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''Exploration of the possibilities of wireless power transfer for e-bikes and business opportunities''

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Preface

This thesis marks the end of my two-year open master's program in Electrical Engineering at the University of Twente. I have conducted this thesis at the Pervasive Systems research group which is part of the Faculty for Electrical Engineering, Mathematics and Computer Science. I would like to express my sincere appreciation to all who supported me in carrying out this thesis. Given that this assignment challenged me creatively, it has allowed me to expand my perspective on problem-solving in the engineering department.

I would like to express great gratitude to my main supervisor, prof. dr. J.M. Paul Havinga and my external supervisor prof. Braham Ferreira, for their valuable and constructive suggestions during the planning and development of this research work. Their willingness to give their time so generously has been very much appreciated. I especially would like to thank my monthly supervisor, MSc. Nguyen Duong for his guidance and dr. ir. Niek Moonen for their patient guidance, enthusiastic encouragement, and useful critiques of this research work. I would also like to thank Martin Schmitter and his team from Accell for their support and constructive feedback. Last but not least, I would like to express my hearty gratitude to my parents, family, and friends for their support and encouragement throughout my entire master's program.

''*Sever the ignorant doubt in your heart with the sword of self-knowledge. Observe your discipline, arise*.''

—The Bhagavad Gita

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Abstract

Bikes are the most popular and main form of transportation in the Netherlands. Over the years the usage of e-bikes is increasing exponentially. Due to the growth in e-bikes, there is a new demand for Wireless Power Transmission (WPT). The contactless charging solution is gaining popularity as a method for charging the batteries of Electric Vehicles and therefore also e-bikes. The technology that is making this contactless EV battery charging feasible is the Inductive Power Transfer (IPT). The advantage of IPT is that it provides benefits in terms of safety and comfort to the driver, due to the absence of a plug-in operation.

In this thesis, we explore the various possibilities for WPT in e-bikes and their business opportunities. The aim is to describe the wireless power technology in e-bikes, propose a framework for a new practical, efficient, and safe wireless charging prototype application and to develop a business plan using a Business Canvas Model.

First, this thesis focuses on the comparisons of different studies done related to wireless charging of e-bikes. Based on investigations of the related work a list of parameters is created that can influence the practical, efficient, and safe character of wireless charging in e-bikes. These parameters are further deliberated to understand their influence on the wireless e-bike charging phenomenon. The best design options for these parameters are further embroidered in new suggested prototypes. The prototypes are based on a combination of standards that exist nowadays. Lastly, a business case implementation framework has been defined which can be implemented by an independent (starter) business for WPT e-bikes or a wholesale e-bike business company.

The proposed prototype is not complete when it comes to building and complete simulation as it became apparent in the thesis. But it does provide a good direction with the framework and particularly relevant focus points for the initiation of a predictive maintenance project. The prototype framework is designed and validated in such a way that it takes practicality, efficiency, and safety into account. The proposed business plan shows various suggestions which can lead to promising results and has the potential to be used more widely in large-scale. The research done showed that it can be concluded that the company Accell would benefit from implementing the proposed busines plan using the BCM tool. The WPT electric bike is a profitable industry and it is open for any aspiring entrepreneur through the Netherlands.

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List of acronyms

AC	Alternating Current
BMC	Business Model Canvas
DC	Direct Current
DSE	Design Space Exploration
E-Bike s	Electric Bikes
EDLC(s)	Electrical Double-Layer Capacitor(s)
EMF	Electromagnetic Field
EV(s)	Electric Vehicle(s)
HW	Hardware
IPT	Inductive Power Transfer
MCS	Magnetic Coupling Structure
PCB	Print Circuit Board
PP	Parallel-Parallel connection
PS	Parallel-Series connection
Rx	Receiver (on the secondary side)
SP	Series-Parallel connection
SS	Series-Series connection
SW	Software
Tx	Transmitter (on the primary side)
WPT	Wireless Power Transmission

Chapter 1. Introduction

1.1 Background

Bicycles are one of the most popular methods of transportation all over the world. They are convenient, inexpensive, environmental-friendly and cycling ultimately leads to a longer and healthier life. According to the statistics provided by the Dutch ministry [1], the bicycle is the second most used transportation form by the residents. The statistics also indicate that in 2018 the Netherlands accommodates 17 million inhabitants and 23 million bicycles, so clearly the bicycles outnumber the inhabitants. Recently a new generation of bicycles has begun to revolutionize the bicycle industry, namely: the electric bicycle. Electric bicycles try to enhance the human-powered way of life. These new cycles can be categorized in the Electric Vehicles (EVs) section together with electric cars, electric trains, etc. Traditionally, each e-bike has its charging device for the battery that needs to be plugged-in indoors. These cable chargers could only be used indoors, where it is secure and has some form of supervision, to avoid vandalism, injury, or theft.

The e-bike aids in the convenience of comfort while maintaining an economic advantage. It is noticed that the demand for e-bikes has increased in the Netherlands over the last years few years and that they are on the rise in bicycle sales. Linked to the increased usage and its high growth in demand, a new demand came in the market which is to create Wireless Power Transmission (WPT) technology for the e-bike. The significant problems can emerge with wireless charging, which are the need for comfort when it comes to the wireless charging equipment for the user, and guarantee of the charging efficiency and safety. Despite the indicated problems, the prospect of the wireless charging application is getting better as the technology is developing. Prior research has come up with several methods that made the wireless power transmission possible for e-bikes. However, most of these methods are defined for specific scenarios, have limited applications, etc. To improve this an investigation will be needed, called Design Space Exploration (DSE). ‘‘*Design space exploration refers to the activity of discovering and evaluating design alternatives during system development prior to implementation*’’ [2]. Therefore, this thesis explores the wireless charging mechanism for the e-bike systematically based on the gathered knowledge of the previously analyzed methods, literature study, and feedback from Accell Group N.V. Accell is the European market leader in e-bikes and the second largest company in bicycle parts and accessories, they also make bicycles, bicycle parts, and accessories. Therefore, their input is also of great value for this thesis.

1.2 Thesis goal & research questions

Main research goal

The main goal of this research is to analyze WPT for e-bikes and propose a prototype for a new practical, efficient, and safe wireless charging application for the e-bike. This will be done by implementing a DSE to find a good design among all the designs in the design space (related work). Based on the available related work, several parameters will be listed and studied. These parameters can have a different effect on the charging cross-cutting concerns: practicality, efficiency, and safety quality of wireless charging. Input from Accell will also be used here. Additionally, a business plan is to be developed for the WPT e-bike to assist large- and small-scale companies. To achieve the main research goal, the next paragraph below contains the main research question which is followed up by three sub-questions that this thesis is set out to explore.

Research questions

This research work seeks to address the main research question: ‘’**How can the studied parameters of wireless power transfer models be set in such a way that is suitable, efficient, and safe for the battery charging of an e-bike**?’’

Sub-Questions:

1. *What are the tradeoffs between the different studied wireless e-bike charging methods?*
   To answer this question, prominent features employed in research on related studies on wireless power transmission are analyzed. These studies are compared and analyzed to observe any significant deviations and similarities. (Covered in Chapter 3)

2. *What are the most significant parameters that can gain the efficiency and safety of the wireless charging mechanism?*
   To evaluate what thrives the practicality, efficiency, and safety of the WPT in e-bikes a few parameters should be defined. The impact of these should be analyzed which influences the quality of charging the e-bike. (Covered in Chapter 4)

3. *How can a vehicle business in the Netherlands expand and develop its services to WPT e-bikes?*
   To see if the concept WPT e-bike prototype can perform as a standalone well-functioning system, a business plan is performed. (Covered in Chapter 6)

1.3 Contribution

The objective of this work is to analyze WPT for e-bikes and to propose a framework for a new practical, efficient, and safe prototype. The specifics aspects that this topic addresses are the parameters that influence the e-bike wireless charging. The proposed framework for building the prototype in this thesis can be used for further studies where engineers can build it and optimize it even further. Motivated by a discussion with engineers from the Accell Group N.V. in the Netherlands this thesis also contains an elaborated business plan for WPT e-bikes which can be implemented.

1.4 Methodology & limitations

For the methodology, the hierarchical order of System Engineering has been considered. In system engineering, there is a specific set of steps defined to design, analyze, and validate a system. This is called the system life-cycle engineering as seen in Figure 1. This thesis focusses on the two initial parts in the acquisition phase: conceptual design & the preliminary design phase and the detailed design & development phase which is further described in **Error! Reference source not found.**.

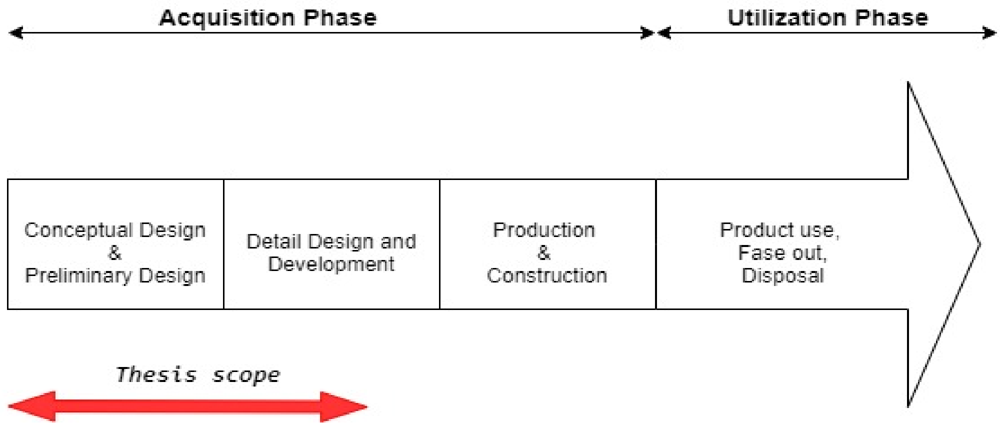

Figure 1. System Life-cycle Engineering

Conceptual Design *(what?[1])* -Chapter 2
During this phase, there is a literature study is done to understand the technology behind WPT in e-bikes and IPT. And to find different parameters that influence the quality of charging.

Preliminary Design *(how?[2])* -Chapter 3 & Chapter 4
For the next phase all the important parameters that have a positive influence on the practicality, efficiency, and safety of the WPT e-bike are listed and analyzed. These are proposed for the new prototype.

Concept Design and Development -Chapter 5 & Chapter 6
Based on the facilities at the time, the model (prototype) can be built in the lab at the University of Twente. Here a Business plan will also be proposed for the WPT e-bike. The goal here is to create the product concept baseline and future recommendations.

The tools, procedures, and materials used to gather data and conduct the research are:

- Documentary analysis of existing data
  - Research papers
  - Master thesis assignments
  - Books
  - Videos (webinars, etc.)
- Interviews with Accell engineers
- Survey regarding business plan

Limitations

During the *detailed design and development* phase of the thesis a few obstacles where encountered which created a disturbance in the original plan. Due to the measurements taken against the COVID-19, the laboratories at the University of Twente were closed until the end of this thesis procedure. Therefore, the proposed concept prototype which was planned to be

[1] The main question here is *what*: What to design, what are the requirements, what are the possibilities? Etc.
[2] The main question here is *how*: How to realize the requirements? How to design? Etc.

built in the lab could not proceed. However, as a substitution, a framework has been created for future engineers to continue with this.

1.5 Thesis organization

The remainder of this thesis is structured in various chapters. Chapter 2 provides the literature background of e-bikes which includes the relevant details to understand Wireless Power Transfer (WPT) in Electric Vehicles (EVs) and Inductive Power Transfer (IPT). In Chapter 3, the literature study is continued where three main existing wireless charging mechanisms for e-bikes are summarized and compared. Chapter 4 discusses the tradeoffs between the highlighted parameters from the previous chapter that demonstrate a difference in various wireless charging mechanisms for e-bikes. This followed by Chapter 5 the framework for the concept prototypes is proposed. Chapter 6 contains the business plan for a WPT e-bike business. And the last one is Chapter 7 which contains a summary of the overall conclusions from previous chapters and some future recommendations. The Appendix contains additional information.

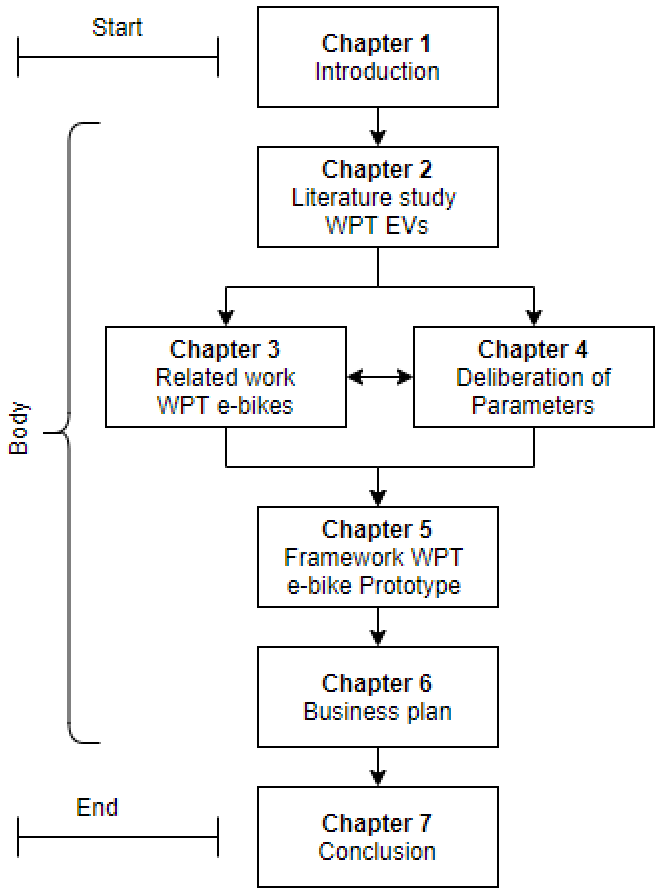

Figure 2. Thesis overview

Chapter 2. Background WPT in E-bikes

This chapter contains the terms, definitions, and technology development for wireless charging of Electric Vehicles (EVs) in section 2.1. Section 2.2 provides information about the basic components a system should have to process wireless charging. Further on this chapter describes the concept of Inductive Power Transfer (IPT) and its application areas in section 2.3. Eventually the second last part of the chapter focusses on the general working mechanism of the e-bike in section 2.4. This is ended with a discussion in section 2.5.

2.1 Introduction

'*'Wireless Power Transfer (WPT) is the transmission of electrical power from the primary power source to a secondary electrical load without the use of physical connectors*'' [3]. The idea behind WPT began with the formulation of Maxwell's equations in 1862. Nowadays WPT is gaining popularity as a method for charging the batteries of Electric Vehicles (EVs) [4]. Also, global development and utilization of new clean green energy created an increase in the use of renewable energy [5] [6] [7]. This decreases the use of energy sources that are employing traditional fossil fuels such as oil, natural gas, and coal. According to recent studies, the use of energy efficiency technologies is one of the major initiatives. This was a motivation for the use of contactless charging. Then also lack of wires is desirable whenever the transmission cable is inconvenient or even impossible to use.

Generally, wireless battery charging frequency can range from ultra-low power levels to ultra-high-power levels depending on the different applications such as electrical toothbrush, watch, mobile phone, laptop, television, electric bicycle, electric car. If compared to the consumer electronic devices, the EVs charging occurs at notably higher power levels, ranging from a few hundreds of Watts (as in the case of the e-bike) to several tens of kilowatts (as in the case of the electric buses). The Wireless Electric Vehicle Charging (WEVC) is still far from full commercialization and standardization. Nevertheless, being implemented through Inductive Power Transfer (IPT) between two coupled coils, it provides benefits in terms of practicality, efficiency, and safety to all the users. More of this can be seen in section 2.3.

The mechanism behind wireless and cable charging can be seen in Figure 3 and Figure 4 and both systems have almost the same components. One noticeable thing that separates these two setups is that wireless charging uses an air core and cable charging uses an iron core in the transformer [8]. Both systems have their advantages and disadvantages, however, this thesis will only focus on the wireless mechanism.

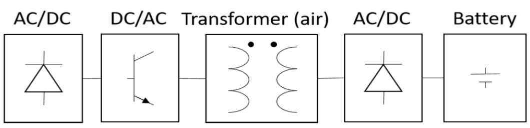

Figure 3. Mechanism set up for wireless charging [8]

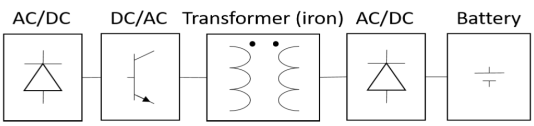

Figure 4. Mechanism set up for cable charging [8]

With WPT technology an electric bicycle can be charged, without detaching its battery equipment and/or plugging it with a cord, simply by placing the bicycle on the specific charging infrastructure. WPT technology can be used as a solution in eliminating many charging hazards and drawbacks related to cables. Compared to the conventional cable-based method of charging, the wireless charging method is more convenient. *''Not only from the consumer perspective but also sustainable energy point of view WPT enabled EVs are greatly beneficial''* [3]. If we look at all the EVs, the electric bicycles particularly fit with this innovative method of power transfer.

2.2 Components of wireless charging

In the paper [9] the writers define the components of wireless charging EVs:

1. **Power-supply**: this connects the system to the electric source to receive power.
2. **Charging infrastructure**: the primary power transmitter, the charging unit that transmits the power by electromagnetic field from the grid.
3. P**ickup:** the secondary receiver is a component that intercepts the power from the power transmitter unit and consists of a pickup unit, attached at the bottom surface of the vehicle to receive power.
4. L**oad**: the entity which is being charged.

Therefore, all these four components will be taken into consideration for the new suggested prototypes.

According to [10], for the wireless charging components, there are 3 different technologies to charge an EV's battery: microwave power transfer (MPT), inductive power transfer (IPT), and inductively coupled power transfer (ICPT). According to paper [11], in table 1 the authors show a comparison of the different wireless technologies. There the IPT-technology for WPT e-bikes is indicated as the best option which will be explained in the next paragraph.

2.3 Inductive Power Transfer (IPT)

The technology that is making WPT in e-bikes feasible is the Inductive Power Transfer (IPT). IPT systems allow the transfer of electric power between its air-cored primary and secondary coils via a high-frequency magnetic field to a consuming device (load) [12] [13] [10]. The technology is seen as a promising solution to be applied in an electrified-road (e-Road) to dynamically charge EVs.

The IPT provides benefits in terms of safety and comfort to the driver, due to the absence of a plug-in operation. The lack of wires can be advantageous when the power cord is difficult or even impossible to use. IPT systems can provide power without any physical contact, thus they are unaffected by dirt, ice, water, and chemicals, making them environmentally inert and maintenance free.

A distinction can be made between 2 specific types of IPT:

1. Distributed IPT (DIPT) [17], [44]
2. Lumped IPT (LIPT)
    a. Closely coupled (IPT)
    b. Loosely coupled (RIPT)

DIPT systems are employed where continuous power is needed whereas LIPT systems are utilized for cases where power needs to be transferred at a fixed location [10]. Based on this LIPT are more suitable for e-bikes because they are generally parked in a fixed location for charging (stationary).
Besides, closely coupled LIPT systems require a relatively small air gap and user intervention. Loosely coupled LIPT systems can operate with a large air gap and require no user intervention. For the e-bike, the *loosely LIPT system* is suggested.

According to [14] and [15], electric vehicles can be recharged through IPT in three options:

1. **Static**: charging whenever the EV is stationary and nobody stays inside it, e.g. in the case of an e-bike.
2. **Contactless/quasi-dynamic:** recharge occurs when the EV is stationary, but here someone is inside it, e.g. in the case of a cab at the traffic light intersections.
3. **Dynamic:** charging the vehicle while it is in motion, e.g. in the case of a car running on a highway or a moving train.

Up till now academic researchers and commercial operators proposed different solutions, as far as the position and characteristics of the coupled coils are concerned. Because this technology is new, the IPT charging is chosen to be applied to the e-bike in *static mode*.

2.3.1 IPT- Basic concept

The whole IPT system can be divided into two parts. First, the primary part, which contains the power sourcing element and the secondary part containing the batteries that are to be charged. The primary and secondary coupled circuits are in the form of coils to increase the magnetic field of the circuits. The transmitter coil (primary/ charging infrastructure/Tx) has a current passing through it which creates a magnetic field. This is coupled to the receiving coil (secondary/pick up/Rx). Changes in transmitter current, this induces a voltage in the secondary coil. The voltage induced in the secondary coil can further be used to drive the battery charger. In Figure 5 a simple IPT WTP system is shown.

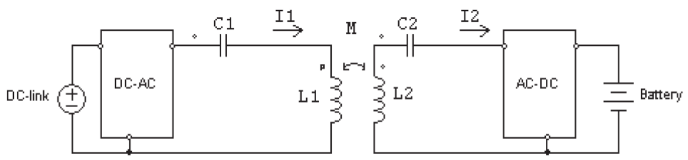

Figure 5. Standard schematic of the IPT system [16]

C_1= compensation capacitor primary part
C_2= compensation capacitor secondary part
M= The mutual inductance
I_1= current primary part
I_2= current secondary part
L_1= self-inductance primary coil
L_2= self-inductance secondary coil

The basic circuit above is further used in Chapter 5. As mentioned before, IPT occurs between two magnetically coupled coils. Their self-inductance are L_1 and L_2 and the mutual inductance between them is M. The coupling coefficient, which can be used to qualify the magnetic coupling, is defined as:

$$k = \frac{M}{\sqrt{L_1 \times L_2}}$$

Equation 1. Coupling coefficient [17]

Since the coils are loosely coupled, a reactive network is needed to maximize the power transfer efficiency and optimize the power factor, if the system works at the resonance. This reactive network is named a compensation circuit and includes two capacitors. In the example of Figure 5Figure 5, both the compensation capacitors are connected in series with the primary and the secondary coils, more of this can be found in section 2.3.2.

2.3.2 IPT- Compensation networks

''For the IPT circuit, a reactive network is required in order to maximize the power transfer efficiency towards the load and the power factor towards the source'' [16]. Since the reactive elements needing to be compensated are the coupled inductors, the compensation elements are capacitors (C_1 and C_2). According to the type of connection between the coils and their compensation capacitors, four different compensation circuits are possible:

1. Series-series (SS)
2. Series-parallel (SP)
3. Parallel-series (PS)
4. Parallel-parallel (PP)

The four different compensation circuits can be seen in Figure 6. The SS topology creates the opportunity to select the compensation capacitances only depending on the self-inductances (L_1 and L_2), regardless of the nature of the load and the magnetic coupling [10]. Therefore, in the case of misalignments between the coils, the system keeps working under resonance despite the mutual inductance variations [18].

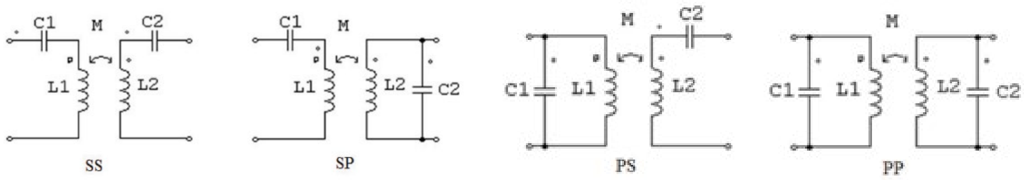

Figure 6. Four main capacitor compensation topologies [16]

According to the previously listed reason and various studies done with the SS [16], the SS circuit is considered to be useful for EVs WPT.

2.3.3 IPT- Power converters

There are two forms of power: Alternating current (Ac), Direct current (Dc). Due to the Alternating current (Ac) nature of the inductive coupling between the coils, the voltages across the primary and the secondary side are alternating. The power source and load come in various forms, which indicates that there is a need for a converter to transfer the power from the source to load while changing the form of power. In Figure 5 a Dc voltage (primary) source is connected to the electrical grid; the secondary-side Dc section is the load representing the battery to be charged. Since the power transfer between the coupled coils is in Ac, two intermediate stages with power converters are needed: a Dc to Ac (inverter) on the primary side and an Ac to Dc (rectifier) on the secondary side [19].

2.3.4 IPT- Transmission efficiency

The magnetic coupling can be influenced by the coupling factor (k) and the quality factor (Q) of the coils. The coupling coefficient (k) is the amount of inductive coupling that exists between the two coils (see equation 1). The coupling coefficient can be a fractional number between 0 and 1, where 0 indicates zero or no inductive coupling and 1 indicates full or maximum inductive coupling. If k is 1 the two coils are perfectly coupled (ideal situation) however in practice even small misalignments are unavoidable.

The efficiency of any IPT system may depend on a few factors including the coupling coefficient between the inductors and their quality factor. In turn, these are dependent upon a variety of other factors including:

- ***Inductor sizes:*** The ratio of diameters (D) of the coils, D_2/D_1 has a direct impact on the coupling. It affects because for maximum coupling all the lines of magnetic flux should pass through the primary and coupled into the secondary coil.
- ***Inductor shape:*** The shape of the coils will change the level of the coupling of magnetic flux.
- ***Distance between coils:*** The distance between the two coils has a major effect on the efficiency of the inductive power transmission. As the coils move apart, the inductive coupling reduces rapidly as it is what is termed a near field effect.
- ***Coil resistance:*** The resistance in the primary and secondary coils will cause the power to be dissipated as heat. This is a reduction in the Q of the coils in the system.

All these factors will be taken into consideration when analyzing the various types of coils used in different studies and to analyze the magnetic efficiency.

2.3.5 IPT – Safety considerations

Despite the beneficial character in terms of practicality and efficiency, it can still be dangerous in terms of human safety. Some concern ought to be addressed to three main risks:

1. Electrical shocks
2. Fire hazards
3. Electromagnetic field exposure

Electrical shock and fire hazards risks in WPT EVs are automatically present because of the usage of high voltages and currents in the primary and secondary coils if high power level systems are considered. However, for e-bikes, this is not the case is there is a relative usage of low power levels. If the IPT correctly implies the insulation between the power source and the e-bike, no electrocution risk involves the user, even in harsh and wet environmental conditions.

Since IPT utilizes Electromagnetic Field (EMF) to transfer power, users and passersby should not be exposed to unnecessary magnetic radiation. The electric fields are generally more dangerous for the human rather than magnetic fields so that the radiation produced by the wireless chargers is considered quite safe for the human body [20]. Nevertheless, if the power levels are high, the EMF exposure must be considered for the safety implications. This is the reason why the magnetic field exposure is a concern for the IPT wireless EV charging, where an accurate investigation on the field distribution should be carried out. There are mainly two international groups that set standards and guidelines concerning human exposure to the electromagnetic fields: the International Committee on Electromagnetic Safety (ICES) [20] and the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [21]. These guidelines deal with the public and occupationally exposed population. With their guidelines, a safety distance from the center of the system can be calculated.

2.4 Electric bicycles

The electric bicycle (e-bike) is a normal bicycle that has an integrated electric motor that can create momentum. It relies on additional parts like an electric motor, a battery, a sensor, and an electric display that work together to allow it to operate.

E-bikes are classed according to the power that their electric motor can deliver and the control system, i.e., when, and how the power from the motor is applied. However, due to legal reasons for what constitutes a bicycle and what constitutes a motorcycle (varies across countries and local jurisdictions), the classification of e-bikes can be complicated. Despite that, the classification of e-bikes is mainly decided by whether the e-bike's motor assists the rider using a **pedal-assist system**[3] or by a **power-on-demand**[4] one [22]. Once the driver is pedaling, they can use the electric display on the e-bike, which is often on the handlebars of the bicycle to turn on the power assist. There are assistance level choices offered which can be altered with the buttons on the electric display or controller. Most e-bikes have four assistance levels: eco, tour, sport, and turbo. These factors add to the advantages of the e-bike.

2.4.1 Main components

In an electric bicycle, there are three main components. The first one is the motor, the second one battery, and last one the sensor. A well-functioning e-bike demands all the components to work together to operate.

Motor

The main goal of the motor is to control the torque. The motor placement can differ for the e-bike where each placement (front hub, rear hub, and the mid-drive) has its advantage.

- **Front hub motors** are located on the front tire and provide propulsion by spinning the tire. The motor creates the sensation that the bike is being ‘’pulled’’ forward.
- **Rear hub motors** provide propulsion by spinning the back tire. They ‘’push’’ the rider forward, which can feel more natural to conventional bike riders than front hub motors.
- **Mid-drive motors** send power to the bike’s drivetrain instead of a hub. Its central location creates a more natural riding sensation than hub motors.

Battery

‘’*Nowadays the automotive industry is going through a transition from Internal Combustion Engine (ICE) vehicles to electric vehicles (EVs), with the main goal of meeting EU targets to reduce the CO_2 emissions from the transport sector*’’ [23]. For the e-bike, the battery placement can vary according to the frame type, size of the bike, and the manufacturer. The average standard charging time revolves around a few hours which is all dependent on the make and model of the battery. Since the type of battery affects the weight, style, range, and charging time of the bike, its choice is crucial [4] [24] [5]. E-bikes took off when lightweight batteries where made available in the market (e.g. Lithium-ion). The lithium-ion batteries represent the most widespread typology of battery and they are the most preferred solution for electrical energy storage, due to their high energy densities and long lifetimes [24] [22]. Most

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[3] Where the motor is activated only when the pedals are already in motion.

[4] Here the motor is activated by a throttle.

of the electric-assisted bicycles on practice use a lithium-ion battery as an energy source. The lithium-ion batteries will fit with several applications: portable electronics, electric vehicles, space and aircraft power systems, stationary power storage.

Sensors

There are two types of sensors used on various e-bikes: a speed sensor and a torque sensor. The **speed sensor** engages the motor instantly once the pedaling starts. This allows riding assistance for the rider. The **torque sensor** reacts with a little assistance of the speed match when the rider is moving. This helps with speed and maneuvers.

2.4.2 Considerations

The **motivation** for wireless charging application in an e-bike:

- User comfort: with the absence of the wired charging can be more convenient.
- Traffic congestion: ‘’*Results of the European literature shows that when e-bikes are made available, they get used; that a proportion of e-bike trips typically substitutes for car use; and that many people who take part in trials become interested in future e-bike use, or cycling more generally’’* [25]
- Health: cycling increases physical activity thereby addressing obesity and other health issues.
- Social: the use of slower modes of transport can make cities livable and social with a positive impact on the mental and social health of its citizens.
- Environment: they are an encouragement to switch to a less air-polluting mode. Statistics show that e-bikes emit 30 - 40 times less CO_2 than cars and therefore they are contributing to the reduction of energy consumption and CO_2 emissions.
- Vandalism resistant: the transmitting source is mounted on a fixed base and is made of robust materials that limit the chances of acting vandalism.
- Durability: using power transfer through of IPT has the entire electric circuits sealed from moisture. There is no need for wires that can break or fail due to corrosion. Eradicate a potential entry point for water, dust, and other corrosive materials that might make their way into the device.
- Interference: the transmitting source is placed in such a way that it provides a minimal impact to the cityscape. It could coexist with existing locking mechanisms if required and other electrical equipment in its surrounding.

However, there still can be some **disadvantages**:

- User comfort: depending on the coils, (size, weight, etc.) the e-bike weight can increase, and depending on the placement it can disturb the e-bike’s equilibrium.
- Costs: depending on the device/equipment type, it might be expensive.
- Efficiency: unavoidable energy loss between coils.
- Time: wireless charging takes more time then wired charging.
- Environment: making and disposing of the batteries can be very polluting [26].

On the one hand, the increased use of e-bikes has positive impacts. But that does not mean they are completely perfect. However, they are certainly a step in the right direction.

2.5 Discussion

This chapter provided the background information on the understanding the technology behind wireless power transfer for e-bikes and the basic working mechanism of an e-bike:

- From the consumer and sustainable energy perspective WPT is more convenient than a conventional cable-based method of charging for the e-bike.
- There are four main components of charging: power supply, charging infrastructure, pickup, and the load.
- The e-bike is assumed to be in static wireless charging mode (the vehicle is stationary).
- For the stationary e-bike lumped IPT is considered where the coils will be closely coupled due to the small air gap.
- For the capacitor compensation network, the SS circuit appears to be useful for Electrical Vehicles WPT.
- Batteries of the e-bike can be evaluated by its cell capacity, resistance, OCV, aging, and its expected lifetime. Most of the electric-assisted bicycles on practice use a lithium-ion battery as an energy source.
- The factors that can influence the IPT transmission efficiency are coil size, coil shape, coil distance, and coil resistance.
- When it comes to IPT different measurements must be taken for safety concerns.

For the upcoming chapter, the literature study was continued, here the related work that was available about wireless charging of e-bikes was studied. From there the three most implemented WPT e-bike methods are summarized and compared to see what the similarities, differences, and future recommendations are.

All the related work and self-suggested parameters that will be presented next in the chapters will be evaluated through three metrics:

1. **Practicality:** This parameter defines the quality or state of the design being useful.
   - Ease of use for the user (comfort)
   - No disturbance in aerodynamics and equilibrium of the bike.
2. **Efficiency:** This is the most important measurement parameter to decide which wireless charging technology is best suited for the e-bike. Further explanation can be seen in 2.3.4.
3. **Safety:** This parameter contains information about the condition of being protected from danger, risk, or injury. Further explanation can be seen in 2.3.5.
   - Safe for surrounding humans (EMF radiation).
   - Safe for the environment (no toxic materials used).
   - Safe and non-interfering with surrounding electrical components.

Chapter 3. Analyzing Related Work

In theory, there are several design possibilities for a WPT e-bike charging mechanism. However, in this chapter, the three most common wireless charging mechanisms are addressed and compared. Section 3.1 is the introduction where the basic parameters are listed with their basic requirements and limitations. This section also contains a bibliometric research for the WPT e-bikes. Section 3.2 summarizes three main implemented wireless e-bike charging methods by different researchers. The discussion in section 3.3 contains the answer to the first sub-research question to gain information that can be useful for the new prototype of the WPT e-bike.

3.1 Introduction

After the literature study, a list of parameters has been created to clarify differences and similarities in the wireless e-bike charging methods. Each parameter has a different effect on the quality of wireless charging. Eventually, with this list of parameters, the DSE can be implemented. Meaning that the effective parameters which can gain the practicality, efficiency, and safety of the WPT mechanism can be defined.

The to be studied parameters for wireless IPT e-bikes:

1. **Type of resource**
    - Grid-connected
    - Stand-alone
        - Renewable sources (solar/wind/hydro/tidal)
            - Direct current (Dc)
            - Alternating current (Ac)
2. **Characteristics of transmitters (Tx) and receivers (Rx)**[5]
    - Material type
    - Physical parameters[6]
3. **Positioning and placement of the receivers (Rx)**
    - Front section
    - Middle section
    - Back section
    - Kickstand
4. **Type of batteries**
    - Lithium-ion
    - Nickel Metal Hydride
    - Other
5. **Allowed airgap**[7]
6. **Power efficiency**
7. **Safety considerations**

All the above-mentioned seven points come under the umbrella of design parameters and the purpose here is to set these parameters in such a way that WPT in e-bikes is practical, efficient, and safe.

[5] Tx is the primary side coil and Rx is the secondary side coil.
[6] Windings, geometric shape, length etc.
[7] Distance between the inductors Tx and Rx.

The first sub-research question reads as follows *''what are the tradeoffs between the studied wireless e-bike charging methods that are defined in theory?''*. To answer this first a summary will be given of three studied methods and then the question will be answered in the last sub-chapter. As for the first part of the second sub-research question, it requires the *''identification of the various parameters''* that can influence the quality of the wireless charging of an e-bike. These parameters as can be seen in this section will be further elaborated in this chapter and Chapter 4.

Basic requirements and limitations

For the listed parameters there are some basic requirements and limitations that should be considered when analyzing the related work and when designing the new WPT e-bike prototype.

Type of resource: The e-bike primary side circuit can be connected to either the grid or it can be powered by a stand-alone unit. As far as the connection with the grid goes there are several possibilities but for now, that is out of the focus. With the worldwide green environmental move nowadays, the preferred power sources are driven by nature, this can be implemented for the stand-alone unit. Renewable energy sources are considered "sustainable" as they will not run out. With the available renewable power, the circuit can be either controlled with a Dc or an Ac.
Type of Tx and Rx: The Tx needs to transfer the required power (dependent on the structure) to the Rx and ensure that stray or leakage magnetic fields are contained.
Positioning and placement of Rx: The Rx in the bicycle can be installed on multiple locations on the bicycle. However, it should be permanently fastened on the bicycle. This because removing and placing the Rx can wear out the material and can also lead to unnecessary misalignments. The Rx should be placed such that it does not interfere with the e-bike usage.
Type of batteries: In theory various battery types are available. The battery for the prototype should enhance the power mechanism, they should be able to last long with short charging time and they should be light weighted.
Allowed airgap: This should be minimalistic to increase the magnetic coupling, prevent magnetic leakage, and eventual other Tx and Rx contact disruption.
Power efficiency: Ideal is a power efficiency of 100%. But the realistic scale is set on 70-90%.
Safety considerations: To ensure the safety of users and passersby, the system should comply with the ICNIRP guidelines and it should not interfere with the surrounding equipment.

Bibliometric research

As mentioned before, there are a lot of studies regarding the WPT in the e-bike. The bibliometric research shows a general overview of the available e-bike publications so far. To present a statistical analysis of official books, articles, or other publications of the e-bike trend two types of queries were implemented, the year evolution and the global distribution.

For the queries, the biggest multidisciplinary and trusted academic bibliographic database resource Scopus was used. The search query used: TITLE-ABS-KEY ("Electri* bicycl*" OR "Electri* Bik*" OR "e-bike"), the received report is exported to refine. This similar methodology has been used successfully in other bibliometric studies [27].

Year evolution of Scientific Document Production

Starting from the year 1973 to 2019 the search yielded 1324 official document results, see Figure 79. Of all the documents 93.34% of them are in English. It must be noted that the search has no data before this date, for this reason, 1973 is considered the first year of this search. It is observed that the increase begins in 2004 and 2013 the scientific production increases remarkably. As far for 2020 currently there are already 87 documents and there will be added more, which is why 2020 is not yet included in the chart. The year evolution query supports the statement that up till now there is a lot of scientific interest in this topic and that is linked together with an increase in the e-bike trend.

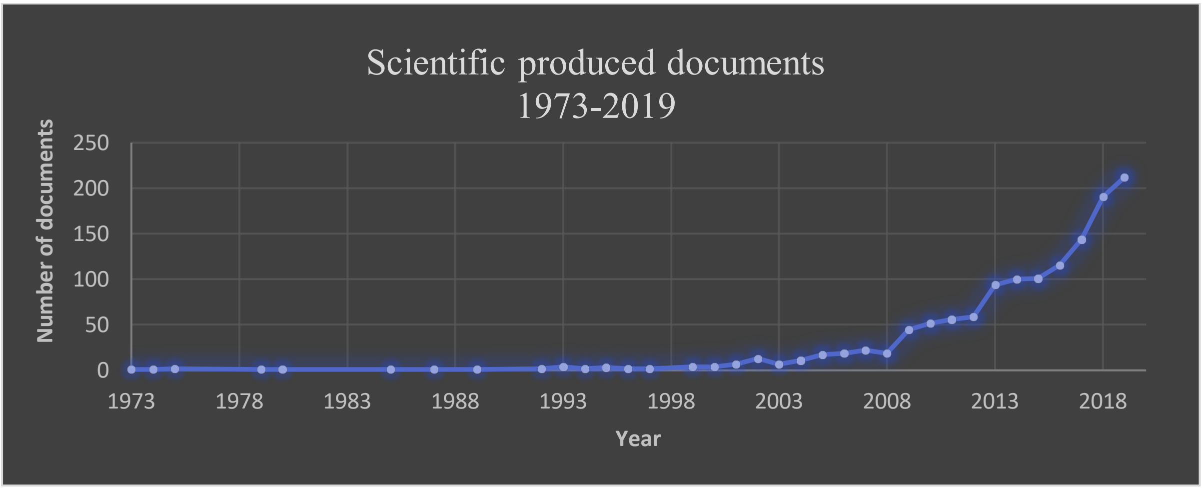


Figure 7. Scientific produced documents 1973 till 2019 [28]

Global distribution of Scientific Document Production

All the 1411 documents (the year 1973 till 2020), originate from different countries as seen in Figure 80. From the global distribution, it can be seen that most publications are from China. In [28]

the top ten countries with the most scientific produced documents are displayed. There it is also shown that the Netherlands is on the 9th Place with 46 scientific publications. From the 46 publications, five belong to authors from the University of Twente. This shows that on a world scale the Netherlands is also very active in this topic.

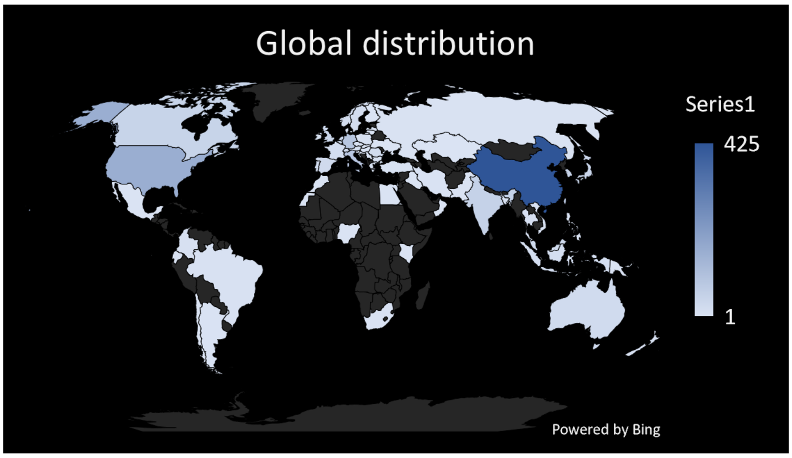


Figure 8. Global distribution produced documents (1973-2019) [28]

Countries	Publications
China	425
United States	159
Germany	89
Italy	81
Taiwan	75
India	52
South Korea	48
Canada	47
Netherlands	46
United Kingdom	41

Table 2. Top 10 countries

Design space exploration (DSE)

DSE signifies the activity of evaluation of the system and its performance resulting from different combinations of parameters (designs) to determine which parameter combinations are 'optimal' [29] [2]. The three WPT e-bike methods contain the points for an effective DSE that are mentioned in [2]. The relation between design choices on the one hand and parameters on the other hand can be complex to establish, due to various aspects that must be taken into consideration.

3.2 Related Work WPT e-bikes

3.2.1 Study 1: EDLC Batteries and Front Basket Antenna Rx

In paper [30] the authors discuss a system design of an electric-assisted bicycle using EDLC batteries and Tx and Rx patch antennas for the IPT. The study provides the following [16] [30]:

- ✓ Overview on the IPT.
- ✓ Design of the EDLCs capacity.
- ✓ Comparison of three kinds of Dc-Dc converters.
- ✓ Investigation of the WPT antenna.

The results indicated that the Dc-Dc boost-type converter is the most compact in the power capacity of the e-bike and their proposed system is experimentally verified as a prototype.

Type of resource: Stand-alone circuit with a direct current (Dc) generator. There is no additional explanation given on why this choice was made. The circuit topology of the interface Dc-Dc converter for EDLCs in the proposed system configuration in terms of volume and efficiency. The boost type is adopted for the bi-directional Dc-Dc converter.

Type of Tx and Rx: Both are two identical microstrip patch antennas. Microstrip antennas are a wireless device to transmit and receive frequency signals. The most used microstrip antenna is the patch antenna which has attracted a lot of attention because of their advantages such as ease of fabrication simple structure, easy integration with microwave integrated circuits [37] [38] [39] [40]. Wire material is copper, and the geometrical shape is a planar octagon. The coils are loosely coupled, a reactive network (SS compensation circuit, chapter 2.3.1) is needed to maximize the power transfer efficiency and optimize the power factor if the system works at the resonance.

Positioning and placement of the inductors: Front section of the e-bike. Rx is placed in front of the bicycle basket and the Tx is placed on the wall as seen in Figure 9. This similar placement method is also proposed and discussed in the paper [31].

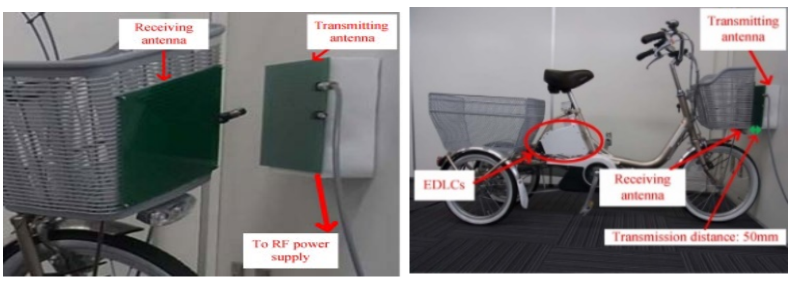


Figure 9. Wireless charging method of the electric bicycle [30]

Type of battery: EDLCs instead of Lithium-ion. The lithium-ion battery is suitable for a long assist time because of the high energy density. However, according to the authors, the lithium-ion battery has a short lifetime and needs a long charging time.

Characteristics EDLCs

''An Electric Double Layer Capacitor (EDLC) is defined as a device using induced ions between an electronic conductor such as activated carbon and an ionic conductor like as organic or aqueous electrolyte'' [32]. EDLCs use the electric double layer to function as the dielectric. ''Compared to aluminum electrolytic capacitors, EDLCs offer a larger capacity, but their larger internal resistance means that their use as ripple absorption for alternating current circuits is not appropriate'' [32] [30].

Allowed airgap: 50 mm.

Items	Values		Remarks
Outline (Length)	250	mm	
Outline (Side)	200	mm	
Number of turns (surface)	10	turn	Short type
Number of turns (reverse face)	10	turn	Short type
Space between copper trace	5	mm	
Width of copper trace	3	mm	
Thickness of PCB	2	mm	FR-4
Thickness of copper trace	70	µm	
Self-inductance L_1	58.27	µH	
Self-inductance L_2	58.70	µH	
Mutual inductance M	21.95	µH	
Designed coupling factor k_0	0.375		
Primary capacitance C_1	586	pF	
Secondary capacitance C_2	500	pF	

Figure 11. Conditions of the experiment [30]

Items	Values	
Frequency of the FG	929	kHz
Resonant frequency	929	kHz
Voltage of the FG	450	mVrms
Gain of the RF power source	100	
Transmission distance	50	mm

Figure 10. System antenna specifications [30]

3.2.2 Study 2: IPT Inductors in Kickstands

The papers [33], [34] and [35] investigate WPT in e-bike with the usage of magnetic couplers installed within/around a kickstand[8]. The studies provide the following [33] [34]:

- ✓ Design options for Rx within a kickstand
- ✓ Design options for a Tx underground pad.
- ✓ Comparison of different geometrical shaped IPT coils: Cylindrical Solenoid; Circular; Solenoidal Bar; Double-D.

As a result, a solenoidal bar pickup with a Double-D provided the highest coupling while the solenoidal bar pickup and primary appears to be the cheapest option, utilizing the least amount of ferrite and copper. The built magnetic coupler was used in a prototype system and was able to produce an output of 200W with an efficiency of 86%.

Type of resource: Stand-alone circuit with an alternating current (Ac) generator. The primary power supply was assumed to supply a constant 13A ac current at a frequency of 38.4 kHz to the primary.

[8] Kickstands are metal rods that are used to keep the bicycle in a standing position.

Type of transmitters (Tx) and receivers (Rx): Both IPT coils have a different geometrical combination as seen in Figure 12. The wire material is copper and the shielding material (to reduce the magnitude of stray magnetic fields) is ferrite. The geometrical shapes are cylindrical solenoid; circular; solenoidal bar; double-d. According to the authors closely coupled lumped system is proposed to be suitable because then the magnetic couplers are small in size to be able to fit within or around the kickstand while supplying sufficient power even with misalignment of the magnetic couplers.

Magnetic Structure	Primary	Cylindrical Solenoid	Circular with ferrite bars	Solenoidal Bar	Double-D
	Pickup	Cylindrical Solenoid	Cylindrical Solenoid	Solenoidal Bar	Solenoidal Bar
Primary turns		20	12	20	10 + 10
Pickup turns		30	30	30	30
Primary size		Diameter: 60 mm Height: 60 mm	Diameter: 142 mm Height: 8 mm	Length: 110 mm Width: 21 mm Height: 14 mm	Length: 180 mm Width: 85 mm Height: 11 mm
Pickup size		Diameter: 30 mm Height: 60 mm	Diameter: 30 mm Height: 60 mm	Length: 110 mm Width: 19 mm Height: 12 mm	Length: 110 mm Width: 19 mm Height: 12 mm
Aluminium shield		None	None	None	None
Psu (centred @ 20mm)		60.6 VA	58.9 VA	68.1 VA	78.2 VA
Psu (X offset = 20mm)		43.24 VA	45.8 VA	43.2 VA	48.7 VA
Psu (Y offset = 20mm)		43.24 VA	45.8 VA	44.0 VA	48.8 VA
Coupling (centred @ 20mm)		0.1646	0.2420	0.2130	0.3236
Primary inductance (centred @ 20mm)		55.80 μH	24.65 μH	37.89 μH	18.72 μH
Pickup inductance (centred @ 20mm)		67.89 μH	69.04 μH	85.80 μH	83.70 μH

Figure 12. Properties of the magnetic couplers [33][9]

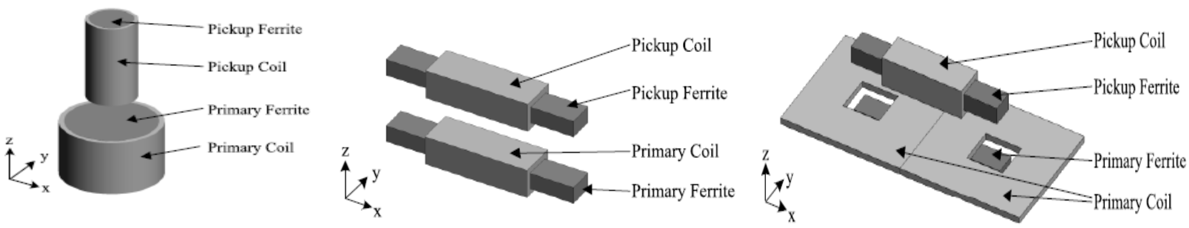


Figure 13. Cylindrical solenoid Tx and Rx; solenoidal bar Tx and Rx; double D Tx with solenoidal bar Rx [33][10]

Positioning and placement of the Rx: Kickstand, which is a metal rod that is attached to a bicycle or motorcycle, it is in a horizontal position when not in use and can be brought into a vertical position to support the vehicle when it is stationary. There are many types of kickstand but generally, they can be split into two types:

- Single support: this utilizes a single leg that can flip out to one side of the bicycle.

Figure 14a. Side stand

Figure 15b. Center stand

[9] **Solenoid** is the generic term for a coil of wire used as an electromagnet. It also refers to any device that converts electrical energy to mechanical energy using a solenoid.

[10] ***PU**=pick up coil/Secondary part.

- Double support: this has two supports, a two-legged stand at the center of the bicycle or a bracket stand installed at the rear wheel of the bicycle that can flip straight down.

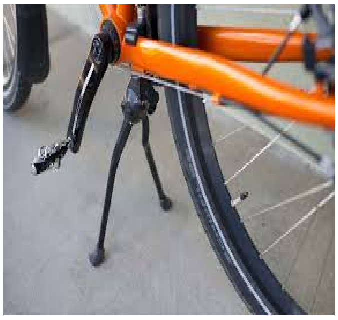


Figure 17a. Two-legged stand

Figure 16b. Bracket stand

The Rx coil is proposed to be installed in or around the kickstand due to some of the advantages that it provides compared to other places in the bicycle (will be discussed in Chapter 4). If Rx coil is installed in other positions, an arm or some sort of mechanism is needed to house the primary coil that ensures that it is close to the pickup during operation. With the pickup in the kickstand and the primary coil underground, no additional arm is required as the kickstand acts as a charging stand, thus saving cost. Therefore, for their prototype, the authors used a side stand. In general, these kickstands are usually thin and made of metal.

Allowed airgap: 20mm.

Power efficiency: The prototype can transfer up to 250W (at the output) with the pickup efficiency of 85% at 200W [34]. Most of the electric bicycles commercially available are powered by 36 V 10-Ah on-board batteries and the charging system needs to provide a suitable charging rate.

Safety considerations: ICNIRP and ARPANSA guideline calculations.

Magnetic Structure	Primary	Cylindrical Solenoid	Circular	Solenoidal Bar	Double-D
	Pickup	Cylindrical Solenoid	Cylindrical Solenoid	Solenoidal Bar	Solenoidal Bar
Primary turns		20	12	20	10 + 10
Pickup turns		30	30	30	32
Primary size		M6 X 60mm	M14.2 X 8mm	110 X 21 X 14mm	180 X 85 X 11mm
Pickup size		M3 X 60mm	M3 X 60mm	110 X 19 X 12mm	110 X 19 X 12mm
Psu (centred @ 20mm)		60.585 VA	63.7 VA	68.07	78.2
Coupling (centred @ 20mm)		0.1592	0.2606	0.2117	0.3212
Primary inductance (centred @ 20mm)		58.6 uH	23.0109 uH	37.2649 uH	18.5861 uH
Pickup inductance (centred @ 20mm)		69.6 uH	69.9163 uH	84.3544 uH	70.5674 uH
Total ferrite volume		169.2690 X 10^{-6} m^3	111.0396 X 10^{-6} m^3	26.4 X 10^{-6} m^3	26.4 X 10^{-6} m^3
Total copper volume		42.7884 X 10^{-6} m^3	39.7348 X 10^{-6} m^3	16.92 X 10^{-6} m^3	47.9175 X 10^{-6} m^3
Psu/Vol. Ferrite		357.92 kVA/m^3	573.67 kVA/m^3	2578.41 kVA/m^3	2962.12 kVA/m^3
Psu/Copper		1415.92 kVA/m^3	1603.13 kVA/m^3	4023.05 kVA/m^3	1631.97 kVA/m^3
Magnetic flux density (150mm away from pad)					
Knee (@ x=150mm & z=350mm)		7.11 uT	4.17 uT	3.83 uT	1.92 uT
Groin (@ x=150mm & z=700mm)		1.39 uT	0.50 uT	0.41 uT	0.38 uT
Chest (@ x=150mm & z=1050mm)		0.68 uT	0.12 uT	0.08 uT	0.23 uT
Groin (@ x=150mm & z=1400mm)		0.55 uT	0.05 uT	0.03 uT	0.19 uT

Figure 18. Calculations for magnetic safety [33]

ICNIRP has stated that the general public exposure limit due to magnetic flux is a body average RMS flux density of 27uT in the frequency range of 0.8 to 150kHz [21]. However, ICNIRP does not detail the measurement techniques for determining whether systems meet the guidelines.
Fortunately, ARPANSA has addressed the measurement techniques based on the ICNIRP guidelines and has suggested taking average exposure level at four points of the human body: the head, chest, groin, and knee [36]. According to the author's calculations, assuming that a 1.5m tall female user is standing 150mm away from the center of the magnetic couplers, the simulated magnetic flux densities at the knee, groin, chest, and head are shown in Figure 17. The magnetic flux densities at those four spots are lower than the spot limit and the body average is well below the 27uT limit. As such, the proposed magnetic couplers would easily meet the guidelines.

3.2.3 Study 3: E-bike powered with Solar Energy

T. Velzeboer from TU Delft [37] describes the redesign of an existing bike shed to a stand-alone WPT e-bike shed. This was the first solar powered WPT e-bike station in the Netherlands. The proposed station should handle four e-bikes at a time with the excess supplied energy transferred back to the system. The study provides the following:

- ✓ Design of the solar charging station
- ✓ Design of the e-bike kickstand coil

The main goal of this report was to change the existing bike shed of the TU Delft to an autonomous solar powered bike shed.

Type of resource: Stand-alone, renewable energy: solar power. The solar panel efficiency, tilt angle, and azimuth from the incident light, and the surface of the panel itself play an important role. The charging station collects the energy requirements from eight solar panels. These solar panels transfer their energy through a direct current net directly to the batter in the bicycles.

Characteristics of Tx and Rx: The primary side magnetics have a different value of self-inductance due to the long cables to the bike shed. The coil wire is copper, the shielding has a ferromagnetic core. Around the stand and tile, a strong layer is formed to ensure the impact of strength. The primary tile is made of a block of PVC. In the PVC, the shape of the magnetic tile is milled out and the magnetics are glued with polyurethane. The polyurethane is partly flexible so it can absorb shocks and the magnetic core can expand a bit because of heat. On top, a polycarbonate layer of two millimeters is placed to give impact strength from the top.

Geometrical shape:

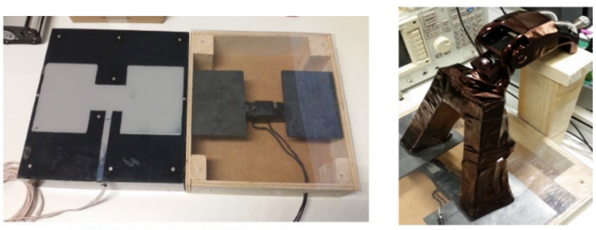


Figure 19. Primary and secondary IPT coils [37]

Positioning and placement of Rx: Kickstand because the bike does not have to be altered and no different systems for different frame types must be designed. When the double stands meet the magnetic tiles of the charging station the bike can be charged through the coil.

Type of batteries: Lead-acid. Most of the lead-acid batteries on the market are not optimal for seasonal storage because of the internal leakage. This calls for more solar cells and less storage. Lead-acid batteries are widely used in cars, boats, and also solar systems. Lithium types have a stable voltage, but great care should be taken with charging and discharging. Overcharge will result in a fire where undercharge will result in permanent damage [37].

Efficiency: According to the author the wireless charging station appears to take no less or more time than the 'conventional' charging of electric bicycles.

3.3 Discussion

The bibliometric research indicated that up till now there is indeed an increase in the e-bike trend when it comes to exploring various methods for WPT. In the top ten countries with the most scientific produced documents, the Netherlands is shown on 9th Place with 46 scientific publications. This indicates that on a world scale the Netherlands is very active in this topic.

In this whole chapter three most used design possibilities for a WPT e-bike charger are studied and compared with each other. The answer to the first sub-research question: *''What are the tradeoffs between the studied wireless e-bike charging methods?"* can be seen in table 2.

Study 1	Technology for WPT: Source: Battery: Airgap: Characteristics coils: Positioning coils:	Loosely coupled -IPT Own circuit- Dc EDLC 50mm Tx/Rx: microstrip patch antennas (identical with Rx). Wire coil: copper Geometrical shape: planar octagon Tx: vertical wall. Rx: front section of e-bike, on the basket.
Study 2	Technology for WPT: Source: Battery: Airgap: Characteristics coils: Positioning coils:	Closely coupled- IPT Own circuit-Ac Lithium-ion 20mm Tx: solenoidal bar Rx: Double-D & solenoidal bar Wire coil: copper Shielding: Ferrite Geometrical shape: Cylindrical Solenoid; Circular; Solenoidal Bar; Double-D. Kickstand (side stand)
Study 3	Technology for WPT: Source: Battery: Airgap: Characteristics coils:	Closely coupled- IPT Stand-alone-Renewal, Solar-Dc Lead-acid 7mm Tx: Self-made Rx: Self-made

	Shielding: Ferrite
Positioning coils:	Kickstand (two-legged stand)

Table 1. Comparison of studied related work

For the stand-alone renewable solar panel power source, it should have a solar tracker to place the panel exactly in line with the sun to receive maximum irradiance. It should be made sure that noting from nature can disrupt the panels because all they can decrease the amount of power the solar panel will deliver (e.g. rain on the surface will reflect a part of the sunlight or other particles of dust or debris can block the incident light. When trees are located nearby, a shade can be placed on the panels or in autumn, low solar income in winter). Due to low resources to build and test this, it will be out of this thesis. And we will assume that the stand-alone circuit is operated by a manually inserted Dc or Ac generator.

All three studies use IPT coils for the WPT in e-bikes. Closely coupled- IPT coils allow for maximum power transfer, while loose coils can be placed anywhere in the field. Which is why most studies chose closely coupled- IPT. In section 2.3 Inductive Power Transfer this is elaborated.

Study 1 chose an EDLC battery over the commonly used Lithium-ion batteries. However, using EDLCs leads to the use of an extra DC-Dc converter in the circuit, and the lifespan is limited because of the use of electrolyte. The energy content of the EDLCs might not be enough whereby several parallel stacks are required. From this context, the use of lithium-ion capacitors could be an interesting solution in vehicular applications where still high peak powers with higher energy content than EDLCs are desired. Also, experimental results from [38] showed that lithium-ion based batteries will replace EDLCs. This because the combination of high power and high energy density can provide better performance compared to the EDLCs in many applications. Study 3 chose lead-acid batteries. Lead-acid batteries are widely used in cars, boats, and solar systems. These kinds of batteries can handle wide temperature ratings (−18 to 50 degrees). However, most of the lead-acid batteries on the market are not optimal for seasonal storage because of the internal leakage. This calls for more solar cells and less storage which increases the costs. In conclusion, the EDLCs and lead-acid batteries will not be used for the prototypes, because on the long term the lithium-ion batteries are much more efficient.

When it comes to the geometrical shapes of the coils and coupling the double-d-Sol configuration provided the highest coupling and the lowest magnetic leakage compared with the rest of the pad configurations. However, the copper usage of the DD-Sol is considerable due to the structure of the double-D primary. The Sol bar–Sol bar configuration was found to be the cheapest option with the least material usage but had the worst magnetic leakage profile in the x-axis when misaligned. In practice, there are many more used geometrical shapes used for the Tx and Rx coils. However, the most common implemented shape and variation of its type that can be found is the cylindrical solenoid. A good shape choice can be made when other values of the parameters are known (size restriction, costs, material availability for wire and shielding, etc.), and this can be validated with tests or simulations.

Study 2 proposed magnetic couplers would easily meet the guidelines according to ICNIRP and ARPANSA guidelines. They addressed the measurement techniques based taking the average exposure level at four points of the human body: the head, chest, groin, and knee [36].

For one charging station it is shown in [33] that if a 1.5m tall user is standing 150mm away from the center of the magnetic couplers, the proposed magnetic couplers would easily meet the guidelines. However, if the charging station is going to charge multiple bikes simultaneously, these calculations need to be repeated for the specific scenario. Also in paper [21] they stated that according to both the simulation and experimental collected data of their experiments, a *25 cm* safety distance from the center of the system, for cyclists and pedestrians, is suggested during the charging operation. Therefore, proper precautions in the building of the parking areas for the e-bike wireless charging operation need to be taken. Nevertheless, experimental results concerning the EMC radiation are not provided in this thesis.

Since IPT utilizes magnetic fields to transfer power across an air gap, users and passersby should not be exposed to unnecessary magnetic radiation. This can be ensured by designing the pads to reduce the stray magnetic field emissions. Due to the close-coupled coils and a reduction in the size of the magnetic couplers, it is possible to reduce the magnetic field leakage. Also, if Tx and Rx are positioned at a low height, that can help to contain the magnetic fields at a ground level. As such, the magnetic radiation towards the body of users and passerby are minimized.

In study 1 there are certain limitations with the placement of Rx. Using the proposed antennas is not too practical due to the size (25cm by 25cm). And not all users prefer to have a basket in front (e.g. athletes with sport e-bikes).

Studies 2 and 3 indicated that the placement of Rx coils in the kickstand can be an option. Because it is practical, convenient because every bike uses a kickstand. The magnetic couplers are small to be able to fit within or around the kickstand while. However, its material should be nonconductive to allow the Rx to couple the magnetic fields from the Tx supplying sufficient power even with misalignment of the magnetic couplers. With the pickup in the kickstand and the primary coil underground, no additional arm is required as the kickstand acts as a charging stand, thus saving cost.

The ferromagnetic cores for the shielding are hard to cut but fragile like ceramics. Therefore, it is advised to form a strong layer to ensure the impact strength (e.g. around kickstand). If needed the magnetics can be glued with partly flexible polyurethane. Therefore, it can absorb shocks and the magnetic core can expand a bit because of heat.

It is observed that none of the previous three studies address the possible option of data communication between the charging system and the user. It is a possibility where the user has information about the charging status, feedback if there is something wrong with the charging process, etc. However, none of the studies discuss an alternative to data communication. This will be addressed for the new proposed prototype in Chapter 5.

4. Theoretical Deliberation of Parameters

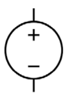
In Chapter 3, three common wireless charging methods for e-bikes are analyzed. Recall that DSE is a process of investigating optimal implementation (parameter) variants. When comparing all the methods a tradeoff can be made with the parameters which are then presented in this chapter. Section 4.1 entails the discussion about the type of resources that are available for the WPT e-bike. Section 4.2 covers the different points that need to be considered for the magnetic coils Rx and Tx in the WPT e-bike technology. Section 4.3 discusses the various battery options and the most implemented battery. Section 4.4 ends with a discussion where the second sub-research question is answered. The obtained results here are further used for the prototypes in Chapter 5.

4.1 Type of Resource

After an interview with Accell Group Nv. in the Netherlands the choice was made to focus on all the four components of wireless charging (see section 2.2). All these four components are linked to each other and can influence the three cross-cutting concerns[11] of the prototype.

One of the four components is the power supply, this connects the other three components to the electric source to receive the power. The power source is on the primary side of the circuit on a separate construction and not on the e-bike. Electrical power can be extracted from either the grid or a stand-alone system which is self-generating. Being connected to the grid refers to a connection with the main electrical power supply we receive from the local energy supplier. While the stand-alone system can be powered by various renewable energy sources without any connection to the electricity grid. In the Netherlands, the biomass, wind, and solar powered sources are mostly implemented [27].

As mentioned in Chapter 3 the preferred power sources are driven by nature: renewable sources and the grid connection will be left out of the scope. In most of the related studies of WPT e-bikes, the authors just focused on a simple power source circuit instead of the full connection with the renewable resource. Here there were two options for the power source: Ac and a Dc generator. Which is why they will also be included here. All these three power source types are weighed out below in Table 2.

	Advantages	**Disadvantages**
Dc generator 	Over the world Dc installations are permanently increasing. The initial cost of Dc generator is less compared to Ac generators. Steady magnetism along the wire. It can be transmitted over very long distance with negligible losses.	Both brushes and commutators of a Dc generator wear out quickly and thus are less efficient. Since the brushes and commutators wear out quickly, sparking, and short circuit possibility is high. Dc generators require frequent maintenance and are less reliable.

[11] Practicality, efficiency, and safety quality of wireless charging.

	IPT patches work best with Dc generators [39].	
Ac generator 	Efficiency of brushes: Since slip-rings have a smooth and uninterrupted surface, they do not wear quickly and are highly efficient. Ac generators require very less maintenance and are highly reliable. Ac generators are very efficient as the energy losses are less. Safe to transfer over longer city distances and can provide more power.	The initial cost of Ac generator is high. Rotating magnet along the wire. If used for the prototype, some additional components must be considered (converters).
Renewable source- Solar Energy 	Less polluting the environment compared to other sources. No harmful polluting gases are produced [40]. Has most abundant energy source available (the sun) [40]. The system can last up till 15-30 years. Diverse applications: it can be used for diverse purposes e.g. to generate electricity (photovoltaics) or heat (solar thermal) [40]. Can be used to produce electricity in areas without access to the national energy grid [40]. Solar energy can also be integrated into the materials used for buildings and in this case also for the charging shed. There are no moving parts, so no wear and tear [40]. Technology in the solar power industry is constantly advancing and improvements can intensify in the future [40].	It requires a high initial investment [40]. The device is dependent on the weather [40]. Supplemental energy may be needed in low sunlight areas. It requires large physical space for the PV cell panels [40]. Solar energy storage can be expensive [40]. Limited availability of polysilicon for panels [40]. The need to keep them relatively clean for optimal working. Also, the cables need maintenance to ensure that the system runs at maximum efficiency [40].
Renewable source- Wind Energy	Clean & environment friendly source [41]. No harmful polluting gases are produced.	It requires a high initial investment [41].

	Cost effective. Low operational costs [41]. There are no emissions [41]. Relatively high output [41].	The output is proportional to wind speed (not a constant energy source) [41]. Wind turbines can generate noise and visual pollution [41]. It is not feasible for all geographic locations [41].
Renewable source- Natural/Biogas 	Improves environment: biogas generation reduces soil and water pollution [42]. Requires low capital investment [42]. It is the cleanest-burning fossil fuel [42]. It is often used in combination with other fuels to decrease pollution in electricity generation [42].	High transportation costs [42]. The lack of infrastructure makes the gas resources unavailable from some areas and it is only feasible in certain locations where raw materials are in plentiful supply [49]. It burns cleanly, but still has some emissions [42]. May contains impurities [42].

Table 2. Advantages and disadvantages of the type of power sources

Discussion Ac compared to Dc:
The difference between Ac and Dc can be seen through the direction of the electrons flow[12]. In an Ac generator, the electrical current reverses direction periodically. In a Dc generator, the electrical current flows only in one direction.

Ac generators produce a *high voltage* which varies in amplitude and time. Dc generators produce a low voltage when compared to Ac generator which is constant in amplitude and time.

For *long distance power transmissions*, Ac can ramp up voltages through transformers results in lesser resistance in the wires which can provide efficient transmission of long-distance power. Compared with Dc this is difficult and costly to efficiently create high voltage Dc. For this thesis which is about the e-bike the distance for the power transmission is not that huge, so depending on that the power source can be either one of them.

If we look at the *ease of usage*, Ac is simple to operate through the usage of wires and transformers for voltage adjustments. And Dc is unable to conveniently convert voltages due to requiring complicated circuits. In this case, Ac is much more convenient and flexible.

For the *compatibility with electronics*, Ac is less compatible with electronics due to the directional changes of current. And Dc is more compatible with electronics as current flows reliably in one direction. The e-bike WPT structure contains a few electronics so in this case, Dc is the solution to power the electronics.

[12] Electricity or "current" can be defined as the movement of electrons through a conductor (e.g. wire).

Depending on the *initial costs*, the initial cost of the Dc generator is less compared to Ac generators. There are studies where their data proves that ''*there are no significant differences in fuel consumption regardless of whether an Ac or a Dc generator is used to power the same Dc load''* [43]. However, according to [44] they stated that *''with rapid technology development in electronics, Dc power systems can be optimized further to achieve better performance and efficiency''*.

Based on the *application area*, Dc is more used in the world for EVs. In previous studies, it is shown that IPT patches generally work best with Dc.

With the green energy movements nowadays, the first choice for the power source type would be renewable resources. If we compare the three renewable sources from Table 2 with each other, the solar energy source is the best option if we look at the necessary power input and the ease of use which is needed for an e-bike. When it comes a separate circuit with the options of the two generators the choice of the power source is a Dc generator because we have a relatively short distance for the power transmission, the structure for the e-bike WPT is compatible with electronics, its initial costs are less and the Dc power source is mostly used for IPT structures.

4.2 Magnetic Coils

Two of the four components of wireless charging are further discussed here. The first one is the charging infrastructure Tx, the unit that transmits the power through an electromagnetic. And the second one is the pickup Rx, which intercepts the power from the primary side. WPT coils have a huge application area e.g. automotive, furniture, infrastructure, medical technology, etc.

When it comes to the WPT coils for the e-bikes, these points must be taken into consideration[13]:

1. **Freedom of positioning Rx:** For all the WPT EV's constructions the Tx is fixed at a specific position on a construction. The Rx can be a single coil, an array (where movement is allowed in one (x)-direction) or it can be a multiple coil array where it can be moved in two (x and y)-directions. For this WPT e-bike prototype, the Rx is one single coil where its placement on the e-bike can vary**.**
2. **Distance between Tx and Rx (airgap):** As indicated in Chapter 2 and Chapter 3, the distance of Tx and Rx should be less for an optimal coupling, therefore it is advised to keep it less than 100mm.
3. **Electrical performance (efficiency, shielding, q-factor**): The main problem with WPT is the poor performance of magnetic coupling that influences the overall efficiency. Factors that play a role here:
    A. The coupling factor (k) can be influenced by the poisoning of the coils and the airgap.
    B. The quality factor (Q) can be improved by the performance of the coils due to its characteristics.
    C. EM field leakage which can be improved using shielding.

[13] Tx is the power transmission coil on the primary side. Rx is the power receiver coil on the secondary side.

These three points should be carefully chosen to increase overall performance (efficiency).

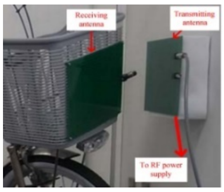
4. **Ease of placement on the bike:** The coils should not be an obstacle and should not create any discomfort for the consumer and the overall electrical system and bike framework.
5. **Safety of EM fields and other electrical components:** As indicated in section 2.3.5 the EM field does not have a huge effect on humans. However, the radiation of the coils regarding unwanted heat flow, unwanted temperature increase should not affect the other components in the WPT system.

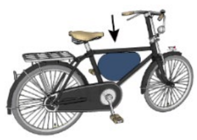
Freedom of positioning Rx

As stated in Chapter 3 the Tx and the Rx can be installed in various locations. The Tx must be fixed on a specific separate construction. However, it is advised to keep the Rx fixed (not detachable) on the metal frame of the bicycle. By keeping the Rx in a fixed position, it can provide the following advantages:

- ✓ Reduce material wear out due to the user and e-bike movements.
- ✓ Reduce change of misalignments with the Tx.
- ✓ Reduce chance of electromagnetic leakage due to huge airgap or misalignments.

The following options for the Rx placement can be listed:

	Advantages	Disadvantages
Front Basket  	It is safe enough: The magnetic field does not influence the human neither on the surrounding equipment. And the coils are far positioned from other EE equipment Depending on the coil characteristics this can be a mediocre efficient system (see section 3.2.1).	Not practical: Not all bikes have baskets. Thus, it is not directly applicable to all e-bikes. Height differences in the basket of the bike can create misalignments between the Rx and the Tx. This mechanism is not theft proof on its own. You need external materials e.g. bike chain and locks.
Kickstand 	Practical: The coils can be easily added to specific types of single and double supported kickstands (e.g. side stand and two-legged stand). With a double stand the magnetic circuit can almost form a closed circuit, if a tile is used for the primary coil. Safe: Due to the coils being on the ground level the EM radiation will not have any major effect on the user. Also, the coils are far	Because of the angle position of the kickstand there is a 65% chance of misalignment where the Tx and kickstand are not perpendicular. This design can create friction to equipment because the Rx is placed directly on the Tx equipment. This mechanism is not theft proof on its own, you need external material e.g. bike chain and locks. Different bicycles have diverse kickstands therefore it is not directly

	positioned from the other electrical equipment’s. Efficient: Due to the placement of the kickstand on the ground the airgap is relatively low between the Tx and Rx, this can increase the magnetic coupling.	applicable to all the e-bikes. However, the coils can be made such that it is applicable to all types of e-bikes.
Handlebar or Headlight  	Practical: It does not bring the bike out of balance. And the coils do not interfere with the handlings of the rider neither the other equipment’s (e.g. lamp/bell etc.). The bike can be locked if the Tx is on a different standing construction. Safe: The EM field does not influence the rider. Also, the coils are far positioned from the other electrical equipment’s.	Possible need for extra equipment to attach the Rx coil. Efficiency: The height of the bike also plays a role when the coils are placed onto the handlebar, Tx will stay on a fixed position, thus misalignments can occur which can lower the magnetic coupling.
Front wheel (around the rim  and in between the spokes) 	Position of Rx is fixed and has minimum maintenance. The bike can be locked if the Tx is on a different stellation that provide the option.	Design of the Tx must me in such a way that there is minimalistic change for misalignments. Tx coil construction might be huge due to the Rx around all the spokes. Not Practical: Around rim: large coils and metal inside the wheel. Spokes: Here metal spokes and rim can heat up from the magnetic field. The radius of the wheels must be taken into consideration because different radius is possible, and the primary system must be adapting to the height to ensure a high coupling.
Between frame 	It can be easily attached to the frame because it is supported in between the frame.	Not practical: This area is also called the Bermuda triangle and it is not advised to keep more components here due to the presence of other e-bike components and wires. Also, the coils may interfere with the rider Only applicable with a specific type of frame of the bike. Many female bike frames are different.

		If bike is made of metal or carbon, the frame can heat up due to currents induced inside the frame or the coils. Not safe: Here the coils are close positioned from the other electrical equipment's which can possibly create an interference. Most batteries of e-bikes are placed near this triangle of the frame.
Under the carrier 	The Rx coil is fully supported by the horizontal framework of the carrier.	Not practical: Some e-bikes do not have a carrier. And is more eligible for damage due to extra passengers that may use the carrier. The coil is placed in the carrier itself, where the bike must be placed backwards in the charging stand. The Tx construction will be more complicated compared to the others. Not safe: Here the coils are close positioned from the other electrical equipment's which can possibly create an interference. Most batteries of e-bikes are placed near the carrier.

Table 2. Advantages and disadvantages of positioning Tx & Rx [37]

Discussion placement Tx and Rx:
Taking everything from Table 2 into account the requirements for the placement of the Rx from chapter 3 can be updated:

- ✓ Coils should be practical
  - o Rx should be fixed on the bicycle and should not be detachable to reduce material wear out and possible misalignments.
  - o Rx should be placed such that it does not interfere with the handlings and riding of the user (positioning, size, weight).
  - o The e-bike appearance should not be changed too much with the addition of the Rx.
  - o It should be applicable for different types of e-bikes, e.g. man or woman and height differences.
  - o The Tx and Rx should operate under the 4 seasonal weather conditions (coil characteristics).
  - o The Rx should not bring the e-bike in to disbalance (positioning, size, weight).
- ✓ Efficient:
  - o It should have a small air gap to increase the possible magnetic coupling and reduce stay EM rays.
  - o It should be placed such that it does not interfere with other EE components.

- The quality factor can be improved by the performance of the coils due to its characteristics, thus it must be selected carefully.
  - Shielding must be used to decrease EM field leakage.
- ✓ Coils should be safe
  - The parts of the bike should not heat up due to eddy currents.
  - The EM field should not affect pedestrians.

After an interview with Accell engineering group for e-bikes the following requirements for the Tx and Rx coils have been stated:

- ✓ The Rx coil's weight should not be more than 2.5 kg.
- ✓ The Rx should not be placed in the Bermuda (triangle) frame zone to keep it far from all the other systems of the e-bike (e.g. motor, battery-pack etc.).
- ✓ The Rx size should be not be big, approximately 5 cm length, 5cm width, and 5cm height.
- ✓ The Tx and the Rx design should be such that the same coil replica can be used for different types and sizes of e-bikes.

The coupling factor (k) can be influenced by alignments of the coils thus the placements of the two coils in XYZ-direction. There are 3 types of alignment lateral misalignment, angular misalignment, and vertical misalignment. Good coupling and maximum energy transmission depend on the size of the effective area of the receiver coil in the magnetic field and the distance between the two coils in vertical direction. Therefore, when it comes to the placements of the Tx and the Rx, the transmitter coil is either placed in a separate construction block or in the ground beneath a tile depending on the position of Rx. Based on Table 2, the requirements and Accell, the position for the Rx can be on one of these places: front frame and kickstand.

Coil characteristics

The quality factor (Q) can be improved by the performance of the coils. This can be defined by the following metrics:

- Geometrical shape
- Size of the Tx and Rx (number of turns; diameter of the coil; wire length etc.)
- Material of wire
- Material of shield

Geometric Shape: In general, the physical construction of the coil may vary. However in the papers [45] and [46] they compared a total of 16 different coil geometries. The strengths and weaknesses of the topologies were evaluated for an analysis in terms of the coupling factor, the power to be transmitted, the copper mass used, and the distribution of magnetic flux density. Based on these findings and feedback from Accell it was possible to identify a few optimum shapes of which three are chosen for the new prototype: U-core; I-core coils, cylindrical circular solenoid coils, and circular planar spiral coils.

Size: The area of the Rx should be equal to or within 80% of the Tx. This should provide a suitable coupling coefficient of k >50%, with a distance between Tx and Rx of 2.5 ~ 5mm as specified in paper [47].

Number of turns: More turns in a coil creates a higher coil wire length and this provides an increase in the amount of the current which leads to a higher the magnetic field. Solenoid example: $B = u \times \frac{N}{L} \times I$ → Magnetic field= permeability * (number of turns / solenoids length) * current. However, too many coil turns can cause more losses in the coil-system due to the rapidly increased parasitic resistance which will limit the coil-system efficiency. If the coil is loosely-wound, the coil-system efficiency can be improved compared to the tightly-wound coils.

Coil wire material: Litz or copper. When it comes to efficient and safe results litz wire is the choice for the coils. Depending on the estimated budget the wire type and gauge can be bought. For example, larger diameter and bifilar wire offer lower the dc resistance and less loss but are more costly. Litz is more costly than other magnet wires. Litz wire is often used to reduce the impedance at the switching frequency. It does this by reducing skin effect[14]. Litz wire also reduces current losses from the proximity effect, the disruption of current flow from nearby magnetic fields. Currently, in the EV charging systems, the litz wire is mostly used.

Shield Material: Ferrite or aluminum. In previous studies (e.g. [46]) it is proven, that material for shielding, guiding, and confining magnetic flux is essential to ensure good coupling as well as to meet the magnetic field absorption limits defined by ICNIRP. Variation of ferrite and aluminum has revealed that the size of both materials significantly affects the coupling factor and the magnetic field. Especially edge effects have a major influence on the behavior of the magnetic field.

For the new prototype, it is suggested to shield the inductive WPT coils with a ferrite shield[15]. Figure 20 shows an example of the coil positioned on a piece of black ferrite shield. The ferrite material contains properties that shield electronics behind the assembly [47].

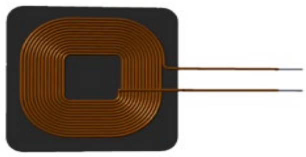


Figure 20. Ferrite shield example

The shield should have two functions:

- ❖ Provide a "short path" for the magnetic flux so that it limits the heating of other components behind the shield, focusing EM field into the ferrite.
- ❖ Improve inductance so that coils can be wound with fewer windings, saving excessive resistance.

Ferrites can be divided into two categories based on their magnetic coercivity (their resistance to being demagnetized). Of the two the soft ferrites have low coercivity and are best for shielding. The ferrite thickness is an important consideration; thicker shields absorb more flux and are less susceptible to saturation, so the thickness is an important consideration. Related studies proved that the shielding should extend a minimum of 2.5mm beyond the edge of the outer winding to allow the flux to flow and not saturate or spill over into other electronics.

[14] Skin effect refers to an increase in a conductor's electrical resistance due to current migration towards the outer surface of the wire or cable.

[15] Shield should extend beyond the outer edge of the coil to reduce EMF from escaping and reduce the saturation point.

Allowed air gap: This should be minimalistic to prevent magnetic leakage and eventual Tx and Rx contact disruption. Most e-bike studies for the wireless application have a range of 1mm-5mm for the air gap. For the prototype, the airgap should be in between the interval.

Wire length: As studied in [10] and [11], the thickness of litz wires and ferrites has a low impact on the coupling coefficient. On the other hand, increasing the length of ferrite can enhance the coupling coefficient. Therefore, to reach the maximum achievable coupling coefficient, ferrite length can be set equal to the outer diameter and outer length of circular coils. Hence, the analysis is limited to variations in the inner diameter (length) and the turn space of coils. And as explained in the number of turns paragraph, the longer the wire, the higher the magnetic field.

EM Safety considerations

To ensure the safety of users and passersby, the system should comply with the ICNIRP guidelines. The magnetic field should also not interfere with the surrounding equipment. To generate the magnetic field for a ubiquitous IPT zone, the transmitting (Tx) coil should satisfy special requirements. First, the Tx coil should provide a long and wide IPT to the devices while satisfying the regulations of magnetic fields to protect human safety, i.e., the guideline of the International Commission on Non-Ionizing Radiation Protection (ICNIRP); the magnetic flux density should be less than 27 μT at 3 kHz ~ 10 MHz in the entire (Ubiquitous IPT zone) U-IPT zone [21].

4.3 Type of batteries

The last component of wireless charging is discussed here. This is the load, the entity which is being charged. E-bike batteries will ultimately determine for how long and how far the e-bike will be able to ride. As a result, choosing the right one is essential to ensure the best experience.

To decide which battery pack is best for an e-bike the main two things that the consumer should keep in mind is to determine what they need (range requirements) and determine what they can afford. After that, a decision can be made based on[16]:

1. Practicality of the battery
    a. Size & Weight
    b. Shape
2. Efficiency of the battery
    a. Battery type (Lead-Acid, NIMH, Lithium-ion, etc.)
    b. Its capacity and power (Voltage, Amps and Watts, Speed)
    c. Long lasting with a short charging time
3. Safety of the battery
    a. For the user
    b. For the environment

[16] The battery pack characteristics is most of the times dependent on the manufacturer of the e-bike itself, however the consumer can change this.

Practicality

Internationally it is suggested to keep the weight scale of the whole e-bike between 100-140 kg. Where most e-bike batteries weigh under 1000grams. Thus, the battery must be in a shape and size that is easily adjustable on the bike without adding much unnecessary weight above the threshold. Accell for example places most e-bike batteries on the carrier of an e-bike in such a way that its weight is supported by the carrier frame and its size is such that it easily fits without forming an inconvenience for the user and other components.

Efficiency

Type of battery

In practice the following types of e-bike batteries have been used:

1. Lead Acid-based
2. NIMH-based
3. Lithium-based [48] [49]

Sealed Lead Acid (SLA)

These batteries were once the standard battery type. Now, most electric scooters still use SLA batteries, while electric bikes have opted for newer battery technologies to keep the e-bike as lightweight as possible.

Advantages	Disadvantages
• Inexpensive • Simple to manufacture • Low self-discharge • Easy to recycle	• Heavy • Shorter life span of about 100-300 full cycle charges which can lead to frequent replacement. • High maintenance. • Needs to be charged immediately after use. • Sensitive to poor treatment. • Environmentally unfriendly.

Table 3. Lead Acid battery

Ni-MH

Nickel Metal Hydride batteries can suffer from the memory effect. Memory effect means that if a battery is repeatedly only partially discharged before recharging, the battery will forget that it can further discharge.

Advantages	Disadvantages
• Contains no toxic metals. It is labeled as environmentally friendly. • Profitable for recycling.	• Generates considerably more heat during charge. • Limited service life. • Limited discharge current. • High maintenance.

Table 4. Nickel-metal-hydride battery

Lithium-ion

The lithium-ion batteries represent the most widespread typology of battery and they are the most preferred solution for electrical energy storage, due to their high energy densities and long lifetimes [24] [22]. A lithium battery has a lifetime roughly 2-3 times that of an SLA battery. Li-ion batteries produce the same energy as NiMH but weighs approximately 20%-35% less.

Advantages	Disadvantages
• Lightweight than many other rechargeable batteries of a similar size. • High capacity. • Lithium ion battery only loses about 5% of its charge per month in comparison to 20% loss for NiMH batteries. • Offer a longer riding range. • Longer life span. • No memory effect. • Quick recharge time. • Their substances are mostly non-hazardous to the environment.	• More expensive. • Requires protection circuit. • Because lithium ignites very easily, they require special handling. • Only a few recycling programs have been established for Li-ion batteries.

Table 5. Lithium-Ion battery

	NiMH	Lead Acid	Li-ion
Gravimetric Energy Density (Wh/kg)	60-120	30-50	110-160
Internal Resistance (mΩ)	200 to 300 6V pack	<100 12V pack	150 to 250 7.2V pack
Cycle Life (to 80% IC)	300 to 500[2]	200 to 300[2]	500 to 1000
Fast Charge Time	2-4h	8-16h	2-4h
Overcharge Tolerance	low	high	very low
Self-discharge / Month	30%	5%	10%
Cell Voltage(nominal)	1.25V	2V	3.6V
Load Current peak **best result**	5C 0.5C or lower	5C[7] 0.2C	>2C 1C or lower
Operating Temperature	-20 to 60°C	-20 to 60°C	-20 to 60°C
Maintenance Requirement	60 to 90 days	3 to 6 months	not required

Table 6. Comparison of 3 types of batteries for e-bike

Advantages that make the Lithium based batteries stand out [37]:

- Lithium battery has the best combination of total weight and capacity.
- Specific capacity of lithium-ion batteries is the highest among all existing types and it is their main advantage.
- Lithium-ion batteries do not have the so-called memory effect.
- Lithium-ion battery compared to the other three has a quicker recharge time.

As mentioned in Chapter 2 the lithium-based battery compared to the others works better in practice. They are also the optimal type of batteries when it comes rechargeable batteries in applications other than e-bikes. According to a digital interview with engineers from GreatEbike group (operating in Europe) and Accell Group N.V. they stated that overall, they prefer to/and use Panasonic battery cells which are Li-ion based.

Capacity and Power

E-bike batteries can come in 24V, 36V, 48V, and 72V batteries. Volts (V) describe how fast electrons move. The most common battery is 36V (nominal voltage) on most e-bikes with some at 24V and some at 48V. Amps-hours (Ah) indicate the capacity, it determines the life of the battery and varies mostly between 10-20Ah. Watt-hours (Wh) determines how far the e-bike can go on a full charge (V*Ah=Wh). By law in Europe [51], the power of e-bikes is restricted to 250W. If you exceed 250W, 25Km/h the e-bike requires a registration, insurance, license plate etc. As mentioned in Chapter 3, for the basic requirements, the maximum achievable output ideal is 100%. However, in practice this is not the case due to losses that are always present. Different studies claimed to provide a power output efficiency of 70% and higher. Therefore, the maximum achievable output for the new prototype should be scaled to be at least 70% of the input power that is provided.

Maximum power transfer can occur when the resistive value of the load is equal in value to that of the voltage sources internal resistance allowing maximum power to be supplied. Measurement of efficiency of any charging system, including wireless charging systems, can be computed from the basic efficiency formula: Efficiency = P_{out} / (P_{out}-P_{loss}), but when these measurements are made, it is important to know the value of all the resistive values from the circuit understand the total system efficiency. This can be implemented when the system is being build or simulated.

Charging time

Another requirement for the battery to stay long lasting with a short charging time. An e-bike with a lithium-ion battery that is fully depleted can take 3.5 to 6 hours to recharge. Batteries that still have a partial charge, will take less charging time. To decrease the charging and thus waiting time of the user there are some possibilities. For example, one of the fast chargers of the brand Bosch needs just over one hour to charge a battery to 50% capacity. But when this is done too often, one might risk decreasing the batteries life expectancy. One can also make use of high-quality packs consisting of high amperage cells, like the Samsung 25R cell, for fast charging. Because the pack is capable of high discharge, it will charge fast without degrading the life expectancy too much. However, they are expensive, and they are not as energy dense as some lower performance high capacity cells. Another option here is to use an advanced variable amperage charger that can either slow charge or fast charge with the flick of a switch.

Safety

E-bikes are zero-emissions vehicles, as they emit no combustion by-products. E-bikes are claimed to have a significantly lower environmental impact than conventional automobiles and are generally seen as environmentally desirable in an urban environment [63]. However, the environmental effects of manufacturing and disposing of the batteries must be considered. After the batteries achieve their end of life cycle they can be recycled. For example, at Eurobike[17] in September 2020, an event is being scheduled to discuss the life span of e-bike battery packs and what should be done with old batteries.

[17] Eurobike is an international leading global trade fair for the bike business in Germany.

Most of the battery packs can be detached from the e-bikes. However, do not remove and carry a battery pack in a pocket, purse, or other container where metal objects can short-circuit the battery terminals. The resulting excessive current flow can cause extremely high temperatures and may result in damage to the battery pack or cause fire or burns.

According to research from Vezelboer T. [37] lithium type batteries have a stable voltage, but great care should be taken with charging and discharging. Overcharge can result in fire where undercharge will result in permanent damage. An expensive Battery Management System (BMS) can be used to solve this by ensuring a correct operation window of the batteries. Some high-quality batteries have a “sleep mode” feature. Basically, a sleep mode refers to a “hibernation state” where the BMS system will protect the cells. Connecting the battery either to the charger or the bike will automatically turn on the system. One can probably get the battery back to a sleep mode but still it will be not as efficient as it was before the first use. Manufacturers have identified that the chargers can also play a role with the battery life. Top devices have a smart configuration that let the charger cuts the power off when the battery reaches a certain point. This prevents the battery to be overcharge, even if it says that is fully loaded.

4.4 Discussion

In this chapter the investigation of the optimal parameter options is discussed. The second sub-research question is: *’’What are the most significant parameters that can gain the efficiency and safety of the wireless charging mechanism’’?* The parameters that influence the WPT in e-bike are: The type of power source, characteristics of transmitters (Tx) and receivers (Rx)[18], positioning and placement of the coils, type of batteries.

The impact which the identified parameters have is explained through this chapter and chapter 3. From this chapter we can summarize that:

- ❖ In conclusion the choice of the power source is a Dc generator because we have a relatively short distance for the power transmission, the structure for the e-bike WPT is compatible with electronics and the Dc power source is mostly used for IPT structures.
- ❖ For this WPT e-bike prototype the Rx is one single coil where its placement on the e-bike can vary. The coils should not be an obstacle and should not create any discomfort for the consumer and the overall electrical system and bike framework.
- ❖ By keeping the Rx in a fixed position, it can reduce material wear out due to user and e-bike movements. Reduce change of misalignments with the Tx. Reduce chance of electromagnetic leakage due to huge airgap or misalignments.
- ❖ After theoretical evaluation and feedback points from Accell the following can be said about the coils: the transmitter coil can be either placed in a separate construction block or in the ground beneath a tile. This will be a stable fixed system mounted to the ground where eventually the bike can be locked and secured in. The Rx can be on one of these places: front frame and kickstand. The Tx and the Rx coil design should be such that it can be used for different type and sized of the e-bike.

[18] (geometrical shape; size of the Tx and Rx; diameter of the coil; wire length; height, wire diameter; number of turns for the Tx and Rx; material of wire; material of shielding; k-factor; Q-factor; airgap)

- ❖ The Rx coil's weight should not be more than 2.5 kg. The Rx should be not be big, approximately 5 cm length, 5cm with and 5cm height.
- ❖ The area of the Rx coil should be equal to or within 80% of the Tx coil. Coil can be made of litz or copper with a shielding of ferrite or aluminum. Coils possible geometrical shapes: U&I-core; Cylindrical solenoid, Circular planar.
- ❖ The k and Q should be carefully chosen to have an efficient WPT because the coupling factor (k) can be influenced by poisoning of the coils and the quality factor (Q) can be improved by performance of the coils.
- ❖ As indicated in chapter 2.3.7 the EM field does not have a huge effect on the humans. However, the radiation of the coils regarding to unwanted heat flow, unwanted temperature increase should not affect the other components in the WPT system.
- ❖ The ideal situation is that the e-bike radiates the same amount of power as received from the power source. However, in practice this is not the case due to losses that are always present. Therefore, the maximum achievable output for the new prototype should be scaled to be at least 70% of the input power that is provided.
- ❖ An optimal battery choice for the e-bike is a lithium-ion based battery. The battery must be in a shape and size that is easily adjustable on the bike without adding much unnecessary weight as possible. To charge a battery faster one can either use fast chargers to charge a battery to 50% capacity or use an advanced variable amperage charger that can either slow charge or fast charge as needed. However, all e-bike batteries have a certain lifespan depending on the chemistry and care. There are some extra tools that can help along the way: Sleep Mode and BMS. After the batterie's lifetime there should be ways to recycle or dispose the batteries safely without any damage on the environment. Different conventions and companies in the world (e.g. Eurobike) are still looking into this matter to find efficient and yet still profitable solutions.

It is of paramount importance to make the right choice when it comes to the parameters. Which is why the next chapter will provide a framework on the building of the prototypes with these parameter choices embroidered in it.

Chapter 5. Framework WPT E-bike Prototype

Up till now different design aspects of the wireless charging methods for an e-bike are evaluated and some choices for the parameters are suggested for the new prototype. In this chapter, a framework will be established for a few new WPT e-bike prototypes, with the focus on the magnetic and the electronic design metrics. Section 5.1 gives a short introduction about the three proposed prototypes. Section 5.2 provides the framework of the magnetic coils from the prototypes. Section 5.3 gives a framework for making the electrical circuit. Section 5.4 entails a brief view of the experimental prototype. The last section 5.5 discusses all the aspects of this chapter.

5.1 Introduction

In section 1.4 limitations, it is indicated that the suggested new prototypes could not be built in the lab due to the COVID-19 lockdown. To cope with this a framework is proposed in this chapter. According to the Cambridge dictionary, a framework is *'' a system of rules, ideas, or beliefs that is used to plan or decide something''*. The framework provides a foundation that future developers can use to build the proposed WPT e-bike prototypes or even use it as a baseline to create their prototype. The theories and suggestions that are developed here are based on existing knowledge, related work, observations, and interviews with Accell.

The prototypes must meet the following requirements:

1. **Practicality**
   - All components should be easily linked together with the e-bike frame without disturbing the functioning of the e-bike and the consumer.
   - Easy application of the Rx coil(s) on the e-bike.
   - Easy application of the Tx coil (s) on a surface.
   - Support easy reuse of the tools across the domain.
2. **Efficient** in power output
3. **Safety**
   - Safety for surrounding humans regarding EMI radiation.
   - Safety for the environment regarding used materials.
   - Non-interfering components (e.g. with surrounding electrical components in the same system).

As suggested in Chapter 4. Theoretical Deliberation of Parameters, the three potential prototypes:

1. **U-core; I-core coils**
   Tx: I-core; Placement: Front frame of e-bike.
   Rx: U-core; Placement: Separate standing construction block

2. **Cylindrical circular solenoid coils**
   Tx: Cylindrical solenoid; Placement: Tile, underground.
   Rx: Cylindrical solenoid; Placement: Kickstand.

3. **Circular planar spiral coils**
   Tx: Circular planar; Placement: Separate construction block.
   Rx: Circular planar; Placement: Front frame of e-bike.

For each of them, the parameters (Chapter 3) should be chosen and designed. The provided information here can be further used for building or simulating the coils. In the suggested prototypes the IPT coils are compensated with SS capacitors to enhance the power flow, efficiency, and power factor of the system. This system can work on the resonance frequency of the compensated system. The prototype IPT system relies on close magnetic coupling and the coil distances are a maximum of 5 mm. The power in the circuit can be controlled by varying the frequency of the coil current. For smaller distances, the efficiency for IPT is higher than RPT and the interference from nearby systems is less due to the strong coupling.

5.2 Characteristics of magnetic coils

The objective of the WPT coils is to transfer the maximum power as efficiently as possible. This can be interrupted by:

- **Airgap** - the distance between Tx and Rx, large distance can lead to a small magnetic coupling coefficient (k).
- **Parasitic resistances** - which can cause losses and reduce efficiency.
- **Q-factor** - which is being influenced by the performance of the coils.

As seen above, the placement and characteristics of the coil, play a huge role in WPT efficiency. Thus, they need to be chosen carefully. In Figure 23 the flowchart is made to design various kinds of WPT coils for e-bikes. The flowchart framework can also be applied to the three suggested prototypes.

At first one needs to identify the design goals or requirements for the specific prototype. In our case, the design goals for the three different coil types are that they need to be practical, efficient, and safe (see 5.1 Introduction). While working on the design goals there are some limiting factors. These are the design constraints that come along, for example, the application area, size, weight, and operating frequency. It is already known from Chapter 4 that you cannot place the Rx coil anywhere on the e-bike because there are many factors (practicality, safety, interference, aerodynamics, etc.) that need to be taken to account. Therefore, two application areas that are chosen: the front side of the bike (front fork on the frame) and the kickstand. This because in these area's it is less in interference with the other electrical components from the e-bike, and in less interference with the user (see 4.2). The kickstand and the front frame side are relatively small and limited in size if you want to attach another component on or in it. The size of the coils should not be huge as this is not practical. The same goes for the weight of the coil because this can influence the rider. The Rx should not be huge, approximately 5 cm length, 5cm with, and 5cm height. And the area of the Rx coil should be equal to or within 80% of the Tx coil (see 4.2). The weight depends on the geometrical shape of the coils chosen, the coil material, and the shielding material used. It is not desirable to add a component on the bicycle that makes this even heavier. The prerequisite is therefore to keep the weight as light as possible. After an interview with Accell it is suggested to keep the weight below 2.5kg (see 4.2. The operation frequency can also play a huge role here because this is dependent on different circuit parameters and available components and power.

The next step is to add various inputs: wire length, wire width, number of turns, inner and outer radius, wire material, shielding material, geometrical shape, air gap, and the lateral misalignment. The number of turns of each coil is oriented to a trade-off between different aspects: the coupling coefficient, the power losses due to the length of the wire, the skin effect, the bifurcation phenomena. This trade-off is well explained in [48]. The diameter of each coil should be chosen according to space constraints of the e-bike specific location. For the coils, the wire that can be utilized is litz to overcome skin effect[19]. The shielding material can be made of a ferrite base to increase inductance and increase the coupling of two coils effectively. There are three geometrical prototypes suggested. As indicated before the air gap should be kept minimum to increase the magnetic coupling (k). Lateral misalignment is a possibility when bringing the two coils (Tx and Rx) together. This should be carefully evaluated and calculated to keep the optimum working of the coils.

If the input does not agree with the design constraints, the design constraints should be looked at again, and according to those factors, the input parameters should be changed. If the input does agree with the design constraints of the coils, we then look at the output power requirements. For the highest efficiency and power transfer in the WPT system, the coupling factor (k) between the primary and secondary circuits must be high. This indicates the coils must be close together (small airgap) or a high permeable magnetic path must be present. Putting the coils close together is not an easy option in the kickstand and tile. Better is to fill the kickstand with ferrite material and at the primary side a u-shape core in the tile so the air gap is small, and a high permeable path is formed. The tile magnetics have an enlarged area on top so the user can place the bike a bit out of line.

After building the coils in a test lab or a simulation program one should validate these. If the results are acceptable then the WPT coils are ready for the e-bike. If not, then the required output power should be checked again.

With the COMSOL Multiphysics software, the magnetic coils can be built and validated. In the user interface start with a new model wizard. Here one can use the specific space dimensions. For the coils, a simplified model can be built in 2D to practice because here certain aspects can be neglected and one can for example assume the coil ‘’can look back on itself’ however it is advised to build the coils in 3D. When selecting the physics for this application it is best to go to the Ac/Dc tab and choose magnetic fields (mf). The study type can be chosen according to the measurement goals, but one can start with the stationary study (field variables do not change over time). The next step will be to build the coil model geometry, set up an infinite element domain, add material properties, implement the Magnetic Fields interface, set up appropriate boundary conditions, adjust the mesh settings, post-process the simulation results, perform a parametric sweep, and more. In conclusion in the software, the values from the graph in Figure 23 can be adjusted to create the required/acceptable result. However, litz is not available as a material property in COMSOL yet. Some properties will not be able available (weight, resonance frequency, material types, load resistance). Therefore, it is advised to also build the applications next to the simulation. After fixing the magnetic characteristics the next step is to add them into the electrical circuit. However, coupling the results (coil settings and structure created) to an electric circuit is not feasible in this software.

[19] The effect by which the current passes only through a certain depth of the conductor at high frequency is known as skin effect.

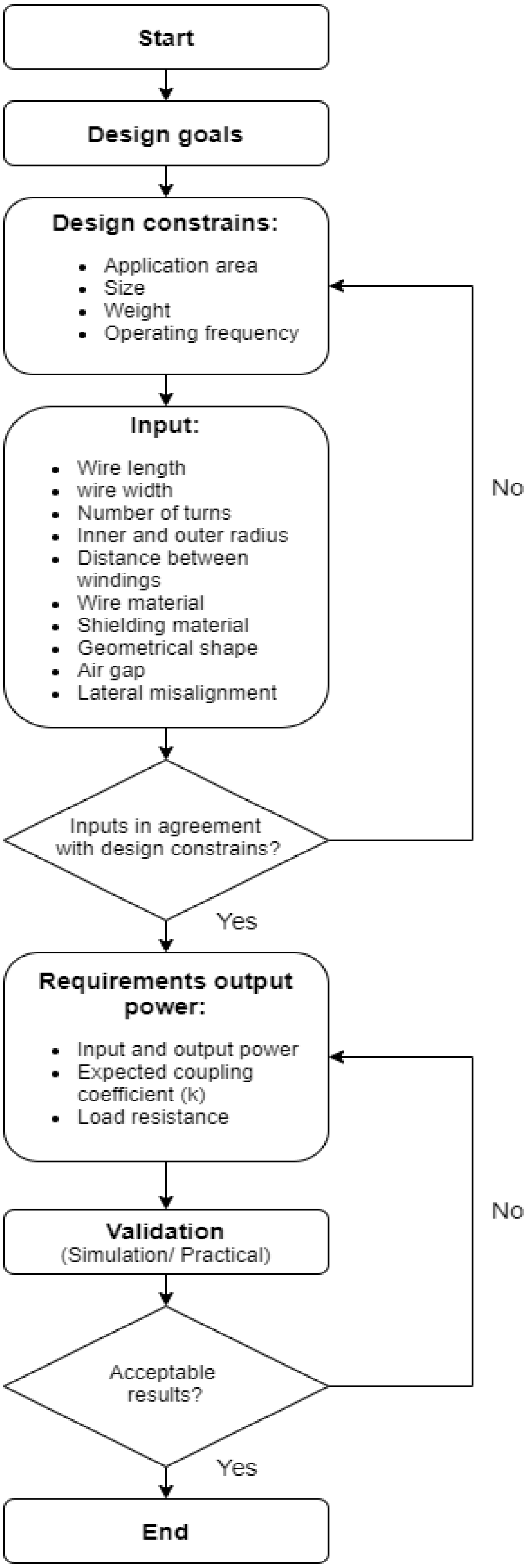


Figure 23. Flowchart to design WPT e-bike coils

Figure 22. Rx placement on front frame

Figure 21. Rx placement on kickstand

5.3 Characteristics of electric flow

Inside the charging station, different loads should be powered where e-bikes are the main loads. Other loads can be the monitoring and control systems together with lighting, communication, and other user peripherals. Therefore, for energy estimation, the calculations are split into two loads: e-bikes and additional equipment.

E-bikes

Here a charging station is proposed where a few e-bikes can be charged at once. The main goal of the proposed station is to charge the electric bike. The station can be placed at different areas. The test location for the station is assumed to be the University of Twente. Due to the collaboration with Accell for the WPT e-bikes, their type of bikes are used for further analysis.

The calculated value of 425 Wh that can be seen in Table 8 is a rough approximation of the minimum necessary energy for one WPT e-bike if we look at the possible traveled distances. For now, the assumption is made that all the e-bikes which will be charged are empty. The largest battery size of the manufacturers will be taken into consideration, which is the 504 Wh (14 Ah x 36V) battery. This means that the charging station must have a minimum of 504 Wh power available for one e-bike. Assuming that the charging station has four open spaces for charging, then the required energy is a total of 2016Wh (504 Wh *4).

Manufacturer	Energy use (Wh/km)		
	ECO mode	Normal Mode	Sport Mode
Accell Group	5	8	13

Table 7. E-Bike energy use per kilometer for Accell manufacturer

Distance to University of Twente	Energy (Wh)		
	ECO mode	Normal Mode	Sport Mode
From Twekkelerveld (4 km)	20		
From Enschede City center (5 km)		40	
From Hengelo City Center (5 km)		40	
From Enschede zuid (10 km)			130
From Gronau (15km)			195
Total	425		

Table 8. e-Bike energy estimation for UTwente

Other additional equipment

Additional power is needed for control and monitoring of the system, this can consist of an embedded PC that takes care of the power balance in the system, makes the charging of the bikes visible to the users, and displays the state and power flow of the system. This PC and screen will approximately have a power of 150 W and is running 24 hours, in total 3600Wh. Lighting is also important. However, the University's parking space is equipped with adequate lighting.

Total load energy

Adding up all the energies using the approximated values the total comes to 5616Wh.

Important factors

Depending on the nominal voltage (V) of the battery and the nominal and fast charging current (A) the calculations can be made for the nominal charging power (W) and fast charging power (W). Then it can be verified which current standards can deliver this amount of power. The charging time can be calculated battery power per hour (Wh) divided by the nominal charging power or the fast charging power (W).

Today's e-bikes are delivered with a battery of at least 250Wh and a nominal voltage of 36V. The normal charging current is 2A and 4A for fast charging. This means a nominal charging power of 72W and a fast charging power of 144W. It needs to be verified if and which current standards can deliver this amount of power. If a battery needs to be charged in 3 hours, it needs 84W.

Lithium batteries from Accell are charged with a special charger that can ensure the safe charging of the batteries. The charge current is one of the limiting factors. Manufacturers of batteries give a safe charging current of 0.3C which means 0.3 times the battery capacity [5]. The highest capacity for the electric bikes is 14 Ah so this gives a safe charging current of (14*0.3) 4.2 Amperes. This current is mostly used for fast charging.

The lithium batteries must be charged with constant current/constant voltage. This means the capacitor's compensation (converter, see section 2.3.2) should have a current output. Due to the load variations while charging the converter must be load independent. Taking this into account the series-series converter will be the best choice. Series-Series capacitor compensation:

- Converter input: Voltage source
- Converter output: Current source
- Primary compensation capacitor depends on: Primary inductance

Note: This compensation circuit is only valid if the number of turns on the primary and secondary side are equal.

In a circuit, the loss from parasitic resistance can occur. Minimizing the absolute resistance of a coil can increase the overall efficiency. Components and isolation that can withstand the stresses are not easy to obtain and will increase costs, so minimizing the voltage and current stresses is an important part of a practical design.

If the frequency of the resonance circuit is high, the losses in the switching parts of the converter can be high; or the semiconductor switches are not fast enough so the system cannot reach the resonance frequency problems arise. To overcome this problem, the resonance wave can be energized at a lower frequency.

Communication

The latest research came with the option where data can be transmitted simultaneously while the e-bike charged. The data includes information for the user regarding the status of the charging process. This communication can be done through techniques, such as Bluetooth, Wi-Fi, or Power Line Communication (PLC), IR, and communication through the coils.

The data transfer can be acquired through the internet-of-things solution (IoT), where it can be analyzed, and streamed in the internal cloud. These data can reveal the state of charge (SOC) and the state of health (SOH) of the battery, which influences each other. The data evaluation results can be made available to manufacturers and users in the form of graphics. On this basis, the e-bike can be optimized and adapted.

Apart from the IoT method data transfer is also possible through magnetic coupling. Communication through the coils has the advantage that no extra communication hardware must be added which can be disturbed by the base frequency of the IPT system. This type of communication is done by modifying the amplitude or frequency of the signal.

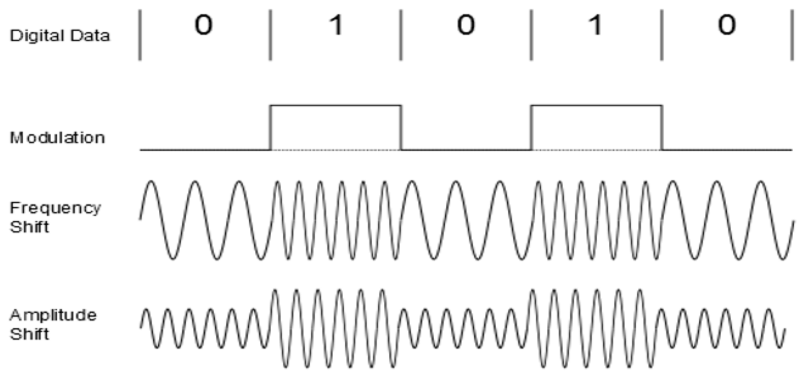


Figure 24. Data modulation example

Data modulation will lead to a change in signal at the receiver side. Amplitude modulation is easy to implement but due to the change of energy in the resonant tank, this type of communication has a slow bandwidth. AM is mostly done modifying the load of the converter so modifying the power transfer and the waveform. With battery charging applications, frequency modulation is a better choice. Load modulation will give problems due to the low internal resistance of the battery and extra power loss in the circuit. Therefore, an FSK- signal is proposed for modulation.

In general communication, errors may occur when the coupling factor (k) is increasing or decreasing due to misalignment. Unwanted coupling, e.g. coils rotation increases the k due to rotation, and the “power transfer flux” can disturb the FSK-receive signal and thereby the data communication. If the coils are moving further apart, e.g. in the x-y plane (angle 0°) the coupling decreases which can also disturb the FSK-receive signal and thereby the data communication. Therefore, the freedom of movement from the Rx coil must be carefully evaluated to see where the threshold lies for minimum communication errors.

Safety

As for the safety of surrounding users near one WPT charging e-bike, it can be concluded that the EM field does not have a huge effect. Paper [21] research stated that according to their experiments, a 25 cm safety distance from the center of the system, for cyclists and pedestrians, is suggested during the charging operation. However, when multiple charging stations are used near each other, new measurements must be done that must meet the requirements set by

INCGS. These can be calculated through the method from APRANSA where the measurement techniques based taking the average exposure level at four points of the human body: the head, chest, groin, and knee are addressed.

In the framework from [50] the iterative procedure for the electrical design can be implemented.

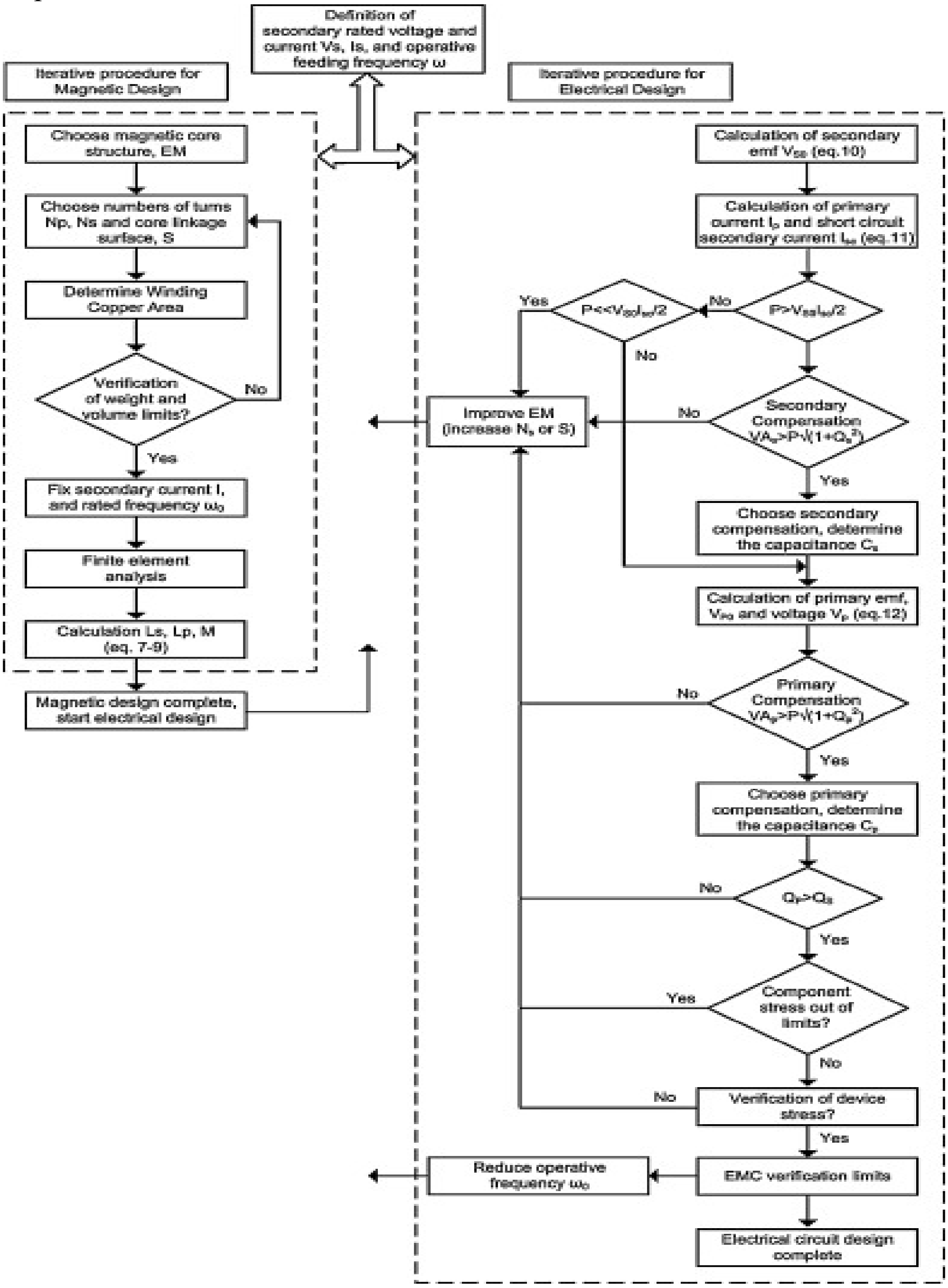


Figure 25. Framework for the WPT E-bike coil setup [50]

5.4 Experimental prototypes

In this section, the concept prototypes are shown. Initially, the goal was to create a prototype for Wireless Power and Data Transfer (WPDT) in a single practical magnetic structure by building the actual circuits and coils. However, due to the COVID-19 outbreak, this could not take place. The campus was closed for students till the end of the academic year. However, with the framework from Section 5.2 and the important starting points from 5.3 the suggested prototypes can be built.

As mentioned in Section 2.3, figure 4 shows the electrical circuit setup for IPT. This circuit is applied for the three concepts. An example of an electromagnetic resonator circuit with a coil, a capacitor, and a resistor is shown in Figure 26. In this circuit, the energy oscillates between the coil (which stores energy in the magnetic field) and capacitors (which store energy in an electric field) at a certain resonance frequency.

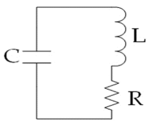


Figure 26. Magnetic resonant circuit

$$wo = \frac{1}{\sqrt{LC}}$$

Equation 2. Circular resonant frequency

$$Q = \sqrt{\frac{L}{C}} \times \frac{1}{R} = \frac{WoL}{R}$$

Equation 3. Quality factor

From Equation 3 if the quality factor of the system increases, decreasing the circuit loss (the reduction of R). In a high-resonance wireless power transfer system, the resonator system must have a high-quality factor for efficient energy transfer. If two resonators are placed close to one another, the resonators can form a link and will be able to exchange energy. The efficiency of the energy exchange varies depending on each resonator and the coupling coefficient (k).

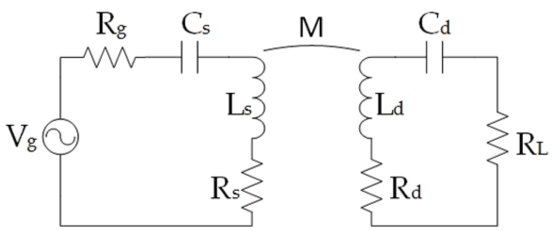


Figure 27. Equivalent circuit of a coupled resonator system

R= the source internal resistance
w= frequency(2πf)
Vg = amplitude of the voltage source
L_s and L_d = source and device resonator coils
M= mutual inductance ($M = k\sqrt{Ls\ Ld}$)
RL= AC load resistance

Each coil has a series capacitor that forms a resonator. Rs and Rd resistors denote unwanted resistance (including ohmic and radiation losses) in the coil and the resonance capacitor for each resonator. The resonance frequency is a key parameter in system design, and the value can be changed by adjusting the distance between the transmission and characteristic impedance of the electrical circuit.

Concept 1: U-; I-Core coils

This concept contains the magnetic coils where the primary side takes the shape of a U-coil and the secondary side takes the shape of an I-coil. The Figure 27 illustrates the proposed set-up of the prototype, generated by researchers at the University of Delft. Initially, this set-up was created by Bart Roodenburg and Prof. J.A.Ferreira. In Figure 28, the circuit above is for the data transfer and the ,circuit below indicates the power transfer which is in this case both based on magnetic coupling. The magnetic power transfer circuit makes use of L_1 (U-core) and L_2 (I-core) which are the primary and secondary coil.

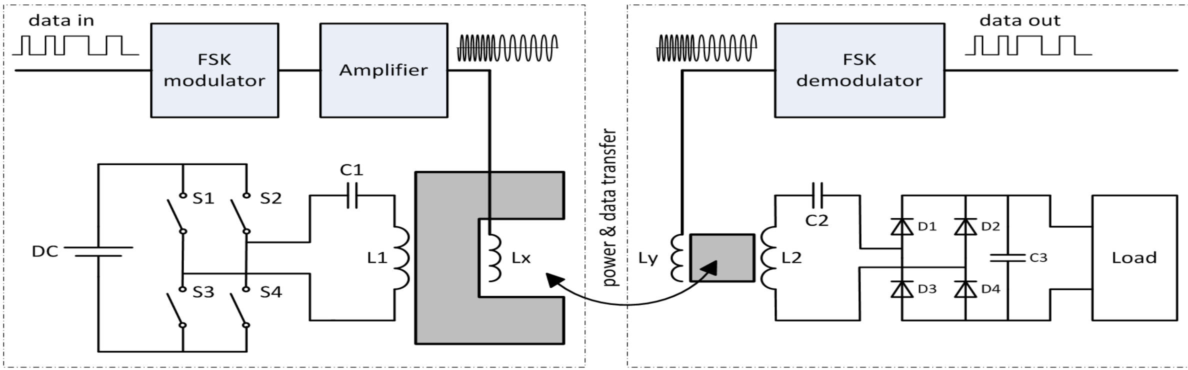


Figure 28. Set-up for wireless power transfer and serial data transfer concept 1 [51]

Thee power source is a Dc-generator (as suggested in section 4.1 Type of Resource) which is then transferred to Ac by an H-bridge (inverter) (S1, S2, S3, S4). This again is transferred to the secondary side where it is rectified by diodes (D1, D2, D3, D4). The used resonant power transfer frequency is 85kHz.

The data transfer circuit contains two extra communications windings L_x (u-core) and L_y (i-core), which are both also integrated into the same magnetic power transfer structure. This data transfer circuit creates a communication path between the primary and secondary coils. The primary serial input data is transferred to two different sinusoidal frequencies 1MHz and 2MHz, which represents the digital “0” and “1” state respectively (i.e. so-called Frequency Shift Keying FSK- modulation). At the secondary side, an FSK demodulator can reconstruct the serial data.

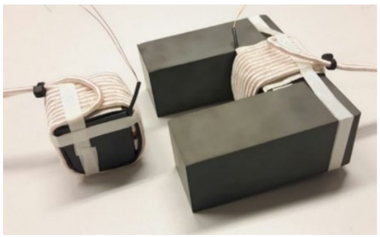


Figure 29. Magnetic coil concept 1: U-core and I-core [51]

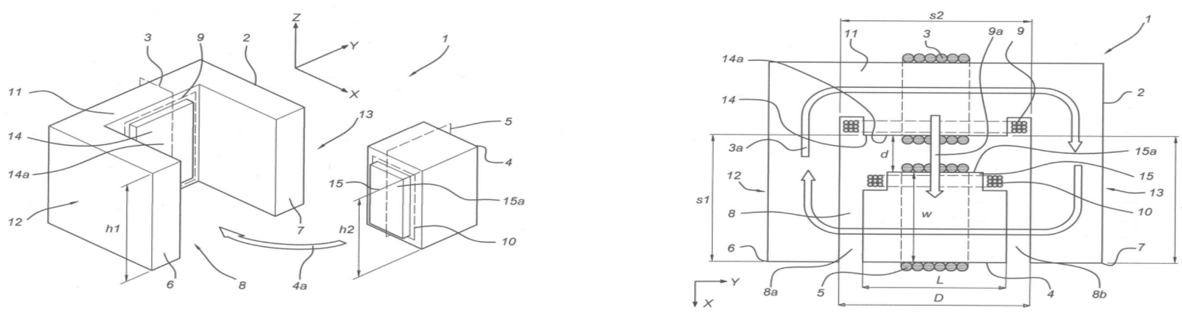


Figure 30. Part 1; part 2 magnetic structure as described in the patent application P9076213NL [51]

Name	Fig 25.	Fig. 27	Material / value / remark
Primary winding	L1	3	Cu litz wire (600x0.071), d=~2mm, n=9
Secondary winding	L2	5	Cu litz wire (600x0.071), d=~2mm, n=9
Power transfer flux path		3a	Perpendicular to 9a
Transmit winding	Lx	9	25x25x2mm, massive Cu d=0.2mm, n=50
Receive winding	Ly	10	25x25x2mm, massive Cu d=0.2mm, n=50
Data transmission flux path		9a	Perpendicular to 3a
Primary core		2	Ferroxcube, 3C6, U93/76/30
Secondary core		4	Ferroxcube, 3C6, part of I93/28/30
Core height		h1; h2	30mm
Leg length		s1; s3	45mm
Sec. core size		w; L;h2	28;28;30mm
Prim. core opening		D; s2	37mm

Table 9. Details on magnetic structure [51]

The power transfer coils (L_1, L_2) and the data transfer windings (Lx, Ly) simultaneously generate fluxes. However, the axis of the data transfer flux generated by Lx is perpendicular to the axis of the power inductor. So, the coupling factor between L_1 and L_2 and Lx and Ly is sufficient to transfer power and data.

When it comes to placements of the Rx and the Tx coils there are few suggestions. For example, the Rx coil (integral with the frame of the bicycle) is arranged on a support in the front of the wheel, while the primary is rigidly coupled to a U-type column with a single stand (Figure 22). The Rx can also be placed on the kickstand of the e-bike where the Tx can be placed under the ground tile (Figure 21).

As mentioned before in Section 5.3, the freedom of movement of the mechanical coupling is one of the main constraints when this WPDT device is applied in a real product. Thus, to develop this WPDT device further, the following steps can be followed:

- Investigate the optimum core size, winding size, and construction.
  - Improve the coupling between the windings Lx and Ly.
  - Decrease the coupling between the "power-flux" and "communication flux"; (reduce the size, flatness, and shape of the send- and receive windings)
- Investigate filtering methods for the FSK-receive signal; (The power communication frequency at 85kHz and FSK frequencies 1-2MHz are separated significantly).
- Investigate the maximum data transfer speed.

Concept 2: Solenoid coils

This concept contains the magnetic coils where the primary side takes the shape of a solenoid coil (Tx) and the secondary side also takes the shape of a solenoid coil (Rx).

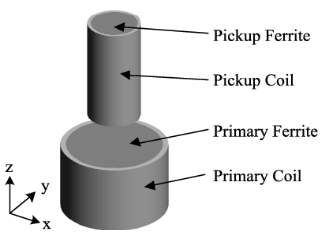


Figure 31. Magnetic coil concept 2: solenoid coils

In this configuration is ideal to pace the pickup (Rx) on the kickstand of the bike and the primary under the ground as a tile. For this prototype, the magnetic and the IoT data transfer methods can be explored. However, when placing the kickstand of an e-bike, most of them make a slight angular misalignment as they do not reach the ground perpendicularly. Therefore, the placement of the Tx should be carefully considered as it might be necessary to slightly tilt it, to achieve the optimal possible magnetic coupling coefficient.

Concept 3: Circular planar coils

For the third option, the circular spiral coil design is suggested, whose coupling and inductance calculations [47] [49] and has proven to work well in WPT applications [50]. This coil can be fixed on the front upper part of the bicycle frame.

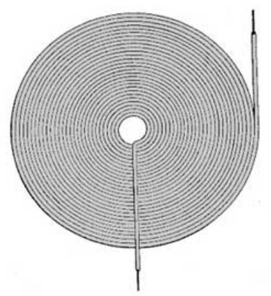


Figure 32. Magnetic coil concept 3: Circular planar coil

For this prototype, the data communication through magnetic coils is not feasible therefore the IoT option can be explored here. For this geometrical coil shape, the maximum coupling factor is obtained when the inner radius is about half the outer radius [50]. Additionally, the coupling factor is not affected much by the number of turns [49]. So, the maximum coupling can be obtained when [49] for identical primary and secondary coils, for a given maximum and minimum coil radii, the coupling of distributed coils is insensitive to the spacing between the windings of the coils.

5.5 Discussion

In Chapter 4. Theoretical Deliberation of Parameters, three WPT coil topologies for the e-bike are proposed, based on the theoretical analysis and feedback from Accell. In Chapter 5 a framework has been created to build the three prototypes in the lab. It is made sure that the requirements that were set for the prototypes are met in both frameworks. One framework from Section 5.2 with Figure 23 is for the magnetic characters of the coils, and the other framework from Section 5.3 with Figure 25 is the procedure for the complete electrical circuit.

By using the framework, the prototypes can meet the following requirements:

1. Practicality
    - The coils can be easily linked together with the e-bike frame without disturbing the consumer. Disturbing factors that have been taken into account in the framework include the coil weight, coil placement, coil size, and the bike aerodynamics. From the analysis, it is clear that all three prototypes comply

with these factors as there are specific weight, placement, and size guidelines provided.
    - From the conclusions taken in Section 5.2, the optimal locations for the coils have been identified as the kickstand and the front frame. The Rx coil of each prototype has been developed in such a way that it can be placed on either one of the optimal locations.
    - Using the identified optimal locations, the Tx coil will be placed accordingly. The U and I core and Solenoid prototypes can be placed under tiles in the ground (Rx is placed in the kickstand) or in a construction built in front of the frame (Rx is placed on the front frame). From making a comparison between these two locations for the Tx, placing the Tx coil underground is the most optimal as placing it in a construction in front of the frame leads to higher costs and usage of more material. However, the extra construction block can be used to lock the e-bike.
2. Efficient power output
    - The magnetic characteristics that affect power efficiency (magnetic coupling coefficient, Q-factor, parasitic resistances) have also been considered in the framework for the prototypes and are displayed in Figure 23.
    - As validation only occurred for the U and I core (Bart Roodenburg [51]), it can be said that it indeed achieved maximum productivity with minimum wasted effort or expense.
3. Safety
    - Safe for surrounding humans.

It is suggested that for each of the prototypes a mathematical model can be developed, and performance analysis should be conducted to determine the voltage transfer function, maximum power transfer capability, efficiency for different air gaps (1–5cm), and misalignments (0.1–2cm). It is suggested that the design of the e-bike battery charger must be validated in terms of rated input voltage and output power for different air-gap configurations.

From theoretical analysis and the requirements set in Section 5.2, it can be concluded that the U and I coil and solenoid coil prototypes are the most prone to being developed. Since the U and I coil has been validated and achieved maximum productivity with minimum wasted effort or expense. Also, different researchers have conducted experiments in implementing the solenoid coil due to its ease in usage and design.

For data transfer through magnetic coils integrated into the same WPT system, an FSK- signal is suggested for modulation. However, errors may occur when the magnetic coupling factor (k) is increasing or decreasing due to misalignment. Therefore, the freedom of movement from the Rx coil must be carefully evaluated to see where the threshold lies for minimum communication errors.

Chapter 6. Business plan

This chapter provides a basic business plan for the rental, retail, recharging, and servicing of WPT e-bikes that alleviate transportation and is ready for urban areas. To answer the third research-question the business plan has been proposed through the Business Model Canvas tool for the WPT e-bike technology. Section 6.1 explains the main idea behind the WPT business and e-bike business. Further on in Section 6.2 an overview and elaboration are given of the Business Canvas Model with its nine connected key elements. In Section 6.3, a brief explanation is given about the feasibility analysis framework. Section 6.4 provides an overview of the SWOT analysis for the particular WPT e-bike business plan. The chapter concludes with the results of the Business Canvas Model section 6.5 performed.

6.1 Introduction

The wireless charging market is a process of charging the batteries or equipment without any cable (wired) connections. This technology is rapidly finding popularity among consumers nowadays. In the wireless power market forecast graph, there is a massive growth predicted in the receivers (mobile phones, tablets, notebooks, wearables, electric vehicles, etc.) and transmitters (technology, power, standalone, public, integrated furniture, etc.), see Figure 33.

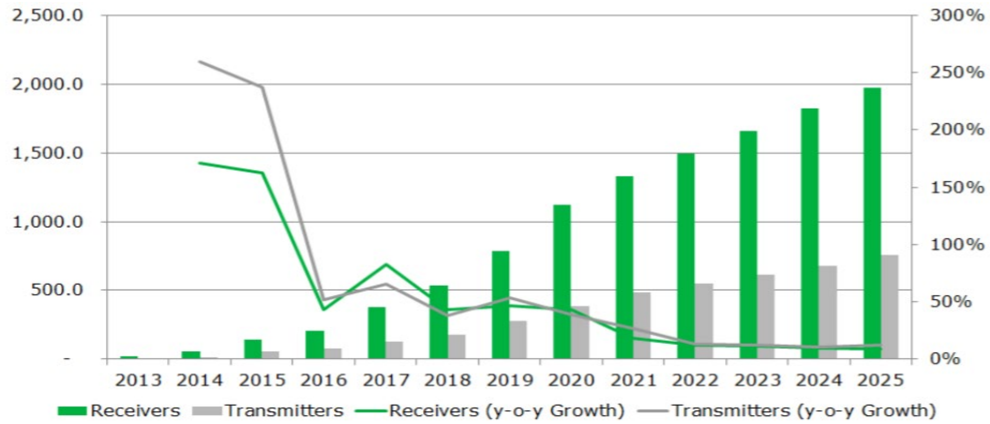


Figure 33. Wireless Power Market Forecast [52]

A few factors which are causing this market growth are [53]:

- Increasing demand for smartphones & other wireless computing devices
- The necessity of a common charging platform
- *Increased demand for electric vehicles*
- Rising Internet of Things (IoT) & semiconductor market

With the third factor also comes the increased demand for e-bikes, which can be seen in Figure 33 with a rising trendline. All this has led to the motivation behind a wireless technology which can also be applied to the e-bikes and this can be transformed into a business.

Building a successful business includes a lot of detailed planning, financial resources, experts or engineers from the specific field, and as last, hard work. One of such businesses can be to start a WPT electric bike lease, retail, and maintenance service.

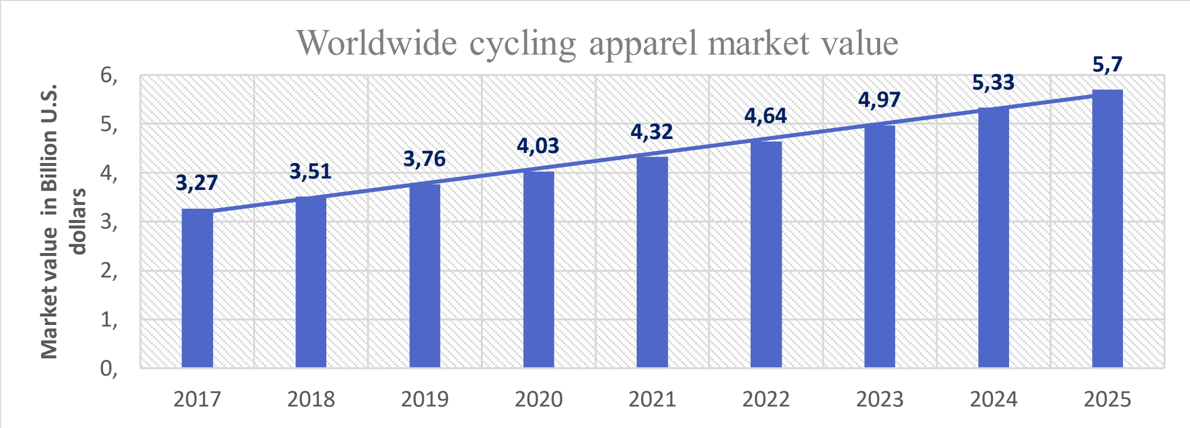


Figure 34. Cycling apparel market value worldwide from 2017 to 2025 [54]

As stated in Chapter 2.4 Electric bicycles, it is known that an electric bike is just like a normal bike with an additional integrated electric motor and other components that can be used for propulsion. In Chapter 3.1 Introduction it is shown that worldwide there are many countries with interest in the electric bicycle (eg. China, United States, Taiwan, Italy, Germany, Japan, South Korea, Australia, Canada, Portugal, the United Kingdom, India, Netherlands, etc.). However, this business plan will focus on application in the Netherlands due to the knowledge of the working environment here.

Cycling, and therefore the bicycle, plays a key role in the Netherlands' mobility System [54]. '*'With an average of 1.3 bicycles per inhabitant, the Netherlands is still the only country in the world that has more bicycles than inhabitants*'' [1]. Not only the number of bicycles in the Netherlands is growing, but the total number of kilometers traveled also shows an increase. In total, they cycle 15.5 billion kilometers according to the national news. In Figure 35 the e-bike market share can be seen from 2011 to 2018 (series 1: E-bike sales in volume; series 2: Total market in volume).

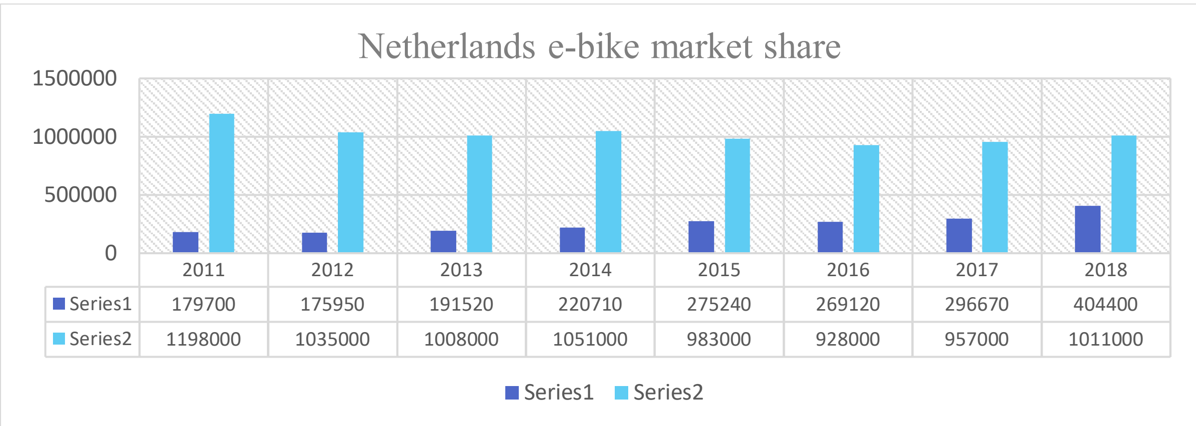
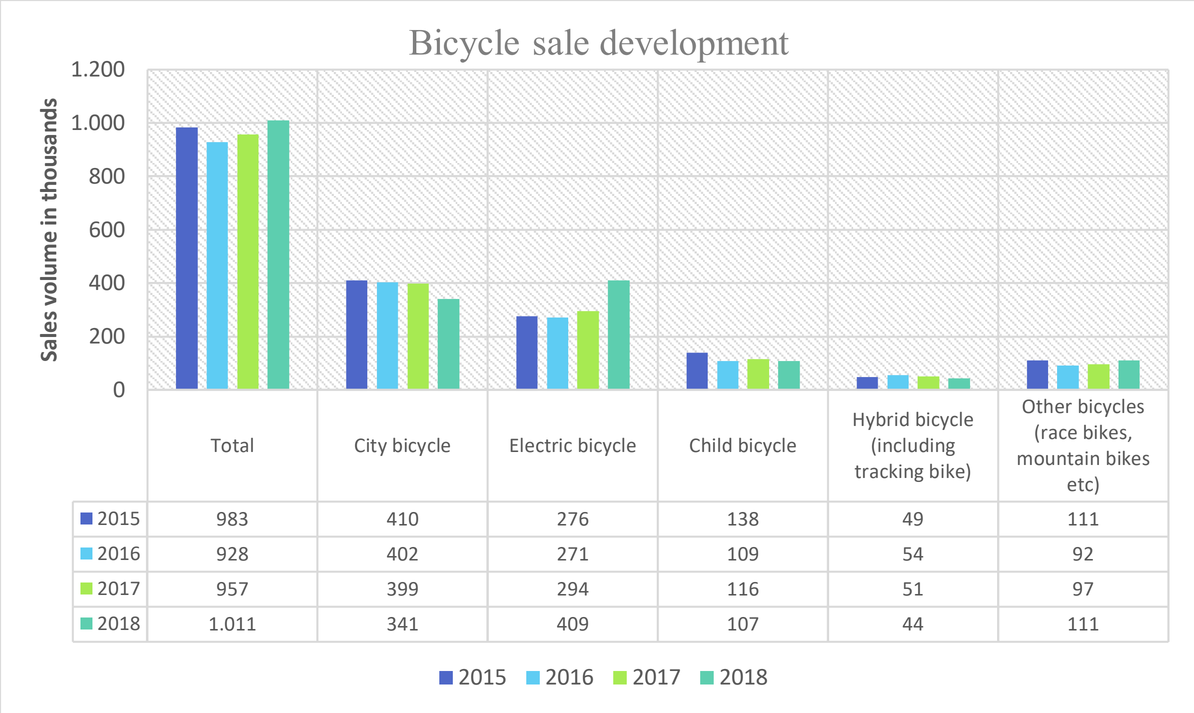


Figure 35. Market share e-bikes in the Netherlands 2011-2018 [55]

In Figure 36 the number of bicycles sold can be seen which shows an increase in sales of the e-bikes. It is seen that sales of e-bikes increased by more than 36% in 2018 compared to 2017. And in the year 2018, for the first time, more e-bikes were sold than regular city bikes. One in four bicycles sold is now an e-bicycle. The sale of city bikes has decreased in recent years. In total, 1.01 million new bicycles were sold in 2018, including 409,000 e-bikes [56].



	Total	City bicycle	Electric bicycle	Child bicycle	Hybrid bicycle (including tracking bike)	Other bicycles (race bikes, mountain bikes etc)
2015	983	410	276	138	49	111
2016	928	402	271	109	54	92
2017	957	399	294	116	51	97
2018	1.011	341	409	107	44	111

Figure 36. Number of bicycles sold by types, 2015-2018 [57]

The Netherlands is active when it comes to innovation in e-bikes, recently the Dutch Cycling Embassy participated in the world's first virtual cycling conference: Digital WorldBike 2020. A spokesman for BOVAG recently said on the NPO Radio that there are currently about 2,000 bicycle shops in the Netherlands and it is increasing. Due to the growth, there is a lot of potential in this business. External competition can be present for the WPT e-bike business however the industry is open for fair competition. The WPT e-bike business can be very profitable if it is located in a dense area consisting of locals, students, and tourists. Even though revenue for the electric bike hire services has grown over the years, many bike dealers had difficulty staying in business during the period of the COVID-19 outbreak. Nevertheless, there is still a rising consumer demand in e-bikes.

In conclusion, the WPT electric bike business is a profitable industry and it is open for any aspiring entrepreneur to come in and establish his or her business; one can choose to start on a small scale or start on a large scale with several outlets in key cities through the Netherlands. The mission is to establish a WPT electric bike rental service, retail, and repair business that will make available a wide range of electric bikes and accessories from top electric bike manufacturing brands at affordable prices to the customers. This can be a new starting business with other services included or it can be added as part of an existing business (e.g. a business addition to an already existing bicycle business).

To open the WPT e-bike business one should ensure to carry out the business plan, feasibility study, and a SWOT analysis which should not be taken for granted. In the following sub-chapters, a framework will be given for an e-bike hire shop business plan that can help to start the business successfully in the Netherlands.

6.2 Business Plan Model

For the WPT e-bike business plan, the business canvas template is used. This design tool is a product from Business Models Inc which was created by the Swiss economic theorist Alexander Osterwalder and the computer scientist Yves Pigneur in 2005[20]. The Business Model Canvas (BMC) can help to understand a business model in a straightforward and structured way. It is popular with both entrepreneurs and intrapreneurs for a business model innovation.

The implementation of BMC can be on an existing business or a new idea. The BMC has five main advantages:

1. **Overview of the essentials:** It shows which activities are not so important or even stand in the way of the goal.
2. **Basis for brainstorming:** It is perfect as a base to let the thoughts about the main elements in the business run free to test alternative models and find new combination possibilities.
3. **Structured presentation:** BMC brings the business idea into a clear structured form from every perspective which others can quickly understand and discuss. It can be easily modified as you go along it.
4. **Dependencies and conflicts of objectives:** With the BMC, start-ups can present the business idea, corporates can also use the BMC for new projects. It can also show dependencies or conflicts of objectives with existing processes.
5. **Transparency**: The business team will have a much easier time understanding the business model because it's laid out on a single page.
6. **Reduces the risk of failure**: It helps with the execution steps required to take the idea to market. Connecting the dots between the value proposition + customer segments + revenue streams is a good input to the marketing strategy and positioning statement.

The BMC breaks the business model down into easily understood segments which will be further elaborated in this sub-chapter. As seen in the BMC in Figure 37, in the framework there are 9 elements (segments), together these elements deliver a coherent view of a business key drivers:

1. **Customer Segments**: People willing to pay money for products and services.
2. **Value Propositions**: Unique solution (products and services) for a customer's problem.
3. **Channels**: Methods to reach out to prospective customers.
4. **Customer Relationships**: Acquire, retain, and grow customers.
5. **Revenue Streams**: Methods through which the income will grow.
6. **Key Activities**: Activities that enable business.
7. **Key Resources**: Resources needed to run the business.
8. **Key Partnerships**: Outside resources that aid the business.
9. **Cost Structure**: All types of costs that the business needs to expend.

The business model is a blueprint that defines your business initially and you later expand on it. The BMC is used for the WPT e-bike business which can be seen in the figure, elaboration on this per segment is provided in the next sections.

[20] Source: Business Models Inc

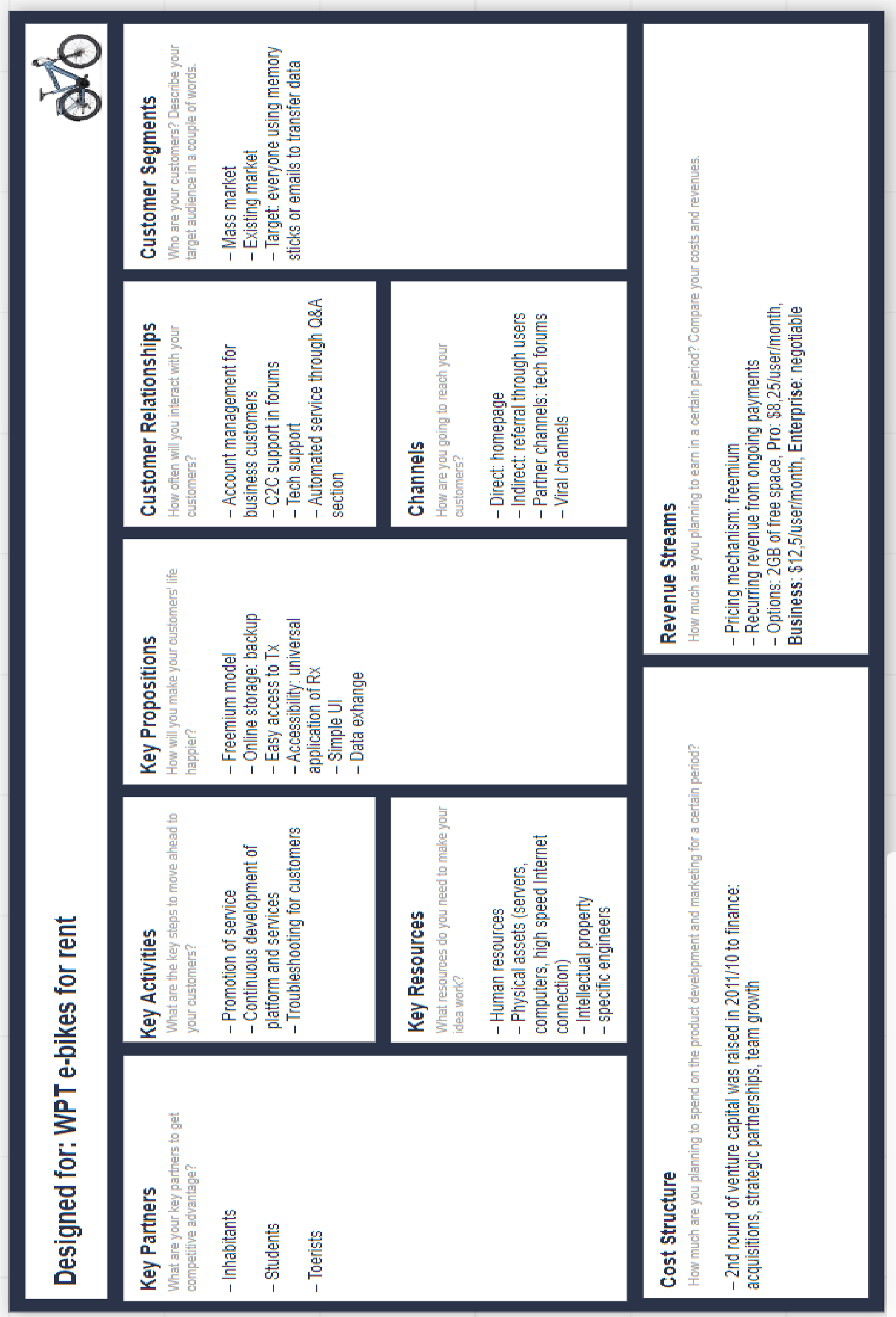


Figure 37. Business Model Canvas WPT e-bikes

6.2.1 Customer Segments

The segments that provide the revenue (income) include simple users and paying customers:

1. **Local inhabitants** – E-bikes can help attract new customers who might not be able to enjoy traditional bikes due to their fitness level or areas of terrain. As indicated in the statistics it is known that inhabitants in the Netherlands do favour e-bikes and there is an increase in usage of them [1]. E-bike users of over the age of 65s accounts for just under half of the distance traveled with an e-bike (46%) [1]. However, the share of the cycling distance that people under the age of 65 travel with the e-bike is increasing in the last couple of years. Between 2013 and 2017, the share of the kilometers traveled by e-bike in the age group 12 to 50 grew from 16% to 20%. E-bike users are getting younger and are increasingly using them for commuting. In the same period, also the share for people aged 50 to 65 rose from 30% to 33% (see Figure 38).

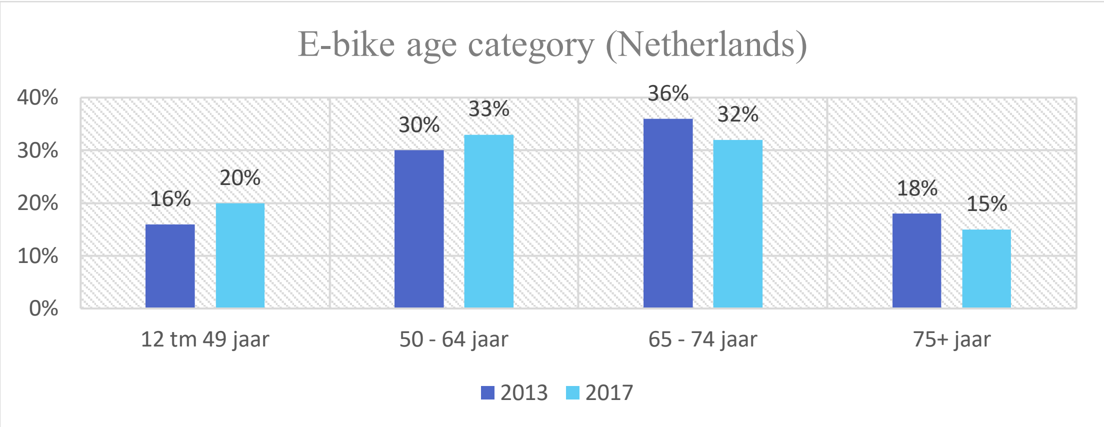


Figure 38. Distribution of the distance traveled by e-bike by age in 2013 and 2017

2. **Students** – International student's main preferred form of transport is the bike. If the price range is convenient for them or there is a special package deal for them, they can provide a huge income.

3. **Tourists** – More than half of all e-bike kilometers in the Netherlands are traveled for leisure purposes, such as recreational touring (see Figure 39) [1]. As seen in figure 41 the forecast predicts an increase of tourists in the Netherlands.

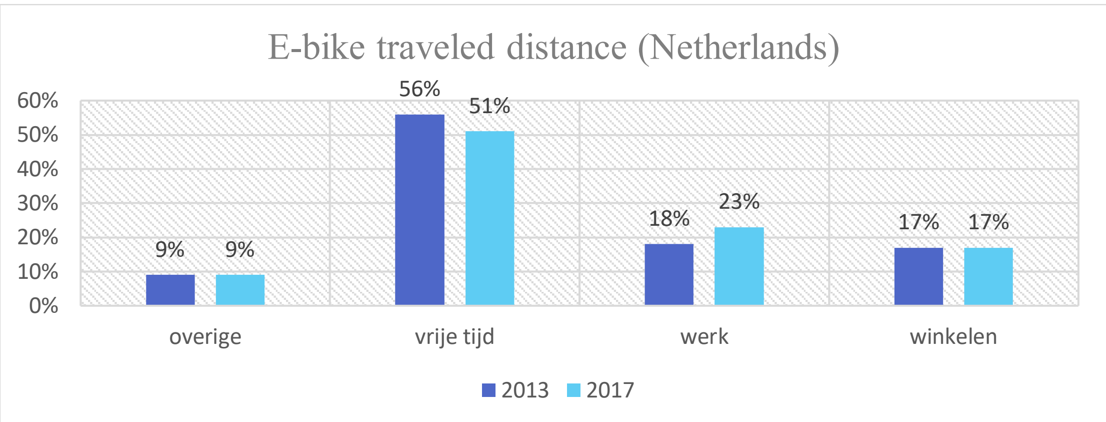


Figure 39. Distribution of the e-bike distance traveled by motive 2013 and 2017

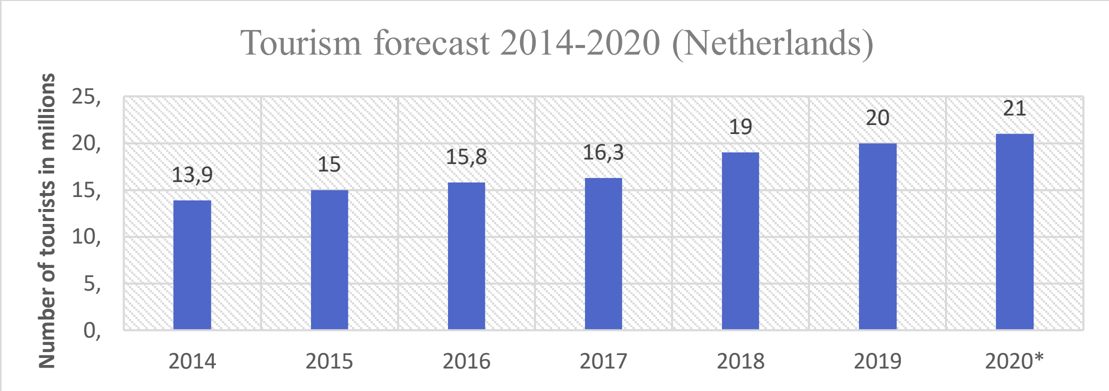


Figure 40. Inbound tourism in the Netherlands from 2014 to 2018, with a forecast for 2020 (in millions)[21]

4. **WPT e-bike wholesaler stakeholders** – Wholesale vendors (e.g. Accell) can easily sell their products. They can sell necessary e-bike and WPT technology to the small vendors where they can also have a business income and can ask interest. The advantage for the wholesaler is that they can sell more through the small vendors that are established throughout the whole Netherlands. The main stakeholders can not settle everywhere however the small business can, and they can have a better sale marge because they are much approachable to the public then the bigger stakeholders. In this way, they both can make some profit.
   The small business can also seek investment from external sources (other stakeholders e.g. in WPT technology materials) in return for a share in the business or some extra income.

These above-mentioned customer segments are the most important customers for the WPT e-bike business. It is of course true that more can be added to this when this business plan is been applied. All four of the customer segments are linked to one or more key value propositions and one or more revenue streams. Everything on the left side of the canvas from Figure 37 must support the right side of the canvas.

6.2.2 Key propositions

The key propositions or value propositions indicate the provided products and services for the customers. The e-bike business is to service a wide range of clients and to make profits. The start-up must ensure that all they do and provide is permitted by the law of the Netherlands to achieve the aim of starting the WPT e-bike business.

The main product and services should include:

A. E-bike rental services with high performance WPT technology.
B. Retailing newest and different brand of e-bikes, e-bike parts, and accessories.
C. Providing WPT e-bikes and components repair and maintenance services (on shops location or at other specific location e.g. home/ road etc.).
D. Price reduction for particular groups (e.g. students).
E. Providing the charging Tx pad facilities on surrounding areas.

[21] Source: Centraal Bureau voor de Statistiek; ING Economisch Bureau

F. The convenience of selling the WPT Tx pad for personal use.
G. Ease of use through an app in Google Play Appstore.
H. Be available for advice and service through social media (email, Facebook, WhatsApp) and calls.

Every value proposition that is presented here needs to be linked to a customer segment and a revenue stream for the business to reach the main goal, this can be seen in section 6.2.10.

6.2.3 Channels

Channels refer to how the value propositions (products or services) are delivered (sold) to the customers. To reach the customers the following sales and marketing approach can be implemented:

- Own channels
  - Direct
    - Activities to attract customers (e.g. openings party)
    - Make use of attractive handbills to create awareness and to give direction to the business location.
    - Introduction letters with brochures to cyclist clubs, corporate organizations, households, and key stakeholders.
    - Position the business signage / flexi banners at strategic places around the location.
    - List business and products on yellow pages ads (local directories).
    - Engage in direct marketing and sales
  - Indirect
    - Encourage the use of word of mouth marketing (referrals).
  - Service:
    - Create a loyalty plan that will enable to reward the regular customers.
    - Engage in roadshows within the neighbourhood to create awareness for our electric bike hire shop.
    - Create discount sessions and package deals for customers and potential customers.
    - Be available for advice and service through social media (email, Facebook, WhatsApp) and calls.
    - Offer house to house service for repairing and maintenance.
  - Online
    - Leverage on the internet to promote the business.
    - Social media
      - Website
      - Facebook
      - WhatsApp
      - Apps for rental availabilities
      - Other
    - Advertising online (Google AdSense, etc.)
- Partner channels
  - Online forums

- Wholesaler/ other affiliates to sell the products from the WPT e-bike business.

6.2.4 Customer Relationships

The customer relationships block answers the question of how the business gets, keeps, and grows customers. The interaction with customers can happen in a certain way:

Get: How do customers find out about the provided business.
- Advertising though hardcopy material and software material (online)
- Social media communities
- Customized prices for particular groups (e.g. students)

Keep: How to keep customers.
- Personal repairing service on different locations (in shop, at home, somewhere in surrounding area).
- Personal advice and information through App/e-mail or calls.
- Personal assistance through technical support.
- Reward the loyal customers especially when they refer new clients.

Grow: How to get the customers to spend more and how to manage them after a purchase.
- Monthly newsletter to keep them informed about latest products, updates, changed price rates and important tips for maintenance.
- Website and other social media platforms with information.

In conclusion the customer relationship can be maintained through:
- Advertisements (online and hardcopy)
- Social media information updates and Q&A sessions
- Technical support
- Newsletters (soft and hard copy)
- Personal assistance and information distribution

6.2.5 Revenue Streams

This building block states where the revenue of the business is generated. Here one can figure out what strategy to use to capture the most value from your customers. Electric Bike business to rent out e-bikes, retail electric bikes and its spare parts, provide WPT charging facilities and provide maintenance service and repairing. The goals of the business to maximize profits due to the new provided innovative WPT technology option.

The main source of income regarding to the WPT e-bike business:
- Renting fees
    - E-bikes with WPT technology
- Retail fees
    - New / second-hand WPT e-bikes
    - Different type and brands of WPT e-bikes
    - WPT e-bike parts and accessories
        - WPT specific: customized personal Tx and Rx
        - E-bike specific: motor, battery, accessories etc.

- Service and maintenance
  - Advise on type of e-bike and WPT equipment.
  - Providing repair and maintenance services.
  - Providing WPT equipment repair service.
  - WPT charging equipment in surrounding area.

The pricing system should be based on what is obtainable in the industry. Students are given special discount. The must be plans in place to offer discount services occasionally and to reward the loyal customers especially when they refer clients to us or when they introduce their friends and family members to the business. Payment policies that can be adopted by the business can be quite diverse. Different customers can prefer different payment options as it suits them therefore customers can pay a one-time fee and certain groups (students and retired people) can have a monthly subscription fee. The business bank account numbers should be clearly visible on the online forums (website; app etc) and promotional materials to clients who may want to deposit cash or make online transfer.

Some practical and ease of use payment options to make available to the clients can be:

- Payment via bank transfer (card/ online/mobile)
- Payment with cash
- Payment via check
- Payment in instalments

6.2.6 Key Activities

The key activities are the most important strategic things to do to make the business model work. Key activities should be directly relatable to the value proposition to make sure to delivering any value to customers.

Key activities can typically be broken down into three broad categories:

1. **Production**: Delivering the product which can be either a high quality or a high quantity.
2. **Problem Solving**: Consultancies and other service with new solutions to individual customer problems.
3. **Platform/Network**: Networks, software platforms can function as a platform. For example, a key activity for Facebook is updating the platform.

Key activities (which only include activities which are absolutely core to delivering the value proposition) for the WPT e-bike business are:

a) Promotion of products and services (online and offline) – All
b) WPT developments -A, B, D, E, F
c) Continual development of platform and services (Website, social media forums, App, newsletters etc.) – D, G
d) Troubleshooting (repair and maintenance) for customers – C, G, H
e) Lower costs and prices for customers

Publicity and Advertising Strategy to intensify publicity for the business. Here are some platforms to promote and advertise:

- Place adverts on community-based newspapers, radio, and TV stations.
- Encourage the use of word of mouth publicity from our loyal customers.
- Leverage on the internet and social media platforms like YouTube, Instagram, Facebook, Twitter, LinkedIn, Google+ and other platforms to promote the business.
- Maintain an own official website.
- Maintain an own App.
- Banners and billboards in strategic positions all around location.
- Distribute our flyers and handbills in target areas in and around the neighbourhood.
- Brand all our electric bikes, WPT Tx charging equipment and ensure that all staff members and management staff wear branded shirts.

6.2.7 Key Resources

This building block describes the most important strategic assets that are required to make your business model work. Broadly speaking resources can fall into one of four categories:

1. **Physical** (e.g. buildings, vehicles, machines, and distribution networks)
2. **Intellectual** (e.g. specialist knowledge, patents and copyrights, partnerships, and customer databases.)
3. **Human** (e.g. people can be the most key resource, this is particularly true in creative and knowledge-intensive industries)
4. **Financial** (e.g. lines of credit, cash balances etc.)

In conclusion the key resources to run the business:

- Physical assets
- Partnerships
- Intellectual assets
- Growing financial resources

6.2.8 Key Partners

Normally there are important tasks and activities that are described for the suppliers and partners to make the business model work. There are usually three reasons for creating a partnership:

- Economies of scale.
- Reduction of risk and uncertainty.
- Acquisition of resources or activities (e.g. music for Spotify).

What non-key activities can you outsource to enable you to focus more on your key activities.

- Strategic partnership with Accell
- Supply chain partners
- Visionaries

The key partners to get competitive advantage are:

[1] Wholesaler companies (e.g. Accell) for providing the different type of WPT e-bikes.

[2] Technical company to supply WPT tools.
[3] Other automotive firms that can form a possible partnership.

6.2.9 Cost Structure

The goal of the cost structure building block is to map key activities to costs. It is also needed to make sure that the costs are aligned with the value proposition. It should be straightforward to determine the most important costs and the most expensive after defining the key resources, key activities, and key partnerships.

List of the top costs by looking at activities and resources:

I. Strategic partnership
II. Storage
III. Development of team
IV. Development of WPT Tx
V. Operations support
VI. Customer support
VII. Sales and marketing
VIII. Salaries and taxes

6.2.10 Discussion

The nine elements that are described above are the basic framework for the WPT e-bike business. These can be altered according to the own business owner. As indicated before the nine elements should work in conjunction with each other and then they can deliver a coherent view of a business.

- ✓ Every customer segment is linked to a key value proposition and a revenue stream. Everything on the left side of the canvas is needed to support the right side of the canvas.
- ✓ Key Activities should be directly relatable to your value proposition to make sure to delivering any value to customers.
- ✓ It is also needed to make sure that the costs are aligned with the value proposition.

Customer segment	Key value proposition	Revenue stream
1.	1,2,3,4,5,6,7	1,2,3
2.	1,2,3,4,5,6,7	1,2,3
3.	1,3,4,5,7	1,3
4.	1,2	2
Key activities	Key value proposition	Costs structure
a)	1,2,3,4,5,6,7	1,2
b)	1,7	3,6
c)	1,2,3,4,5,6	1,3,6
d)	3	1,2,3,4,6,7
e)	4	All

Table 10. Conjunction key elements

As indicated earlier, one can add the wireless chargeable e-bike business to an already existing business, or one can start with a completely new business in which the WPT e-bike is also a provided service.

The location of the business is critical and determines who the main target market is, what products and services needs to be offered and provides an overview of possible competition one may encounter. One needs to inform about the different demographics of the area. Many towns and cities have strong cycling cultures and local councils are increasingly keen to promote cycling. Local cycle routes etc are also great opportunities for shops to capitalise upon.

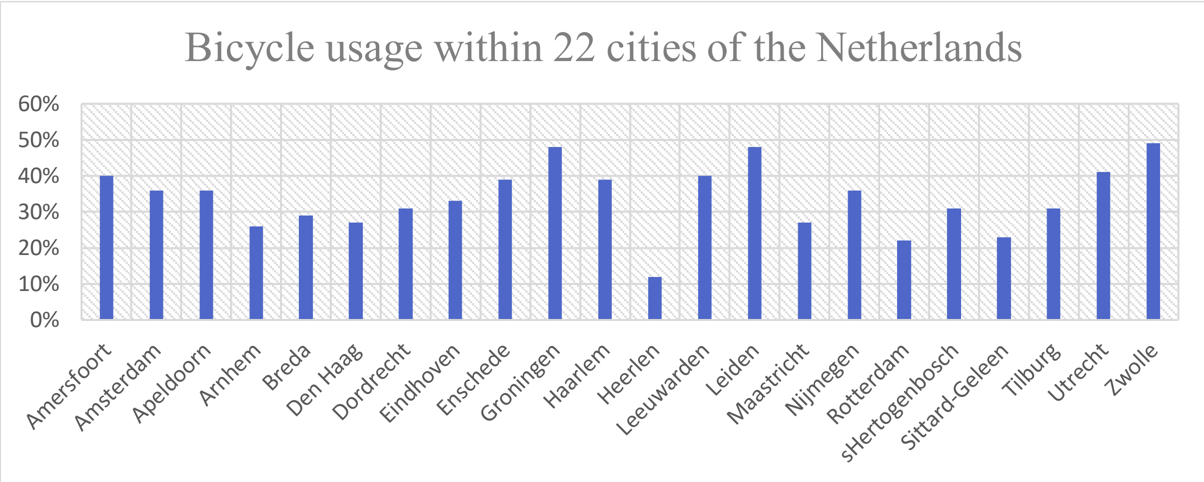


Figure 41. Bicycle usage in the Netherlands cities [22]

6.3 Framework feasibility analysis

This sub-chapter is about the market feasibility of the business idea WPT e-bikes. The term "feasibility" describes the capability and suitability of a business. The business idea is renting and selling wireless chargeable e-bike and providing the charging infrastructure in the surrounding area. The idea is quite new, until now there are only a few similar services in the market. Before implementing the business idea, it is advisable to conduct a market feasibility research before entering the target market to discover the true potentiality of a business idea in the market.

Main question that can be asked here: Is WPT e-bike feasible enough to become a real business? The first step would be to answer whether there is a need for WPT e-bikes? The one can look at the technology that is available. Second step would be to check whether there is an equilibrium in demand and supply.

A feasibility study includes:

- Product or Service – Description in section 6.1
- Technology - Chapter 2 and Chapter 5
- Market Environment – Section 6.2.1
- Competition – Section 6.1

[22] Source: CBS, OViN 2017 -Ministry of Infrastructure and water management.

- Business Model – Section 6.2
- Market and Sales Strategy – Section 6.2.3 and 6.2.4

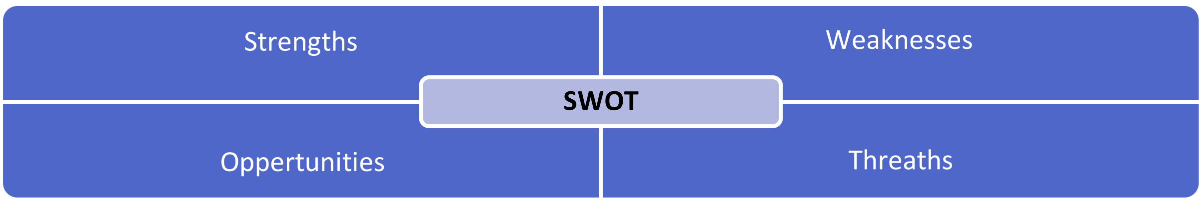
And the following points can be further developed depending on the type of company and its structure:

- Production Operations Requirements
- Management and Personnel Requirements
- Regulations and Environmental Issues
- Critical Risk Factors
- Probability of Success: Financial Predictions Including: Balance Sheet, Income Statement, Cash Flow Statement, Break Even Analysis, and Capital Requirements

6.4 SWOT analysis for WPT e-bike business

SWOT is an acronym standing for *strengths*, *weaknesses*, *opportunities*, and *threats*. These four elements are displayed in a two-by-two matrix. The matrix uses both internal factors (strengths and weaknesses) and external factors (opportunities and threats) to identify the worthiness of an identified opportunity or goal. This analysis is commonly used analysis tool in business. The tool is quite simple to use, and it can be applied to basically any business situation and therefore also the WPT e-bike business. The main purpose for SWOT-analysis is to discover and exploit strengths as well as opportunities, to understand the weaknesses and to manage and eliminate threats.

As seen in the Table 11, strengths and weaknesses represent the internal positive and negative factors influencing the business "from the inside". Opportunities and threats, in turn, propose the external positive and negative factors, that have an impact on the business "from the outside".



STRENGTHS • New innovative idea • Large market opportunities • Affordable prices for customers • Large customer target group	WEAKNESSES • Limited resources • Customer tailored • Market saturation • Technology still in development
OPPORTUNITIES • Target markets • Expansions in services • Expansions in business partners	THREATS • Competitive intentions • Questionable market demand • Unpredictable costs • Taxation issues

Table 11. SWOT analysis WPT e-bike

Accell Group NV designs and manufactures racing, children's, hybrid, mountain, electric, and luxury bicycles. The organization responds strongly to the dynamic consumer market through a wide and modern range and a striking market approach for the sector. The company manufactures its bikes under the brands Batavus, Hercules, Koga-Miyata, Lapierre, Mercier, Loekie, Sparta and Winora. Accell also makes bicycle accessories and fitness equipment. The Company markets its products in Northern and Central Europe.

Strengths factor in the SWOT table for Accell: Worldwide WPT e-bike is still a new and innovative business idea that has a lot of potential. Due to the exponential growth in demand for e-bikes, implementing WPT for it can lead to large market opportunities. The advantage of Accell has an already existing business for other products and services, and thus so also available resources (financial, partners, stakeholders, technical expertise). Due to their wholesale character they can offer affordable prices for customers and therefore reach a large customer target group.

Opportunities factors: As Accell markets its products in Northern and Central Europe, their target markets can increase together with the increasing demand in WPT e-bikes. With the WPT comes more technology products and services relating to the IPT transmitters and receivers for the e-bike. That means that Accell should expand their services which can also lead to an expansion in business partners in the new lease/rental WPT e-bike connections and connections relating to the providing the WPT tools and materials.

Weakness factors: Since WPT for e-bikes is relatively new and the technology behind it is still developing, limited resources will be available in this phase. Even though there is a rise in demand, the WPT e-bikes are a customer tailored product. Due to the new character of the WPT e-bikes, where other related businesses can also implement this idea. Therefore, there is a possible risk of the market saturation.

Threat factors: As mentioned above there can be competitive intentions for this business idea, creating the possibility for smaller companies which are a customer of Accell and key partners within the company to seize the opportunity. In the early stage's unpredictable costs for the wireless transmission transmitter can occur.

In a discussion with engineers from the Accell Group N.V. in the Netherlands-Apeldoorn, the question came whether the WPT e-bike can be a good business opportunity for them. Accell already has e-bikes from various brands thus only the WPT coils need to be implemented. Based on the Business Canvas Model and SWOT analysis, it can be concluded that taking the opportunity of developing and implementing the WPT e-bike business can lead to expansion and profit.

As for the customer segment for Accell as a wholesaler:

1. Electric bicycle lease companies
2. Electric Bicycle retail shops
3. Individuals (elders, students, tourists)

One scenario: Accell is only responsible for producing and selling the e-bikes and WPT components which they trade to smaller companies (lease and/or retail). This means that the responsibility of set-up, maintenance of the coils and maintenance of e-bikes lies with the smaller companies (customers).

Scenario two: If Accell wants to increase their customer range and income, they can use the aid of smaller bicycle lease shops. Here, they can provide not only the WPT e-bikes and the charging pads as products but also use their engineers and facilities to repair, recondition and place the e-bikes with the charging coils. Although implementing this requires more engineers on the work floor of Accell, there will be an increase of their products and services in terms of reaching more customers through smaller businesses. These businesses are spread out over the entire country therefore reaching many customers as mentioned in the BCM.

Scenario three: Accell can also sell the WPT e-bikes to individual groups however this not as profitable compared to the other two scenario's. This due to the fact that Accell will have to produce, sell, maintain and build charging stations on its own which will result in high financial expenses. Another factor that should be taken into account is that Accell is located on just a few specific places in the Netherlands. Since the large group of customers (locals, elderly, students and tourists) as indicated in the BCM are widely spread throughout the country, Accell might not get the full potential of these focus groups but can receive customers from the nearby area and key partners.

6.5 Discussion

The third sub-research question was: *''How can a vehicle lease business in the Netherlands expand and/or develop their services to WPT e-bikes?''* Companies searching for a long-term and sustainable business idea, can utilize the electric bike industry as it has a bright future.

From Chapter 6. Business plan, is shown that the interest in e-bikes and WPT technology increases throughout the Globe (e.g. China, United States, Taiwan, Italy, Germany, Japan, South Korea, Australia, Canada, Portugal, the United Kingdom, India, Netherlands, Thailand, Belgium, etc.). However, this business plan will focus on application in the Netherlands due to the knowledge of the working environment here and the contacts made with Accell engineers. From the top ten countries with the most scientific produced documents, the Netherlands places 9th with 46 publications so far. Therefore, it can be concluded that the WPT e-bike business is of interest for the Netherlands. Due to the growth in e-bike demand, there is a lot of potential in this business. External competition can be present for the WPT e-bike business however the industry is open for fair competition.

In Chapter 6. Business plan it is shown that there is a worldwide increase in wireless technology and in the EVs industry. The technology keeps evolving and the WPT technology for e-bikes keeps getting closer to a larger group of public. As for the e-bike, the WPT technology must be practical (easy integration of components, cost effective, comfortable for the user), efficient in power, and lastly safe for user and surrounding equipment. As indicated in the first section of this chapter, the WPT electric bike is a profitable industry and it is open for any aspiring entrepreneur to come in and establish his or her business; one can choose to start on a small scale or start on a large scale with several outlets in key cities throughout the Netherlands. The mission is to establish an WPT electric bike rental service, retail and repair business that will make a wide range of electric bikes and accessories from top electric bike manufacturing brands available at affordable prices to the customers. This can be realized by applying the business plan model from Section 6.2. The model here can be used as a baseline on which the owner can embroider its own needs and requirements to it.

This business plan model can be part of a new starting business with other services included or it can be added a part of an existing business (e.g. a business addition to an already existing vehicle business). The advantage of adding it to an existing business (example Accell) is that they already have another business running on the background, so they already have a set of key partners, and a good income to start with the new WPT e-bike business.

The business idea was inspired by feedback points from Accell where the question was whether they should start with this business idea or not. After the BCM and the SWOT analysis it can be concluded that the WPT e-bike business is indeed a good opportunity for Accell. If they want to increase their reach, they can use the aid of smaller bicycle lease shops where they can provide the WPT e-bikes and the charging pads for which Accell can receive an income. However, this business plan can also be followed by an independent small bicycle shop. To do so they will need key partners (e.g. Accell) for wholesale e-bike connections, WPT charging pad technology tools, and engineers. Therefore, it can be seen that Accell is still a useful source where profit can be made from both perspectives. The advantage of Accell is that they already have another business running on the background, key partners and a financial stability to start with the new WPT e-bike business. By being one of the leading developers of this product their profit, partners, and customers can increase in these areas.

Chapter 7. Conclusion and Recommendations

This thesis presents a framework for three proposed WPT e-bike prototypes where the three cross-cutting concern requirements (practicality, efficiency, and safety) are met. Prior research has shown that there are specific parameters that can influence the e-bike wireless charging. These parameters have been assessed in this thesis to aid in building the framework for the prototypes. The proposed framework for building the prototype can be used for further studies in which engineers can further build and optimize the prototype. Motivated by a discussion with engineers from the Accell Group N.V. in the Netherlands this thesis also contains an elaborated business plan framework for WPT e-bikes which can be further implemented.

7.1 Conclusion

The comparisons between the three most common related work in Wireless Power Transfer (WPT) e-bikes can be seen in table 2. The technology behind WPT in all three is Inductive Power Transfer (IPT) through magnetic coils. According to the studies, there is no standard placement of the coils and magnetic characters differ depending on the writer's design choice. From research conducted in three different studies no complete design was built due to the fact that there were still multiple errors occurring. Therefore, the designs from these studies are in their preliminary phase where it is not ready for the production and construction phase. It can be concluded that there is a still need for an WPT e-bike prototype with the cross-cutting concern requirements which is applicable for production.

The power source, charging infrastructure, pick-up, and the load are the wireless components that are taken into account in this thesis. From the literature study it can be concluded that there are certain parameters which influence the WPT in e-bikes when it comes to practicality, efficiency, and safety. These are: the type of resource for the transmitting coil, characteristics of the WPT coils, positioning and placement of coils and the type of batteries. Therefore, in order to reach these cross-cutting concerns the above mentioned parameters have to be taken into consideration whilst developing the prototype.

After conducting research on estimating the most optimal value of each parameter, using different studies, results show: For the stand alone renewable powered source the DC current is an appropriate choice. This due to the relatively short distance for the power transmission, the compatibility with electronics, its inexpensive initial costs and its applicability in IPT structures. For the coil characteristics, the area of the Rx coil should be equal to or within 80% of the Tx coil to achieve an optimum coupling coefficient factor. The Rx should be not be big, approximately 5 cm length, 5cm with and 5cm height. The Rx weight should not exceed 2.5 kilograms. Until now the best results are shown with litz material for the coils with a ferrite shielding. The magnetic coupling coefficient (k) and coil quality (Q-factor) should be carefully chosen to have an efficient WPT. Magnetic coupling coefficient (k) between the Tx and Rx, can be influenced by the positioning of the coils and the airgap between them. A large distance between Tx and Rx can lead to a small coupling coefficient (k). The positioning of the Tx and the Rx coils can influence the magnetic coupling, power transfer efficiency and if not placed well it can disrupt the rider. Q-factor can be influenced by the performance of the coils. The performance of the coils is dependent on the different characteristics of the coils (shape, size, weight, number of windings, material etc.). For the coil placements, theoretical analysis and discussion with Accell concluded that the best places to position the Rx coil are on the kick-stand and the front frame of the e-bike. By keeping the Rx in a fixed position, it can reduce material wear and minimize chances for misalignments caused by the user. There are parasitic resistances from the coil, used materials, also the circuit components which can cause losses and reduce the efficiency. For the batteries, the lithium-based battery has shown to be the best compared to other types in terms of usage, weight, capacity, no memory effect, and a quicker recharge time. To increase the charging time, this can be done through an advanced variable amperage charger that can either slow charge or fast charge with the flick of a switch.

Different coils have been assessed to find the most optimal geometrical shape in terms of the coupling factor, the power to be transmitted, the material mass used, and the distribution of magnetic flux density. From all possible geometrical shapes it can be concluded that, U&I-core, cylindrical solenoid and circular planar, are the most optimal and go together with the placement of the coils. The above-mentioned shapes are proposed for the prototype.

To successfully develop the prototypes a framework was set up containing various requirements. The framework is designed and validated in such a way that it takes practicality, efficiency, and safety into account. However, to apply IPT in EVs is not as straight forward because different aspects (all connected to each other) are needed to be taken into consideration.

As for the safety of surrounding users near one WPT charging e-bike, it can be concluded that the EM field does not have a huge effect. However, when multiple charging stations are used near each other, new measurements must be done that must meet the requirements set by INCGS. These can be calculated through the method from APRANSA where the measurement techniques based taking the average exposure level at four points of the human body: the head, chest, groin, and knee are addressed.

Another important focus of this study was set on developing a business plan for the WPT e-bike technology. The research done showed that it can be concluded that the company Accell would benefit from implementing the proposed busines plan using the BCM tool. The WPT electric bike is a profitable industry and it is open for any aspiring entrepreneur to come in and establish his or her business through the Netherlands. The bibliometric research indicated an increase in demand in e-bikes and e-bike WPT scientific research thereof. In the top ten countries with the most scientific produced documents are displayed, the Netherlands is on 9th place with 46 scientific publications. It can be concluded that the Netherlands indeed interested in WPT e-bike business.

7.2 Recommendations

Due to some challenges, a few aspects of this thesis could not be fully addressed. However, the framework can be implemented by engineers, to build the three prototypes. It is recommended to evaluate and validated them for the efficiency of the power output and evaluate possible implementation shortcomings.

In the digital survey, most users indicated to expect the e-bike battery to be charged much faster. This should be taken as a recommendation for further studies to be implemented on the prototype.

In the related work, it was seen that none of the studies addressed data communication for the WPT e-bike application. In general communication, errors may occur when the coupling factor (k) is increasing or decreasing due to misalignment. Therefore, it is recommended to evaluate the freedom of movement from the Rx coil for all the three prototypes to see where the threshold lies for the minimum communication errors.

More research should be done to improve the knowledge based on the use and safety of the e-bikes, particularly on two key issues: firstly, EMI field radiation effect on communication EE components and secondly improving road safety.

When it comes to the business plan for the WPT e-bikes the BCM tool can be further optimized with tools such as lean canvas or lean design thinking to obtain a better result of the feasibility study.

If more charging spots are placed next to each other the multiple chargers can have interfering communication with each other. A controller can ensure a correct transfer of energy, but the primary electronics are not robust enough. Further research is needed to ensure safe operation.

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Appendix

A. List of symbols

C_1, C_2	Primary and secondary capacitor
L_1, L_2	Self-inductance primary and secondary coil
M	Mutual inductance between L_1 and L_2
N	Number of secondary coils
T	Number of turns in coils
V_1, V_2	Voltage primary and secondary side
I_1, I_2	Current primary and secondary side
ω	Frequency of track supply
V_{oc}	Open-circuit voltage induced in secondary coil
I_{sc}	Short-circuit current of secondary coil
P_{su}	Uncompensated power rating
Q	Operating quality factor
k	Coupling coefficient of the pads

B. Extra figures

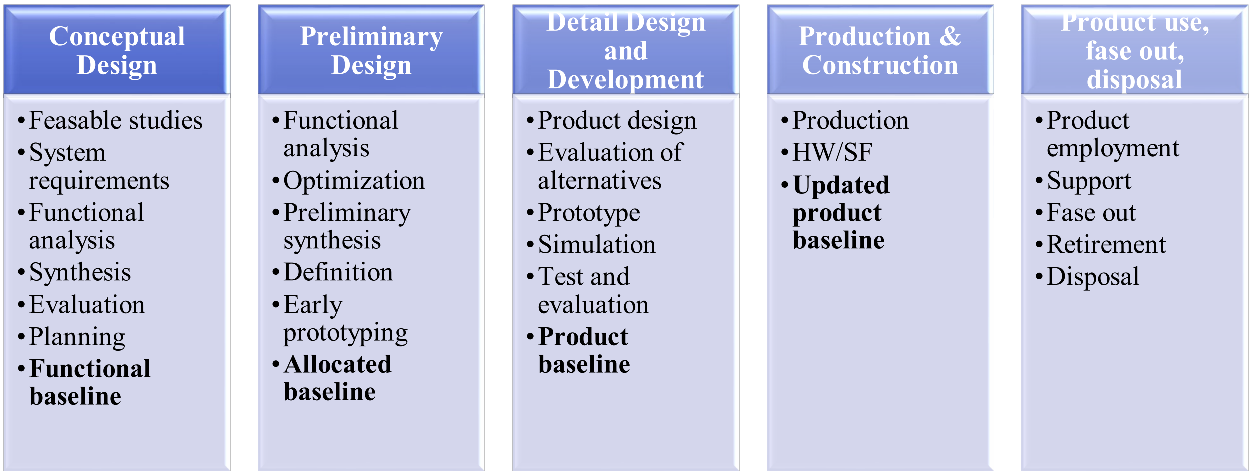

Figure 42. System Engineering process model