$

$$Reduced\ NO_x\ (diesel) = 0.08 * 6000 * 0.44 * 4074 = 860428.8\ g\ of\ NO_x/year$$

$$NO_x\ from\ vans = 0.06 * 10 * 100 * 365 = 21900\ g\ of\ NO_x/year$$

$$Total\ NO_x\ emission\ reduction = 96798.24 + 860428.8 - 21900 = 1806511.2\ g\ of\ NO_x/year$$

Reduction of $SO_x$ ($SO_2$) emissions can be calculated as follows:

$$Reduced\ SO_2\ (gasoline) = 6000 * 0.66 * 4074 * \frac{8}{100} * 0.031 = 40009.9\ g\ of\ SO_2/year$$

$$Reduced\ SO_2\ (diesel) = 6000 * 0.44 * 4074 * \frac{6}{100} * 0.1249 = 80600.7\ g\ of\ SO_2/year$$

$$SO_2\ from\ vans = 10 * 100 * 365 * \frac{8}{100} * 0.031 = 905.2\ g\ of\ SO_2/year$$

$$Total\ SO_2\ emission\ reduction = 40009.9 + 80600.7 - 905.2 = 119705.4\ g\ of\ SO_2/year$$

Reduction of PM's emissions can be calculated as follows:

$$Reduced\ PM's = 6000 * 0.005 * 4074 = 122220\ g\ of\ PM/year$$

[3] Unit conversion from ppm to g/litter was done

$$PM\ from\ vans = 0.005 * 10 * 100 * 365 = 1825\ g\ of\ PM/year$$

$$Total\ PM\ emission\ reguction = 122220 - 1825 = 120395\ g\ of\ PM/year$$

Therefore, yearly emissions of $NO_x$, $SO_2$ and PM's can be reduced by 1806.5, 119.7 and 120.4 kg's respectively in case of having electric bicycle sharing system with a fleet of 6000 units.

Furthermore, in order to see the ecological input of the electric bicycle sharing systems in the urban environment, it would be good to compare the saving of emissions with the general levels of emission in the city where it will be operating.

Although in this project it is not specified the exact city where the system will operate, emission calculations will be done for Barcelona city, because of the availability of statistical data and also because it is one of the cities which planes to have a large scale electric bicycle sharing system in the nearest future.

In order to highlight the reduction of greenhouse gas emissions and air pollution level it will be compared not with the total emissions and pollutions in the city, but only by the fraction which belongs to the transportation system. According to the report published by the City Hall of Barcelona the emissions of greenhouse gases by transport in 2008 was 1061890 tons (90).

The same report also provides information concerning the level of $NO_x$ in the city, its total annual pollution is equal to 10413 tons out of which 48.2 % or 5019 tons comes from transportation. Lastly, the total emissions of PM10 (i.e. particles with diameter 10 micrometers or less) in Barcelona city is 458 tons per year (90).

Unfortunately for $SO_x$ pollution there was not up to date information available for Barcelona and therefore comparison cannot be done.

The outcomes of the calculations are summarized in Table 23.

*Table 23 – Outcomes of environmental analysis*

| | GHG (Tons/year) | PM (Tons/year) | $NO_x$ (Tons/year) | $SO_x$ ($SO_2$) (Kg/year) |
|---|---|---|---|---|
| Emission in the city | 1061890 | 458* | 5019 | - |
| Emission reduction | 4423.7 (only $CO_2$) | 0.12 | 1.807 | 119.7 |
| Emission reduction in % | 0.42 | 0.026 | 0.036 | - |

*Only PM10 was considered

Although numbers in Table 23 show that the reduction of emissions due to electric bicycle sharing systems is not high, still it can be valuable tool and a step toward the improving the global and urban environment. Additionally, it is worth to mention that the values emissions in the city which are given in Table 23 are for 2008 and to date they should be lower. Therefore, the stake of the emission reduction will be higher from what is mention in the table.

## Conclusion of environmental analysis

In this chapter the possible environmental benefits and drawbacks were discussed. It was calculated and proved that having a large scale electric bicycle sharing system can reduce local emissions of $CO_2$ produced by vehicles with internal combustion engine. Moreover, it will also have some input in reducing air pollutants such as PM's, $NO_x$ and $SO_x$ which are dangerous for the human health. Furthermore, the discussion of problems in urban transportation and health issues which it causes leads to conclusion that bicycle and electric bicycle sharing systems can be useful tools for decreasing the level of these problems, and thus it would be beneficial for the urban environment to have such system as an alternative to public or personal transport.

# Conclusions and future works

Taking into consideration all the information reviewed, calculated and analyzed it can be stated that nowadays electric bicycles are gaining popularity all over the world with an increasing number of sales. Furthermore, utilization of electric bicycles in sharing systems is also becoming more common in several countries across the globe and it is believed that the trend will continue. What is more, looking on the benefits which electric bicycle can provide to user, for instance less physical effort during cycling, and the problems which it can solve for the sharing company, such as reduction of the fleet redistribution, it is highly possible that electric bicycle sharing systems will become a next generation in the bicycles sharing systems and will fully or partially replace the old ones. This statement can also be justified by the financial analysis which showed that although sharing systems with electric bicycles require higher investment costs, for the long term of exploitation they can be cost competitive with the regular bicycle sharing systems. Lastly, the fact that some big bicycle sharing companies have already started projects with electric bicycles adds an additional confidence concerning the future trends in the market of shared bicycle systems.

Additionally, the technical analysis performed in the project allowed to select necessary components of the electric bicycle for the specified market of sharing systems. As a result of the study of various technologies for different types of motors, batteries, sensors and other devices the components which match the best with the requirements of the electric bicycle for using in a sharing system were selected. Furthermore, considering the fact that for better user experience the way of taking and returning the electric bicycle should be similar to regular sharing systems, an automatic charging system which is connected to the locking mechanism of the bicycle was proposed. Lastly, the environmental analysis proved that electric bicycle sharing systems can have a vital input in reducing local emissions, improving the health of the users and the urban transportation system in general.

In the further development of this project some of the important aspects are designing, prototyping and building the electric bicycle and the docking station. Additionally, it would be an interesting to select an exact location where the system will operate and based on its energy demand and local climatic conditions evaluate the feasibility of operating the system only with solar energy. Doing this, it will be possible to avoid emissions related to the power production and also avoid necessity for connecting to the electric grid.

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# Appendix

*Table 24 – Capital costs of bicycle sharing systems. Source: Bicycle-Sharing Schemes: Enhancing Sustainable Mobility in Urban Areas by Peter Midgley*

| City | Montreal | New York | Washington DC | Lyon | Paris |
|---|---|---|---|---|---|
| Program | Bixi | 2007 Estimate | SmartBike Expansion | Velov' | Velib' |
| Operator | Stationnement de Montréal | ClearChannel Adshel | ClearChannel Adshel | JCDecaux | JCDecaux |
| Number of Bicycles | 2,400 | 500 | 500 | 1,000 | 20,600 |
| Capital Cost | No Data | $1,800,000 | $1,800,000 | No Data | $90,000,000 |
| Capital Cost/Bicycle | $3,000 | $3,600 | $3,600 | $4,500* | $4,400 |

All data provided by the operators or providers unless otherwise noted.

* This figure is cited to European programs in general in Becker, Bernie, "Bicycle-Sharing Program to Be First of Kind in U.S.," The New York Times, 27 April, 2008

*Table 25 – Operating costs of bicycle sharing systems. Source: Bicycle-Sharing Schemes: Enhancing Sustainable Mobility in Urban Areas by Peter Midgley*

| City | Montreal | Lyon | Barcelona | Washington DC | Paris | New York |
|---|---|---|---|---|---|---|
| Program | Bixi | Velov' | Bicing | SmartBike Expansion | Velib' | 2007 Estimate |
| Operator | Stationnement de Montréal | JCDecaux | ClearChannel Adshel | ClearChannel Adshel | JCDecaux | ClearChannel Adshel |
| Number of Bicycle | 2,400 | 1,000 | 3,000 | 500 | 20,600 | 500 |
| Operations Cost | No Data | $1,550,000 | $4,500,000 | $800,000 | $35,000,000 | $972,000 |
| Operations Cost/ Bicycle | $1,200 | $1,500* | $1,500** | $1,600 | $1,700 | $1,944 |

All data provided by the operators/providers or the city unless otherwise noted.

* Buhrmann, Sebastian, Rupprecht Consult Forschung & Beratung GmbH, "New Seamless Mobility Services: Public Bicycles;" Niches Consortium

** Nadal, Luc, "Bike Sharing Sweeps Paris Off Its Feet," Sustainable Transport, Institute for Transportation and Development Policy, Fall 2007, Number 19

*Table 26 – Ananda m130 V motor characteristics. Source: www.ananda-drive.en.alibaba.com*

| **Design** | **Brushless** |
|---|---|
| Drive | Front |
| Power in Watts | 200 W ~ 330 W |
| Voltage | 36 V |
| Unloaded speed | 230 ~ 320 rpm |
| Max current | 15 A |
| Maximum Speed EU/US | 25 Km/h |
| Max Torque | 36 N.M |
| Max Load | 100 Kg |
| Efficiency | 78 % |
| Weight | 2.9 Kg |
| Wheel Size | 700 C |
| Open Size | 100 mm |
| Miles per hour | 25 km/h |

*Table 27 – Recommended charging rates for electric scoter/bike battery packs. Source: www.electricscooterparts.com*

| **12 Volt 5-8 Ah Pack** | **12 Volt 9-12 Ah Pack** | **12 Volt 17-20 Ah Pack** | **24 Volt 5-8 Ah Pack** | **24 Volt 9-12 Ah Pack** | **24 Volt 17-20 Ah Pack** |
|---|---|---|---|---|---|
| slow rate: 12V 1A quick rate: 12V 2A | slow rate: 12V 1.5A quick rate: 12V 3A | slow rate: 12V 3A quick rate: 12V 6A | slow rate: 24V 1A quick rate: 24V 2A | slow rate: 24V 1.5A quick rate: 24V 3A | slow rate: 24V 3A quick rate: 24V 6A |

| **36 Volt 5-8 Ah Pack** | **36 Volt 9-12 Ah Pack** | **36 Volt 17-20 Ah Pack** | **48 Volt 5-8 Ah Pack** | **48 Volt 9-12 Ah Pack** | **48 Volt 17-20 Ah Pack** |
|---|---|---|---|---|---|
| slow rate: 36V 1A quick rate: 36V 2A | slow rate: 36V 1.5A quick rate: 36V 3A | slow rate: 36V 3A quick rate: 36V 6A | slow rate: 48V 1A quick rate: 48V 2A | slow rate: 48V 1.5A quick rate: 48V 3A | slow rate: 48V 3A quick rate: 48V 6A |

*Table 28 – Multicore 70°C Thermoplastic Insulated and Thermoplastic Sheathed Cables, Non-Armored. Source: www.csecables.com*

| Conductor cross-sectional area | Reference Method A (enclosed in conduit in thermally insulating wall etc.) | | Reference Method B (enclosed in conduit on a wall or in trunking etc.) | | Reference Method C (clipped direct) | | Reference Method E (free air or on a perforated cable tray etc, horizontal or vertical) | |
|---|---|---|---|---|---|---|---|---|
| | 1 two-core cable* single-phase a.c. or d.c. | 1 three-core cable* or 1 four-core cable, three-phase a.c. | 1 two-core cable* single-phase a.c. or d.c. | 1 three-core cable* or 1 four-core cable, three-phase a.c. | 1 two-core cable* single-phase a.c. or d.c. | 1 three-core cable* or 1 four-core cable, three-phase a.c. | 1 two-core cable* single-phase a.c. or d.c. | 1 three-core cable* or 1 four-core cable, three-phase a.c. |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| ($mm^2$) | (A) | (A) | (A) | (A) | (A) | (A) | (A) | (A) |
| 1 | 11 | 10 | 13 | 11.5 | 15 | 13.5 | 17 | 14.5 |
| 1.5 | 14 | 13 | 16.5 | 15 | 19.5 | 17.5 | 22 | 18.5 |
| 2.5 | 18.5 | 17.5 | 23 | 20 | 27 | 24 | 30 | 25 |
| 4 | 25 | 23 | 30 | 27 | 36 | 32 | 40 | 34 |
| 6 | 32 | 29 | 38 | 34 | 46 | 41 | 51 | 43 |
| 10 | 43 | 39 | 52 | 46 | 63 | 57 | 70 | 60 |
| 16 | 57 | 52 | 69 | 62 | 85 | 76 | 94 | 80 |

Note:
* With or without protective conductor.

*Table 29 – Voltage drop. Source: www.csecables.com*

| Conductor cross-sectional area | Two-core cable d.c. | Two-core cable single-phase a.c. | Three- or four-core cable, three-phase a.c. |
|---|---|---|---|
| 1 | 2 | 3 | 4 |
| ($mm^2$) | (mV/A/m) | (mV/A/m) | (mV/A/m) |
| 1 | 44 | 44 | 38 |
| 1.5 | 29 | 29 | 25 |
| 2.5 | 18 | 18 | 15 |
| 4 | 11 | 11 | 9.5 |
| 6 | 7.3 | 7.3 | 6.4 |
| 10 | 4.4 | 4.4 | 3.8 |
| 16 | 2.8 | 2.8 | 2.4 |

*Table 30 – Permissible continuous current for bus-bars with rectangular section. Source: almih.narod.ru (Electrical Code Book)*

| Размеры,мм | Медные шины | | | | Алюминиевые шины | | | | Стальные шины | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Ток*, А, при количестве полос на полюс или фазу | | | | | | | | Размеры, мм | Ток*, А |
| | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | | |
| 15 x 3 | 210 | - | - | - | 165 | - | - | - | 16 x 2,5 | 55/70 |
| 20 x 3 | 275 | - | - | - | 215 | - | - | - | 20 x 2,5 | 60/90 |
| 25 x 1 | 340 | - | - | - | 265 | - | - | - | 25 x 2,5 | 75/110 |
| 30 x 4 | 475 | - | - | - | 365/370 | - | - | - | 20 x 3 | 65/100 |
| 40 x 4 | 625 | - /1090 | - | - | 480 | - /855 | - | - | 25 x 3 | 80/120 |
| 40 x 5 | 700/705 | - /1250 | - | - | 540/545 | - /965 | - | - | 30 x 3 | 95/140 |
| 50 x 5 | 860/870 | - /1525 | - /1895 | - | 665/670 | - /1180 | - /1470 | - | 40 x 3 | 125/190 |
| 50 x 6 | 955/960 | - /1700 | - /2145 | - | 740/745 | - /1315 | - /1655 | - | 50 x 3 | 155/230 |
| 60 x 6 | 1125/1145 | 1740/1990 | 2240/2495 | - | 870/880 | 1350/1555 | 1720/1940 | - | 60 x 3 | 185/280 |
| 80 x 6 | 1480/1510 | 2110/2630 | 2720/3220 | - | 1150/1170 | 1630/2055 | 2100/2460 | - | 70 x 3 | 215/320 |
| 100 x 6 | 1810/1875 | 2470/3245 | 3170/3940 | - | 1425/1455 | 1935/2515 | 2500/3040 | - | 75 x 3 | 230/345 |
| 60 x 8 | 1320/1345 | 2160/2485 | 2790/3020 | - | 1025/1040 | 1680/1840 | 2180/2330 | - | 80 x 3 | 245/365 |
| 80 x 8 | 1690/1755 | 2620/3095 | 3370/3850 | - | 1320/1355 | 2040/2400 | 2620/2975 | - | 90 x 3 | 275/410 |
| 100 x 8 | 2080/2180 | 3060/3810 | 3930/4690 | - | 1625/1690 | 2390/2945 | 3050/3620 | - | 100 x 3 | 305/460 |
| 120 x 8 | 2400/2600 | 3400/4400 | 4340/5600 | - | 1900/2040 | 2650/3350 | 3380/4250 | - | 20 x4 | 70/115 |
| 60 x 10 | 1475/1525 | 2560/2725 | 3300/3530 | - | 1155/1180 | 2010/2110 | 2650/2720 | - | 22 x4 | 75/125 |
| 80 x 10 | 1900/1990 | 3100/3510 | 3990/4450 | - | 1480/1540 | 2410/2735 | 3100/3440 | - | 25 x4 | 85/140 |
| 100 x 10 | 2310/2470 | 3610/4325 | 4650/5385 | 5300/6060 | 1820/1910 | 2860/3350 | 3650/4160 | 4150/4400 | 30x4 | 100/165 |
| 120 x 10 | 2650/2950 | 4100/5000 | 5200/6250 | 5900/6800 | 2070/2300 | 3200/3900 | 4100/4860 | 4650/5200 | 40 x 4 | 130/220 |
| | | | | | | | | | 50 x4 | 165/270 |
| | | | | | | | | | 60x4 | 195/325 |
| | | | | | | | | | 70x4 | 225/375 |
| | | | | | | | | | 80x4 | 260/430 |
| | | | | | | | | | 90x4 | 290/480 |
| | | | | | | | | | 100 x4 | 325/535 |