MDP 1
Wireless Power Supply
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Abstract

In this study, various ways of wireless power transfer are discussed. Nine specific applications of wireless power transfer are suggested. They are analyzed based on a list of criteria, regarding user-friendliness, technological and economical feasibility, sustainability and health safety. The feasibility of the two best applications was investigated further.

The first chosen application is the standby saver, which uses the power of a radio pulse sent by a remote control to turn on a device, eliminating the use of standby power. We suggest that it could be possible using a frequency of 5.8 GHz, with pulses of 500 milliseconds at about 12 Watt input power. This application has environmental and economical benefits, but they are limited because it can only be used in new devices, and is not applicable to many devices other than televisions. Based on calculations of the Specific Absorption Rate (SAR), it can be concluded that there are no health hazards associated with this application.

The second application is the wirelessly powered bicycle lights, where power generated by a hub dynamo is sent to the lights, using radio waves. It was calculated that the lights require more power than what can be achieved. Recharging the batteries while cycling and thereby increasing the time the LED lights can be used, is possible. However, to use the lights for 1 hour one has to cycle 34 hours to recharge the amount of used power. The calculations of the SAR show that this application perfectly complies with the limits. The economic aspects of the wireless lights are not large and will not be very important for consumers when deciding which type of lights to use.

Contents

1 Introduction

Wireless power transfer may seem like science fiction, but the idea is more than 100 years old. Around 1900 Nicola Tesla claimed to be able to radiate power over long distances with minimum loss of power, took a patent and even got some industrial finance for trials. These failed. Hundred years later, an electric toothbrush using contactless inductive charging device is a common commodity in many households. Even more recently new breakthroughs are claimed to radiate enough energy from a power outlet to feed a nearby low-voltage lamp or electronic device using radio-frequency radiation over a distance of one meter.

In this project, we came up with nine possible applications of wireless power transfer. They were analyzed based on a list of criteria, and based on this, the feasibility of the two best applications was investigated further. These criteria were:

- User-friendly, easy to use and easily standardized.
- Technologically possible to make.
- Economically feasible.
- Sustainable.
- Safe for both health and environment.

In chapter 2 of this report you will find the theory about the various ways of wireless power transfer. In chapter 3, all applications we came up with are mentioned, and these applications are analyzed and rated based on the criteria in chapter 4. Then in chapter 5 and 6, the two selected applications are investigated more thoroughly. In chapter 7, a conclusion on these applications is drawn, and some recommendations are given.

2 Theory

There are different ways to achieve wireless power transfer from a power source to a receiver. This chapter will discuss the basic theory behind several ways of wireless power transfer.

2.1 Induction

When the magnetic flux through a circuit changes, an electromotive force (emf) and a current are induced in the circuit. This effect is for example used in dynamos, electric motors and transformers. The central principle behind electromagnetic induction is Faraday's law, which relates to the induced electromotive force (emf) in any closed loop including a closed circuit[1].

Induction can be used as a means of wireless power transfer. A changing current in one coil 1 creates an emf, which in turn induces a current in a coil 2, as shown in Figure 1.

The coils are not in contact and in this way energy can very simply be transported over short distances. This is used in for example an electric toothbrush charger. The short distance that is required for induction is the largest drawback of this way of wireless energy transfer, because it limits the applicability to very close-range situations[2].

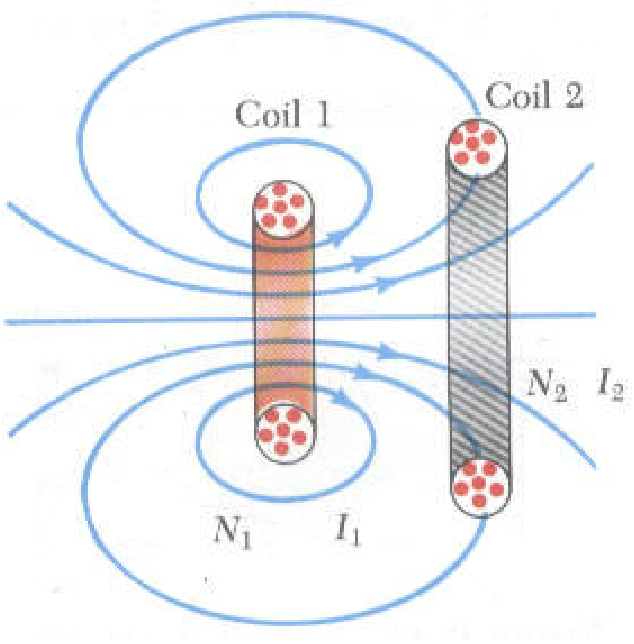

Figure 1: A time-changing current in coil 1 causes a time-changing magnetic flux through coil 2 which induces a time-changing current in that coil[3].

2.2 Radio Waves

The key component for wireless power transfer by radio waves is the rectenna. A rectenna is a combination of a rectifying circuit and an antenna. The antenna receives the electromagnetic power and the rectifying circuit converts it to DC electric power. A schematic rectenna design is shown in Figure 2.

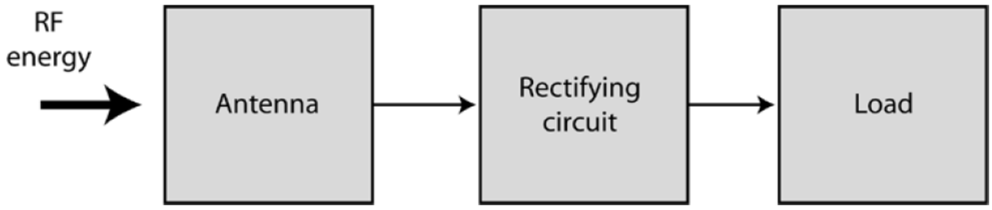

Figure 2: A schematic rectenna design[4].

A simple rectenna can be constructed from a Schottky diode[5] placed between the antenna dipoles. The diode rectifies the current induced in the antenna by the microwaves. Schottky diodes are used because they have the lowest voltage drop and highest speed and therefore waste the least amount of power due to conduction and switching.[6]

The amount of power that can be transferred is limited. For safety reasons, the transmitted power is limited by regulations, for instance by the Federal Communications Commision (FCC)[7], and the received power is attenuated, mainly due to free-space path loss.[4] Furthermore, because portable devices have small dimensions, the rectenna should have small dimensions as well. This results in a small antenna area and, consequently, a low amount of received power. Because of these limitations, wireless power transfer using radio waves is mainly suitable for low-power applications, e.g. a low-power wireless sensor.[6,8]

2.3 Light

Power delivery that starts with sunlight has many advantages such as sustainability and the fact that the sun is present every day. However solar cells have limited efficiency and sunlight is not available at night. An alternative is to generate artificial light, from a laser, transmit it through air, and then convert it into electricity. New refinements are making this alternative more attractive.[9] NASA has demonstrated flight of a lightweight model plane powered by laser beam, directed at a panel of infrared-sensitive photovoltaic cells mounted on the bottom of the aircraft.[10]

A theoretical setup consists of a laser (Light Amplification by Stimulated Emission of Radiation)[11] and a photovoltaic, or solar cell. First electricity is converted by the laser into a laser beam, which consists of coherent radiation. Next this beam is pointed towards a photovoltaic cell receiver, which in turn converts the received light energy back into electricity.[12] This is generally called "power beaming".[2]

Both steps are not highly efficient[13] and also a direct line of sight between laser and the photovoltaic cells is required.

2.4 Electrical Conduction

Power is normally supplied by means of a conducting wire, where the conductive material is a metal. In the case of wireless power supply through conduction, this conducting wire is replaced by ionized air.

Air is a good insulator and a high potential difference, called the breakdown voltage, is required to generate a current. In the case of lightning this can easily be 10.000 volts.[14] In order to lower this breakdown voltage one can ionize the air by means of a high-power ultraviolet beam. This concept works as follows: The high-power ultraviolet beam strikes the air molecules thus exciting the electrons. The electron that formerly occupied the HOMO (Highest Occupied Molecular Orbital) level of the molecule is no longer bound to the molecule and the oxidation state of the molecule is increased thus generating an ion (Figure 3). This way, the laser beam creates a plasma channel in the air which contains free charge carriers (Figure 4). The air has been made conductive and can now serve as a conducting medium just like a metal wire.[15,16,17]

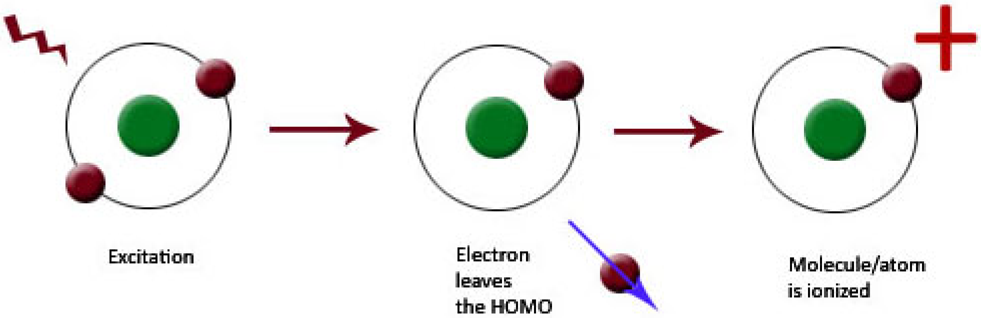

Figure 3: An electron in the HOMO is excited by a photon. The electron leaves the molecule thus generating an ion.

In order to actually transmit power, it is necessary to create a loop, so in the case of supplying power through ionized air, actually two paths of ionized air have to be made. It is also possible to connect both sender and receiver to the ground.

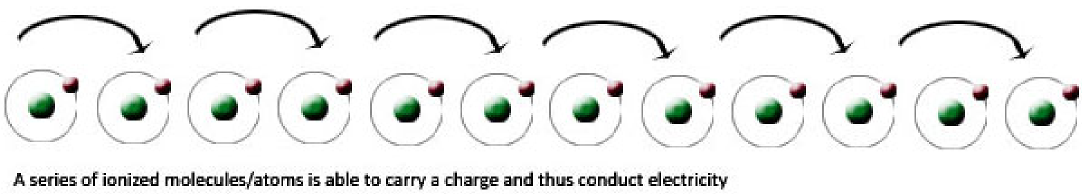

Figure 4: Conduction by means of ionized air molecules.

2.5 Evanescent Wave Coupling

Evanescent wave coupling (or "WiTricity"[18]) is a technique that has recently been investigated by researchers at MIT.[19,20]

The physics behind this technique is rather complicated. At a glance, it basically extends the principle of magnetic induction to mid-range applications up to a few meters. The main difference is the use of resonance; if sender and receiver have the same magnetic resonance frequency, energy can efficiently be transported, while losses to the non-resonant environment are small. Using resonance, for the same geometry, power can be transported approximately 10^6 times more efficiently than without resonance.[19]

The experimental setup used by the MIT researchers is shown in Figure 5. The coils can be compared to antennas; the electric and magnetic fields produced by antennas can generally be divided into the *near field*, which is dominant at close ranges, and the *far field*.[21] The far field, responsible for electromagnetic waves, radiates energy into the environment. The near field does not radiate, so no energy is lost, except when the sender and receiver have the same resonance frequency. In that case energy is transported from the sender to the receiver. The main achievement of the MIT team is to have figured out how to fine tune the system so that the near field extends to distances of a few meters[20], simultaneously limiting the power radiated through the far field.

Figure 5: A demonstration of power transmission through evanescent wave coupling.

One of the benefits is that most common materials do not interact with magnetic fields, so obstructing objects do not have much influence. This also goes for human tissue and therefore health risks are low. The coils shown above are too large for applications in i.e. a cell phone, but the receiving coil can be made smaller. The researchers state that the transmitted power can be kept constant, if the size of the sending coil is increased to keep the product of the sizes of both coils equal.[19] The efficiency of the above setup is around 40 to 50% for wireless power transfer over 2 meters. However, the efficiency from power outlet to light bulb was 15%, because a very inefficient component (Colpitts oscillator) was used.[20]

3 All applications

In this chapter, possible applications using wireless power supply are introduced. The applications came up during a brainstorm session. Powercast (section 3.5) is an application that is already being developed commercially. The contactless energy desktop application of section 3.2 is based on research currently conducted at Eindhoven University of Technology[22]. All other applications are ideas of our own.

3.1 Combination of wireless power and network

Wireless networks eliminate cables by using radio waves to transfer the data from computer to router. However, the battery life of a laptop is still limited, so there still is the need of carrying a cable for powering the laptop itself. It would be nice to combine these two into one: using the radio waves of a wireless network, not only for internet but also for powering the laptop itself.

3.2 Contactless Energy Transfer Desktop Application

Contactless Energy Transfer (CET) is the process in which electrical energy is transferred between two or more electrical devices through inductive coupling. The CET desktop application is a new development in the area of wireless power transmission, where a table with embedded "power transmitting coils" powers and recharges different electronic devices, which normally need to be charged by Plug & Socket connectors, like cellular phones, music players and laptops[22]. This is done by simply placing them on top of the desk.

The CET desktop uses a matrix of hexagon spiral windings embedded underneath its surface, to transfer power to CET enabled consumer electronics devices placed on the wooden or plastic table. When electronic devices fitted with power receiving coils are placed on the table, the increase in electromagnetic coupling between primary and secondary coils, allows power to be transmitted from the desktop to the devices. To improve efficiency and limit stray magnetic fields, clusters of only three primary coils, located closest to the receiving devices, are excited (Figure 6). The coils are excited with out-of-phase currents to further reduce stray magnetic fields. The power transfer efficiency is not constant but varies throughout the surface of the table, because the magnetic field of a coil is not homogeneous.

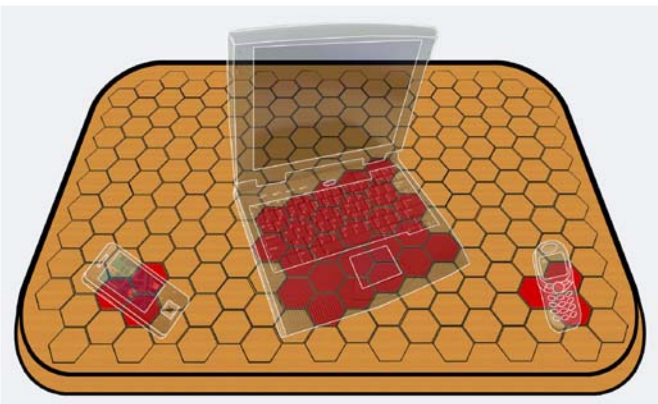

Figure 6: The CET desktop application showing activated coils powering the devices placed on the table[22].

3.3 Wireless powered LED bicycle lights

Removable LED lights are used worldwide on bicycles that do not have wired lighting. The advantage of these lights is that they do not require a dynamo to power them, because they use batteries. However, the batteries can unexpectedly run out of power and need to be replaced often which is not environmentally friendly. As an alternative a new application, using a dynamo to wirelessly power LED lights using radio waves, is introduced. Because this is one of the applications that were chosen for further research, more information can be found in chapter 6: Wireless Bicycle Lights.

3.4 Wireless powered and controlled laptop screen

A common defect in laptops is that the cable that connects the display is damaged causing the screen to flicker or to go black. Normally this is caused by wear and tear and it has the tendency to occur outside the laptop's warranty. One way to avoid the cable to break is to have no cable at all. As a new application the wireless powering and controlling of a laptop screen is introduced.

Figure 7: Wireless powered and controlled laptop screen.

Since the display is attached to the rest of the laptop via a hinge, it is very close to the bottom part of the laptop. Powering of the display can be easily achieved using mutual induction, a principle that has been very well proven to work for all kind of applications. Controlling the contents on the screen can be achieved using a radio signal[23]. This can be done just like with wireless internet on for instance the 2.45 GHz band.

The application would work the same way as a power transformer: a changing current in the first circuit creates a changing magnetic field; in turn, this magnetic field induces a changing voltage in the second circuit[24]. If the primary circuit (in the laptop bottom part) and secondary circuit (in the display) are very close, which will be the case for this application, a very high efficiency can be achieved. Everything inside a laptop is DC powered. To be able to use mutual inductance, this DC must be inverted to AC first. There are already small inverters around to be able to cope with the 8-10 Watts power requirement[25] of a laptop display[26,27]. Depending on the efficiency of the inverter, it could be so that not much extra power is consumed powering a wireless display, compared to powering a wired display.

3.5 Applications using Powercast technology

Powercast is a company that has invented a way to wirelessly transfer energy using radio waves to a so called harvester module. The modules are made to power small devices such as cell phones, lighting, remote controls, sensors and toys[28,29]. Recently, the first commercial product using Powercast was released, a Christmas tree with wirelessly powered lights[30]. While it is presented as wireless power, Powercast isn't just a replacement for a universal charger. Instead, it is meant to either continuously charge a battery or replace the need for them altogether. It works like this: a transmitter can be placed anywhere. This transmitter sends out a continuous, low radio frequent (RF) signal. Anything with batteries set within its range (and equipped with a Powercast receiver, which is the size of your fingernail) will be continuously charged.

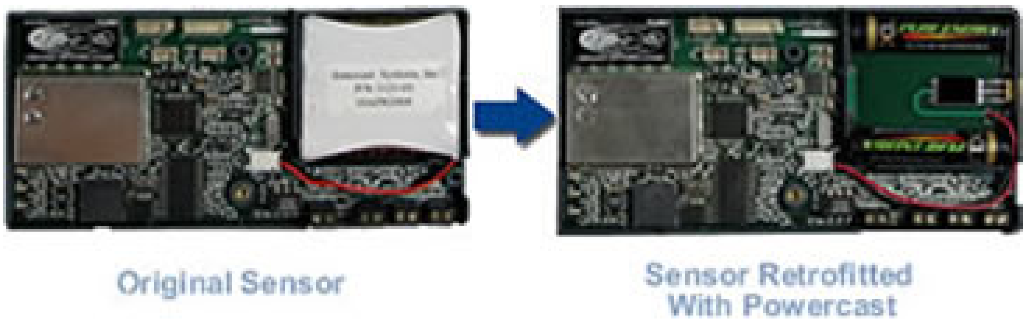

Figure 8: Using a Powercast module reduces the number of batteries required in this sensor from 4 to 2 and they also become rechargeable.[31]

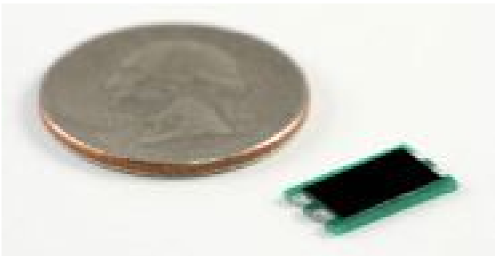

Figure 9: A harvester module compared to a US quarter.[31]

3.6 Solar powered recharging backpack

Currently existing models of backpacks that have flexible solar panels on them use batteries and wires to charge the equipment in them. Wireless power supply could be a nice alternative to charge these electrical devices without the necessity of plugging them in. Just by placing the device inside the backpack, it will be charged.

The distance from the transmitter to the receiver is quite short, therefore mutual induction can be used, but it is also possible to use evanescent wave coupling. It is even possible that energy is shared among various people wearing these backpacks. If for instance a person has excess power, because his devices are already charged, he can share this surplus power with other persons in his vicinity, thus making efficient use of the solar energy harvest.

Figure 10: Solar panel on backpack.[32]

Figure 11: A wireless speaker (not wirelessly powered)[33].

3.7 Wireless audio speakers

One interesting application is wireless powering of speakers. For example, a typical home cinema set has five speakers, each with its own cable. Installing these cables is quite a hassle, and it often looks very ugly, especially for the rear speakers far away from the receiver unit. Already, a lot of wireless audio sets are available on the market, but these all use batteries for the power. Usually only the two rear speakers are wireless, but even changing only these batteries can be frustrating when the speakers are placed high on the wall. Furthermore you don't want your system to stop functioning when you are out of batteries, and batteries are quite expensive compared to normal electricity and hazardous to the environment.

The most suitable method of wireless power supply for this application seems to be evanescent wave coupling (WiTricity). It is suitable for distances to a few meters, and has a high efficiency compared to, for example, RF energy that is radiated in all directions. Methods requiring an interrupted line of sight such as laser light are not suitable in a living room setting.

3.8 Wireless powered vacuum cleaner

Vacuum cleaning your floor can be a tedious job, but this can be automated using robotic vacuum cleaners. Current models (Figure 12) use an internal battery and a loading station for power supply. It is however possible to implement a power grid into the floor (Figure 13), similar to the power grid in the CET desktop. At the exact spot where the vacuum cleaner is cleaning, this power grid can be turned on, thus providing power to the cleaner by means of mutual induction.

The contact distance between the floor and the vacuum cleaner is quite short, so a relatively high efficiency is possible. The power level supplied to the cleaner can also be higher than with batteries, thus increasing its cleaning capacity which is of interest for companies (for instance workshops and bakeries) where the floors tend to be filthier as compared to normal households.

Figure 12: Roomba: The robotic vacuum cleaner[34].

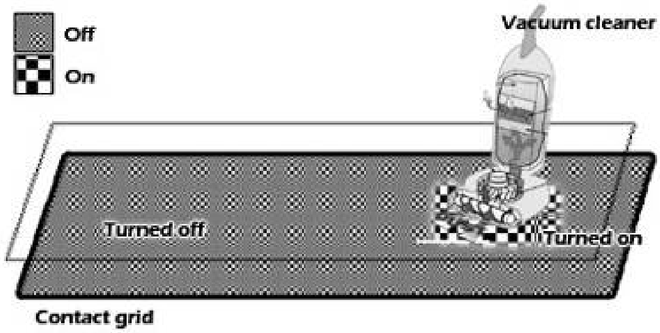

Figure 13: Wireless vacuum cleaner: Power is supplied by the contact grid on the floor.

3.9 Wireless power-on function

A lot of in-home applications are constantly in standby-mode, waiting for the user to press the power button on the remote control. This consumes a significant amount of power. Also, standby modes increase fire risks. It would be great to let devices have a "passive" standby mode, which uses no power at all but still makes sure the device can be powered on by the remote control. Perhaps, it could be achieved by using the power of the signal sent by the remote control to turn on the device.

Probably the most convenient way of doing this is by installing a RF transmitter in the remote control, and a receiving rectenna in the device. When the signal reaches the rectenna, it induces a current which can be used to change the state of a latching relay[35]. A relay is an electrical switch that opens and closes under the control of another electrical circuit, in this case the rectenna. A latching relay differs from a normal relay in that it has two relaxed states, so that you don't need a constant current to keep the switch turned on. This way, a single pulse is enough to turn the device on or off.

Because this is one of the applications that were chosen for further research, more information can be found in chapter 5: Standby Saver.

4 Analysis of applications

In this chapter, the applications from chapter 3 are judged by the criteria mentioned in the introduction.

The criteria are listed and elaborated below.

- The application has to be user-friendly and easy in use with regard to the people involved. The application should be easily standardized so it can be easily incorporated into different societies. If an application replaces an existing one, it should be an improvement in user-friendliness.
- The application should be technically possible to make at the moment and not only in the future.
- The application should be economically feasible. It should be able to financially compete with current technology.
- It should be sustainable. Sustainability relates to the continuity of economic, social, institutional and environmental aspects of human society, as well as the non-human environment. In other words: the application should meet the needs of the present without compromising the ability of future generations to meet their own needs.
- The application should be safe for your health. The application should comply with FCC regulations now or in the near future.

The first two criteria are self-defining; there is no point in developing an application that nobody wants to use and is impossible to make. Economical feasibility is also an essential requirement, because manufacturers should be willing to make it. Sustainability is also important, because we should not put any additional strain on earth's valuable resources. It is a trend that many new products are sold as environmentally-friendly. Of course, health safety is an absolutely necessary boundary condition.

In Table 1, the applications are rated from 1 to 10 for each of the criteria. The sum of all points for each application, give an indication of which applications are most interesting. A justification for the ratings is given in the rest of this chapter. Based on the results of this cursory analysis, the Bike Light and Standby Saver were selected for an in-depth investigation. After this investigation, the ratings in Table 1 may turn out to be too high or too low.

Table 1: Rating of the applications, based on the criteria.

	Laptop power	*Desktop*	*BikeLight*	*Screen*	*PowerCast*	*Backpack*	*Speakers*	*Cleaner*	*Standby*
User-friendliness	10	9	8	6	8	8	9	8	8
Technical feasibility	3	8	8	7	9	7	5	7	8
Economical feasibility	7	7	9	5	7	5	8	6	9
Sustainability	5	7	9	5	8	8	8	7	9
Health	3	5	8	8	8	8	7	5	8
Total Points	**28**	**36**	**42**	**31**	**40**	**36**	**37**	**33**	**42**

Combination of wireless power and network

This idea is very user-friendly, since it would finally make a laptop truly mobile. It is also easy to standardize, since it could be integrated into existing Wi-Fi standards. These are all advantages over existing technology. So a 10 for user-friendliness. This is one point higher than for the CET Desktop, which also powers your laptop, because it puts less restrictions to where your laptop must be placed.

However, powering a high-power device like a laptop with radio signals is not feasible at all. Power output of the routers will have to be significantly increased to power a laptop. For internet, the power output is in the range of hundreds of milliwatts[36] and this complies with FCC regulations. However, a laptop generally uses 30 Watts of power[37]. Transferring this with radio waves will certainly not comply with FCC regulations. This is even more the case when the same range that wireless internet routers have nowadays (32 meters indoors and 95 meters outdoors[36,38]), must be met for the power. This would also imply serious health hazards. The low power WiFi signals could however be used to slowly recharge a battery, however the increase of battery cycle length would probably be negligible. So a 3 is given for both technical feasibility and health.

The application would waste a huge amount of energy because of the inefficiency of RF-transfer, so the application is not rated highly in terms of sustainability. Also, batteries would still be needed for places where there is no WiFi.

If the application would be possible, the economical feasibility would probably be quite good, because a completely wireless computer is a dream for every laptop-buyer. However, if it would waste a lot of power, this would cost a lot of money which decreases feasibility. So therefore an in-between rating of 7 is given.

CET desktop

This wireless powered application (CET desktop) is a user-friendly application for charging and powering electrical power-consuming devices and it does not require any special knowledge for being used. By simply putting the device on it you can be sure the process starts. It can also be easily standardized for worldwide markets. However, the need for a special table is a drawback. So a 9 (instead of 10) is given for user-friendliness.

It is technically possible because the process is not much more complicated than other systems with mutual induction. Prototypes are already being developed[22]. So an 8 is given for technical feasibility.

The economical feasibility can be quite high because it can be used for a wide range of daily-used devices. But again the need for a costly special table reduces the rating to 7.

The efficiency of induction is quite good, at more than 50%. Of course, a cable will always be more energy-efficient. But the difference in energy use will not be that big, because all chargers consist of a power transformer that uses the same principle of induction. Not having to produce a separate charger for each device will reduce the use of valuable materials. So in terms of sustainability, a 7 might be reasonable.

Because of the magnetic fields involved, the system does not yet comply with FCC regulations, but since the magnetic coils are locally powered-on at sites where there is a power-consuming device exactly above them, this might be possible to avoid. Also there is the possibility of some proper shielding for this application. But because it is still uncertain whether it will comply with the regulations, a 5 is given for health.

Wireless powered LED bicycle lights

With this application you will never have to replace batteries in the bike lights. Also, it will prevent the lighting from failure due to cable damage. These two things make the application very user-friendly, so an 8 is given there. This is lower than for instance the PowerWiFi idea, because it is not something the user will notice every day. Batteries can be recharged while cycling or the lights can be directly powered; in both cases, never throwing away batteries is a big plus in terms of sustainability, and since no environmental drawbacks can be thought of, a 9 is justified here. The elimination of battery costs, in addition to an expected high demand (especially in new bikes since a special dynamo needs to be installed), makes the application economically attractive: a 9 there.

As Philips has announced LED sticks powered by the low-power RF Powercast technology[39], it will probably also be feasible to power the LED bicycle lights by the same technology, so an 8 is given for technical feasibility. Since no high power levels are produced by a dynamo, we do not expect health safety problems, which explains the 8 there.

Wireless powered laptop screen

The user won't notice any improvement in ease of use, so a 6 is given there.

It is technically possible to transfer power over such a short range using induction. However, there might be a problem with the produced magnetic fields influencing the screen and hard-drive, so a modest 7 is given for technical feasibility.

The wireless powered and controlled laptop screen could be economically attractive, especially for manufacturers. They do not have to worry about having to repair display cable damage within the warranty period. Also, the components required are not expensive to manufacture. The good news for consumers is that they do not have to pay for an expensive repair if the cable breaks outside their laptop's warranty. But the extra energy cost, resulting in a higher battery drain, and increased production cost will probably outweigh the small benefits, so a 5 is given.

The additional energy use and materials used for the extra components are also bad in terms of sustainability, so a 5 is given there.

Transformers are common in use, so no health issues are foreseen for this application: an 8 is given there.

Applications using Powercast technology

This application is very user-friendly, because batteries can be recharged without removing them from the device they are in or plugging in a charger. But the power is so low that if, for example, you use your cell phone frequently, you will still need to plug it in a charger occasionally, only less often. So an 8 is given for user-friendliness.

There are already some applications available such as the Christmas tree lights, so Powercast is technically feasible (a 9). This is the highest grade given for technical feasibility, because it is the only application that has been proven to work.

As there are a lot of low-power battery-powered devices in households nowadays (remotes, phones, pc peripherals, etc.), this application could be economically very feasible since it can be used by all of these.

It is more sustainable than regular battery uses, since fewer batteries, which still contain toxic substances, are required[40]. However, although the power used is low, power transmission through RF remains a highly inefficient process, so in terms of energy costs it is not that sustainable. Overall, an 8 is given for sustainability. This is higher than for example PowerWiFi and CET desktop, because it eliminates batteries in some devices.

Health issues may be a problem, but calculations show[41] that for a transmitter with an average power of 1 Watt over 30 minutes, one should maintain at least a 15 cm distance from the transmitter. This is a reasonable restriction, so an 8 is given for health.

Backpack

This application is quite user-friendly; just by placing the devices in the bag, they will be charged, which is an improvement over existing models. But we think this improvement is not as big as the CET Desktop or PowerWiFi. So we rate it with an 8.

Solar-powered backpacks are already available, thus technically feasible. Power transmission within the bag using induction is also well possible, but because of the short range it puts restrictions on where in the bag the devices can be. Not much is known yet about evanescent wave coupling, so there is still a long way to go before the energy-sharing feature becomes reality. So overall, a 7 is given for technical feasibility.

Charging equipment with a solar powered backpack is also an already existing application and a cable is used to connect the solar cells to the equipment. This application on itself is already quite expensive and adding the ability to charge equipment wirelessly only adds to the costs. We think the extra costs and reduction of energy-efficiency will outweigh the benefits of the wireless backpack with respect to the wired version, so the economical feasibility is a low 5.

Because solar energy is used which otherwise would have been lost anyway, the application is quite sustainable, so an 8 is given there. Since it does not reduce the amount of used batteries, this is not a perfect 10.

Because the frequencies used with evanescent wave coupling do not interact sufficiently with human tissue to impose any serious health hazards and since the power density is also quite low, the application will comply with FCC regulations, so an 8 is given for health.

Speakers

This application will be very user-friendly because no cables or batteries are required. Also, it is possible to standardize the technology, so that speakers from different manufacturers would be interoperable, so a 9 is given for user-friendliness.

The application will not be too hard to produce, however research on WiTricity has just started so it could take some time before it is developed enough to make it suitable for practical use. With respect to the power requirements: a typical rear speaker requires 40 W power[33], so this seems achievable since a 50 Watt light bulb was already powered in the first ever experiment with this technology. A problem could be interference with other devices. Overall, we give a 5 for technical feasibility because practical application of WiTricity is still far away.

Because this application is a great improvement, we expect that it will be a serious option for people buying a new sound set. Since the market for sound systems is very large, economical feasibility should not be a problem, so an 8 is given here. This is still lower than for the bike lights and standby saver, because it will lead to an increased energy consumption which also costs money.

The application is more sustainable than the technology it replaces because it eliminates the need for batteries. The efficiency of the WiTricity technology also plays a role in sustainability and not much can be said on that at the moment. Overall, an 8 is given for sustainability.

The use of WiTricity for this application is probably safe for your health[42], but again not much is known yet, so a 7 is given. This is lower than the backpack, which would also use WiTricity for its energy-sharing feature, because the power levels involved are significantly higher.

Wireless robotic vacuum cleaner

The concept of a vacuum cleaning robot can be very handy. Powering it wirelessly by means of mutual induction can make it even more autonomous because the device will not require any recharging or changing of batteries anymore. Also, implementing the wireless technology enables more powerful robotic vacuum cleaners in comparison with battery-powered versions, thus making the application able to compete with current technology. However, if we look at the cleaning performance of vacuum cleaning robots there is certainly room for improvement and manual cleaning is still better. So it is quite user-friendly but not perfect, hence the 8.

Robotic vacuum cleaners are already available on the market. The only difference is that an induction coil has to be implemented. Also the floors need to have a contact grid consisting of inducting coils installed. Especially this last change requires quite some effort, but it is in principle technically possible, so a 7 is given there.

The economical feasibility is doubtful, because not many people are expected to invest in an entirely new floor just for a robotic vacuum cleaner. However, the infrastructure might also be used by other devices, like lamps and heating elements. But overall, we reward it with a 6.

In terms of sustainability it eliminates batteries in comparison with current robotic vacuum cleaners. But is requires more power than a conventional cable-powered vacuum cleaner. We rate the sustainability with a 7.

The magnetic fields involved can be quite high which might be a problem with health regulations, but they are very local (at the place where the vacuum cleaner is currently cleaning) and since no user is actually required to operate the cleaner (it is a robot), the system does not impose that many health hazards. However, you can not just assume that there are no people in the vicinity of the device and this application will probably not meet FCC requirements, so a 5 is given here. This is the same as the CET Desktop, which uses the same technology.

Standby Saver

Instead of pressing the “hard” power button, one can now use the remote to completely turn the device on or off. This is a slight improvement of user-friendliness with no drawbacks, so we reward it with an 8.

With regard to the technological feasibility, the energy picked up by the antenna has to be enough to switch a latching relay, which is not expected to be that much. Probably, it is necessary to make the transmitter directional, so that all power is radiated over a limited angular range. This has the drawback that the remote control needs to be directed properly by the user. But since a remote control using infra red also has to be pointed towards the device, this should not impose a problem. An 8 is given for technical feasibility. It is not a 10 because there are still some unanswered questions, and it is not as high as PowerCast because that already exists.

The application can easily be implemented in new devices. Older devices can, for instance, have an external version of the device between the power cable and the TV. A downside may be that this application requires the development of a completely new sort of remote control, combining infrared for controlling the device and a radio wave transmitter for the power-on function. This will for certain increase the production costs of a device a bit, but looking at the yearly power consumption of the ordinary stand-by function there may be a market for this application. Therefore a 9 is given for economical feasibility.

The application is also sustainable, because when all standby devices would use this, a lot of valuable energy is saved. On average a household uses around 400kWh a year on stand-by of devices[43]. The only drawback would be a slight increase of battery use, because the remote control occasionally has to transmit power pulses and also its original infrared signals. Because of the power-saving capabilities, we give a 9 for sustainability.

Because RF is a relatively inefficient way of energy transfer, the power transmitted by the remote may have a high peak value. But since the pulses sent by the transmitter are very short and infrequent, no serious health hazards are to be expected, so an 8 is given there.

5 Standby Saver

The Standby Saver application eliminates the need for standby power of devices like televisions. The idea is to use the energy contained in an RF pulse, sent by the remote control, to power a switch that turns the device on.

5.1 Technological design

The basic design includes a transmitting antenna in the remote control, a receiving rectenna, and a latching relay connected to the latter. This is pictured in Figure 14. Instead of pressing the “hard” power button, one can now use the remote to completely turn the device on or off and save power this way. This is a slight improvement of user-friendliness.

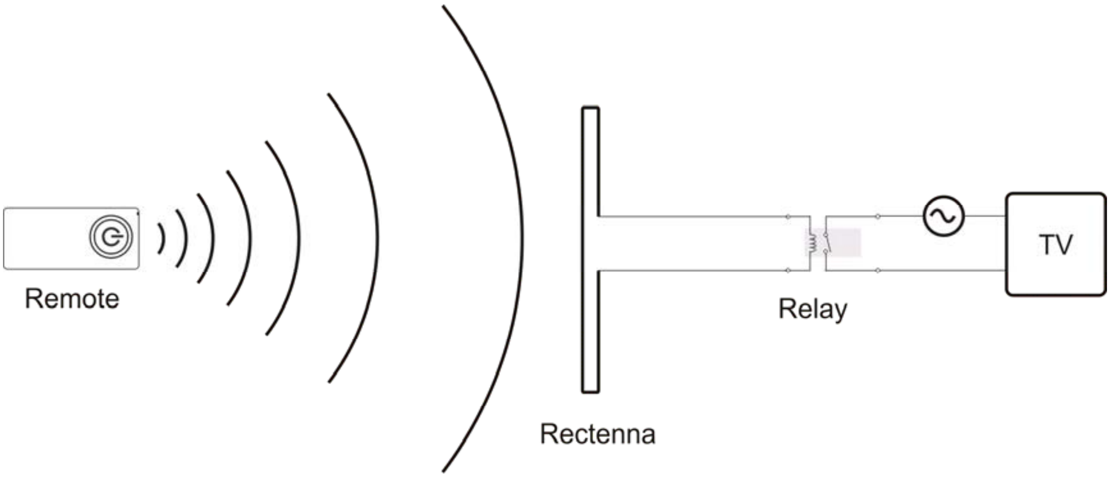

Figure 14: Schematic setup of the Standby saver. When the latching relay switches due to a power pulse received by the rectenna, the TV is connected to outlet power and turns on.

It is of course important that the amount of power that is received by the rectenna, is enough to switch the relay. In order to switch, a typical latching relay[44] needs at least 90 mW of power, during a pulse period of 3 ms. The power transferred from one antenna to the other is given by the Friis transmission equation[45]:

$$P_r = P_t \frac{G_t G_r \lambda^2}{(4\pi r)^2}.$$

In this equation, P_r is the received power, P_t is the transmitted power, r is the distance between transmitter and receiver, λ is the wavelength and G_t and G_r are the antenna gains of the transmitter and receiver, respectively. This equation assumes optimal alignment of the transmitter and receiver. The antenna gain says something about the directivity of the antenna. A gain equal to 1 means isotropic radiation in all directions (or reception from all directions for receiving antennas), a higher gain means the power distribution is more focused. The antenna gain is given by[45]:

$$G = \frac{4\pi}{\lambda^2} A_e = \frac{4\pi}{\lambda^2} \varepsilon_{ap} A_p.$$

Here, A_e is the effective aperture of the antenna, which is equal to the aperture efficiency ε_{ap} times the physical area of the antenna A_p. The directivity of an antenna thus increases with frequency (decreases with wavelength). The aperture efficiency of a typical antenna is approximately 0.5 [46]. Equation (1) can now be written as:

$$P_r = \eta P_t \frac{A_{p,t} A_{p,r}}{4r^2\lambda^2},$$

where the extra η factor accounts for the conversion efficiency of the rectenna. Thus, to optimize power transfer, the antennas should be made as large as possible, and the frequency as high as possible. However, when the frequency becomes too high, the antenna becomes too directive, making it harder for the user to point the remote control correctly. A reasonable size for the antenna in the remote control could be 3cm x 1cm. The one in the television could be larger, say 10cm x 50cm. A reasonable frequency is 5.8 GHz, which is a license-free ISM-band[47]. If we assume 5 meter distance between sender and receiver, and incorporate the limited conversion efficiency of the receiving antenna (η = 83% for printed dipole rectennas[48]), it can be calculated that the following power is required at the transmitter:

$$P_t = \frac{4P_r r^2 c^2}{\eta A_{p,t} A_{p,r} f^2} = \frac{4 \cdot 90 \cdot 10^{-3} \cdot 5^2 \cdot \left(3 \cdot 10^8\right)^2}{0.83 \cdot 0.03 \cdot 0.01 \cdot 0.1 \cdot 0.5 \cdot \left(5.8 \cdot 10^9\right)^2} = 1934\text{W}.$$

This is a very high power level for a battery-powered device. But this amount of power is only required for 3 milliseconds. A solution could therefore be to divide the radiated energy over a larger amount of time. For example, 500 milliseconds at 11.6 watts yields the same energy as 3 milliseconds at 1934 watts. A capacitive element between rectenna and relay, could accumulate this energy and discharge with a 3 millisecond pulse. This could however lead to additional losses.

Summarizing, this application could be possible at 5.8 Ghz, with pulses of 500 milliseconds at about 12 watt input power. However, in practice the power requirement may be higher because of additional losses which are not accounted for in the above discussion. Also, the user has to point the remote control correctly for half a second. On the other hand, it may be possible to optimize relays to have minimal power requirements, which could again decrease the power needed.

5.2 Environmental analysis

The power saved by the Standby Saver will of course be an improvement to the environment. Currently standby-leakages contribute to 5% of the total domestic power use in developed countries[49], thereby using 45 billion kWh of electricity per year in the United States alone. Leaking electricity will account for 90% of the increase of CO_2 emissions from offices and households between 1990 and 2010. Strong reduction of this type of energy wastage will both save the environment as well as reduce the operating costs of various domestic electric devices.

The standby power used, varies widely among different modern TV's, from a modest 0.31 Watt to an astonishing 76.11 Watt[50]. Average standby power of a TV is estimated at 1.9 Watt[51]. The average standby energy consumption of TV's in households is 21.1 kWh/year[51]. This is not much for a single household, but summed over all households and all other devices, it does become significant.

However, the Standby Saver will draw more power from batteries than a regular remote control. By still using infrared signals, or low power RF signals, for the functions to be performed when the device is on, this extra power is limited. The energy needed for one on/off switch is $0.5s \times 12W = 6$ Joule. The energy contained in two alkaline AA batteries (typical for a remote control) is 30.8 kJ [52]. Hence, ideally, one could turn a TV on or off more than 5 thousand times before replacing batteries. So, because the on/off button is used much less frequent than the other buttons, the extra battery use is negligible.

One must however keep in mind that the Standby Saver is not suitable for all electronics that have a standby mode, but only for ones with a remote control. Also, some devices can lose some functionality when not used in standby mode, like VCRs that use a timer. So relative to the total standby power consumption, only a small fraction is removed.

Furthermore, implementing this technology in current electronic household devices is probably not possible since it requires the replacement of current circuitry, which is too expensive to be beneficial. Hence, only new products can be equipped with this feature. Summarizing, we have to realize that if this application would become common in new televisions, only a very slight reduction in domestic power use will probably be noticeable, over several years of time.

5.3 Health hazards

In the past, numerous studies have been carried out on the possible health hazards of RF radiation. There are a few different ways by which non-iozing electromagnetic radiation can be hazardous.

The predominant effect of exposure to RF fields is the heating of body tissue as energy is absorbed by the body. Prolonged exposure to strong RF fields may increase the body temperature, producing symptoms similar to those of physical activity. In extreme cases, or when exposed to other sources of heat at the same time, the body's cooling system may be unable to cope with the heat load[53].

Thermal effects include heat damage to organs which have poor temperature control, such as the lens of the eye and the testes, skin burns, deep burns, tissue damage, heat exhaustion, heat stroke, decreased ability to perform mental or physical tasks and even birth defects. [54,55,56]

Besides thermal effects, one of the most important issues to be considered is the possibly increased risk of cancer by exposure to radiofrequencies. Most epidemiological studies have found no significant correlation between exposure to radio frequency radiation and an increased risk of cancer[57,58]. There is also no replicated evidence of DNA or repair damage due to RF exposure[57]. Most of RF studies concluded that RF exposure is not genotoxic or mutagenic[57,58].

The nature and the degree of the health effects of overexposure to RF fields depend on frequency, intensity of the fields, duration of exposure and distance from the source.

As mentioned before, the most problematic effect of RF radiation on the body is the heating effect. A measure that is often used in this context is the Specific Absorption Rate (SAR), which is the power absorbed by the body per unit mass[59]. At an exposure to electromagnetic radiation in the frequency range 10 MHz to a few GHz at a SAR value of 4 W/kg for 30 minutes, the body temperature can increase with almost 1 degree Celsius. This result was found from a study with volunteers.[60,61]

In terms of tissue properties, the SAR value can be defined as[62]:

$$SAR = \frac{\sigma E_{\text{rms}}^2}{\rho} = \frac{\sigma E_{\max}^2}{2\rho}.$$

In this formula, SAR has units W/kg, σ (S/m) is the electrical conductivity of the absorbing tissue per meter, ρ (kg/m) is the mass density and E_{rms} is the root-mean-square value of the electric field, which is equal to $\frac{1}{2}\sqrt{2}\ E_{\max}$, where $E_{\max}$ is the amplitude of the electric field.

From the intensity of an isotropic radiating source[14]:

$$I = \frac{c\varepsilon_0\varepsilon_r E_{\max}^2}{2} = \frac{P}{4\pi r^2},$$

the amplitude of the electric field can be calculated:

$$E_{\max} = \sqrt{\frac{P}{2\pi c\varepsilon_0\varepsilon_r r^2}}.$$

Here, I is the intensity, c is the speed of light, ε_0 is the permittivity of free space, ε_r is the relative permittivity, $E_{\max}$ the amplitude of the electric field, P the power of the source and r the distance to the source. So the SAR value can also be written as:

$$SAR = \frac{\sigma P}{4\pi\rho c\varepsilon_r\varepsilon_0 r^2}.$$

For a male human, the average density ρ is approximately 1070 kg/m^3. The speed of light c = $3 \cdot 10^8$ m/s and the permittivity of free space is $\varepsilon_0 = 8.85 \cdot 10^{-12}$ F/m. The parameters σ and ε_r depend strongly on the type of tissue, and the frequency. To determine the SAR value for the entire human body, an average has to be found for these parameters. In Appendix A, we have made a calculation of the average σ and ε_r; the results are $\sigma = 3.87$ S/m and $\varepsilon_r = 36.9$.

Table 2: SAR limits for unaware exposure of the general public, according to several international organizations[63].

	ACA (Australia)	FCC (USA)	ICNIRP (Europe)	MPTC (Japan)
	ARPANSA	C95.1	EN50361	ARIB
Whole body exposure, (W/kg)	0.08	0.08	0.08	0.08
Partial body exposure, (W/kg)	2	1.6	2	2
Average time (m)	6	30	6	6

In Table 2, a distinction is made between the limits of average exposure of the entire body, and the exposure of only a part of the body. For the remote control application, we estimate that on average, the body is 0.4 m, and the part closest to the transmitter (the thumb) at 0.02 m. Using the input power of 12 Watts proposed in section 5.1, the whole body and partial body SAR during the transmission of the pulse would become 0.22 W/kg and 88 W/kg, respectively. However, the SAR limits are defined as an average over 6 minutes (in Europe). Assuming that you will not press the power more than once in six minutes, the SAR values have to multiplied by (0.5 seconds / 6*60 seconds). This yields 0.00031 and 0.12 W/kg, respectively, which is well below the allowed values. The SAR will still be in compliance with regulations if used up to 16 times in the six minutes averaging time.

In the above calculation, the transmitter is assumed to be a perfectly isotropic source. This is obviously not the case in our application, because the beam is made more directive. If the user is outside the directive beam, the SAR value will be lower than calculated. Only if the user is in the course of the directive beam, the SAR will be higher. Based on this, we can conclude that there are no health hazards caused by this application, because the SAR value is below allowed safety values. As said before, effects other than body heating have never been consistently proven, so that is not something to worry about either.

5.4 Economic aspects

Batteries are more expensive than electricity from the power grid. This is mainly because of the cost of producing batteries and the materials involved. Even though they can be two thousand times more expensive, consumers still use them in cases where it is impossible or very inconvenient to use the power grid[64]. This influences both our applications, as in the bicycle lights we are replacing batteries, while in the power-on function there will be a bigger drain on the batteries in the remote control.

The standby function on electrical devices, such as TVs, computers and video and DVD players uses a lot of electric energy[65]. As mentioned before the average standby energy consumption just for TV's in households is 21.1 kWh/year[51]. At an energy cost of € 0.20 per kWh[66], this means that just € 4.20 is lost. As there are seven million households in the Netherlands[67], this is still almost thirty million euros in the Netherlands. An earlier calculation shows that on normal batteries, the application can be used 5000 times before the batteries run out. This puts very little extra drain on the batteries. It can be concluded that though the price of batteries is approximately two thousand times the power grid price[64], battery use will not stop customers using this application.

The antenna in the remote control will take up physical space. This will make the remote bigger and more expensive to make also increasing the price at which consumers buy the TV. This is even more true for the receiving antenna circuit in the TV. Compared to the total price of a TV, the extra costs for antennas will not have a large influence.

In conclusion, the TV will become more expensive because of more materials that are used and using the Standby Saver will save also a little money. But this will not be the deciding factor in buying one; the environmental aspects will be of more influence.

6 Wireless Bicycle Lights

Removable LED bicycle lights are used worldwide on bicycles, especially on those that do not have wired lighting. The advantage of these lights is that they do not require a dynamo to power them, because they use batteries. However, the batteries can unexpectedly run out of power and need to be replaced or recharged often. The idea of this application is to eliminate the need for batteries completely or, if this is not feasible, to recharge the batteries during cycling.

6.1 Technological Design

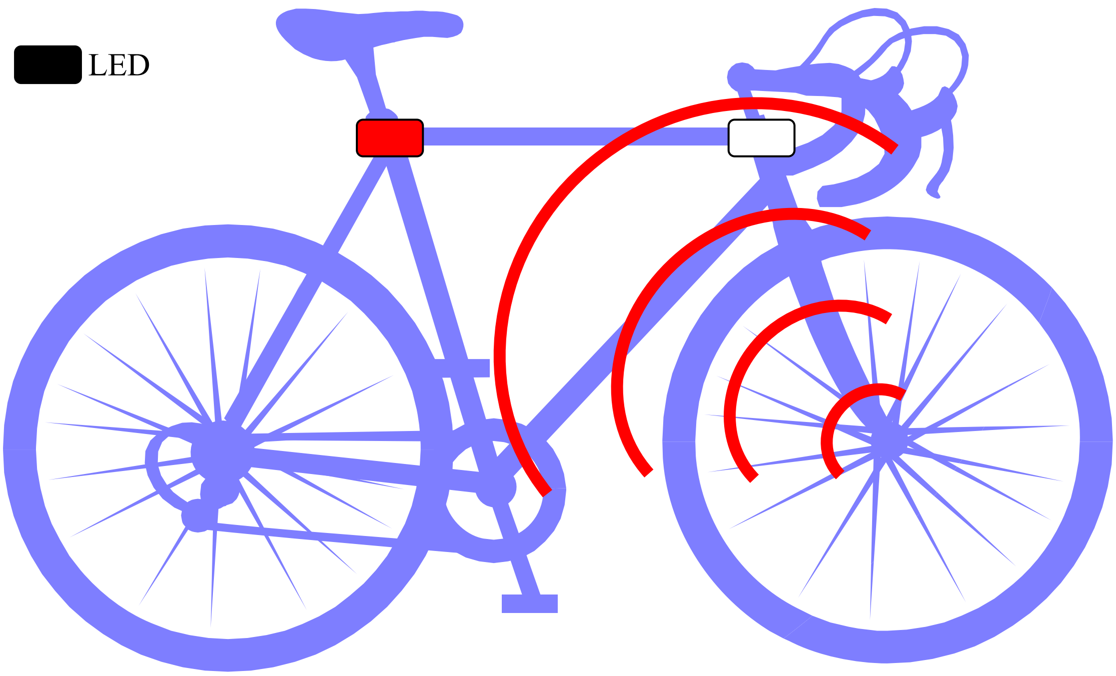

Figure 15: Wireless bicycle lights setup.

The LED front and back lights will contain a circuit that can deliver power to the LED lights by converting radio waves sent by the transmitter that is powered by a hub-dynamo to DC power, by means of a rectenna. A hub dynamo is a small electrical generator built into the hub of a bicycle wheel and is therefore permanently mounted on the bicycle. The dynamo is used in the same way as it would be used for wired bicycle lighting, only now the hub-dynamo will power a 5.8 GHz transmitter. Reducing or eliminating battery consumption will result in less frequent changing of batteries and thus add to the user-friendliness of this application.

The main question is: Will it be possible to power LED bicycle lights wirelessly without the need for batteries? To answer this question first a calculation of the power requirement of a LED bicycle light has to be made. A typical LED has a power consumption of around 20mA at approximately 3V. These are typical values for blue and white LEDs[68].

In current LED bicycle lights 3 or 4 LEDs are used, so a total of 60-80mA will be needed. For a 3V circuit this is around 180-240mW of power consumption.

The maximum power output of the transmitter is dependant on the power output of the hub-dynamo. The maximum power output of a typical hub-dynamo is 3W[69]. This is the power that the transmitter can use.

The distance *r* from the transmitter to the front LED light is around 30cm. The surface of the transmitting antenna is assumed 5cm^2 and the surface of the receiving antenna is assumed to be 40cm^2, which is equal to the back surface of a standard LED bicycle light.

From the above the received power P_r can be calculated using the Friis transmission equation which gives the relation between the transmitted power P_t and the received power P_r:

$$P_r = \eta P_t \frac{A_{p,t} A_{p,r}}{4r^2\lambda^2}.$$

$$P_r = 0.83 \cdot \frac{3000 \cdot 0.004 \cdot 0.0005 \cdot \left(5.8 \cdot 10^9\right)^2}{4 \cdot 0.3^2 \cdot \left(3 \cdot 10^8\right)^2} = 5.17\text{mW}.$$

From the above equation for the received power P_r it can be seen that the 120-180mW of power that is needed to power the LED light cannot be achieved. Therefore it is not feasible to wirelessly power the LED bicycle lights without the need for batteries. With respect to powering the back lights the received power will even be lower, because the distance between the transmitter and receiver is larger. Also, the cyclist may interfere with the radio waves sent by the transmitter because he/she is in between the transmitter and receiver. This will probably further decrease the received power for the back light.

Because batteries are still needed, recharging the batteries while cycling and hereby increasing the time the LED lights can be used in between charging of the batteries is proposed. To make the application more attractive for recharging the backlight, a second hub dynamo and transmitter may be built into the rear axle of the bicycle.

Also to make this application more attractive, electronic devices such as mobile phones, mp3 players etc. could be fitted with a 5,8 GHz rectenna to allow wireless recharging.

6.2 Environmental analysis

Assuming the batteries will only be recharged while the LED light itself is being used an estimation of the ratio of the time the LED lights can be used with and without recharging T_r can be made

$$T_r = \frac{\text{Use without recharging}}{\text{Use with recharging}}.$$

When using rechargeable batteries and having a power use of 60mA and recharging with 1,72mA (5.17 mW / 3V) this will give:

$$T_r = \frac{60}{60 - 1.72} = 1.030.$$

So in this case one will see an increase of 3.0% of battery stamina. When using rechargeable batteries with a capacity of 2500mAh the time the LED lights can be used would be:

$$t = \frac{2500}{60} = 41.7 \text{ hours.}$$

An increase of 3.0% of this amount of time is almost negligible. When the lights are not on, for example during daytime, the batteries can also be recharged, increasing the time the LED lights can be used. However, for 1 hour use of the LED lights one has to cycle 34 hours to recharge the amount of power used. This also has no significant contribution to the battery stamina. Therefore it is safe to assume there are no environmental benefits to be gained with this application.

6.3 Health Hazards

For the wireless bicycle lights we can conduct an analysis of the SAR values similar to what was done for the Standby Saver in section 5.3. By assuming the average distance to the body to be 0.5 m and the distance to the nearest body part (the foot/leg) to be 0.3 m, with 3W input power, the whole-body and local SAR values are found to be 0.035 and 0.098. Since a biker will usually bike continuously for six minutes, this SAR value will not change when averaged over 6 minutes. Note that again, an isotropic source was assumed. This assumption is reasonable, because the beam will be directed from transmitter to the receiving bike light, so the user will probably not be in this beam, and certainly not in the center of it. Therefore, the SAR will probably be even lower. So also for this application, we can conclude that the SAR is perfectly within the limits.

6.4 Economic aspects

The only difference between the wireless lights and normal, dynamo powered bicycle lights is that hub dynamos are more expensive than normal dynamos and that there are extra costs of the rectennas and transmitter. There are no other benefits or disadvantages, apart from possible lower maintenance costs.

Compared to battery powered lights, which are used more and more, there are other considerations. The batteries have to be replaced or recharged. This costs money, though the recharging costs can be neglected, because of the low price of electricity from the grid compared to batteries[64]. Normally batteries powering the LED lights can last for several months[70] before needing to be replaced. The cost for batteries will probably not even exceed € 10 per year.

The economic aspects of the wireless lights will not be very important for consumers when deciding which type of light to use. But convenience will be an issue, if it is possible to eliminate the need for battery replacing.

7 Conclusions and Recommendations

7.1 Conclusions

A study has been done on new applications that could use wireless power supply. Out of nine possible applications, the two with the most potential were chosen after a selection phase in which criteria were used as a filter. These two applications are the standby saver and the wireless bicycle lights.

The standby saver could be possible using a frequency of 5.8 GHz, with pulses of 500 milliseconds at about 12 Watt input power. However, in practice the power requirement may be higher because of additional losses. One must keep in mind that the Standby Saver is not suitable for all electronics that have a standby mode, but only for ones with a remote control. Based on the SAR calculations, it can be concluded that this application is safe to use. Also the TV will become a little more expensive because of more materials that are used, but using the Standby Saver will save also a little money. Furthermore, implementing this technology in current electronic household devices is probably not possible since it requires the replacement of current circuitry, which is too expensive to be beneficial. The environmental aspects will be of more influence than the economic influence of buying a standby saver.

The bicycle lights cannot be powered wirelessly by a hub dynamo. They require too much power (120-180mW), which is more than the lights receive in our design. It is not feasible to power the lights of a bicycle wirelessly with this technology. Therefore batteries are still needed. Recharging the batteries while cycling and hereby increasing the time the LED lights can be used in between charging of the batteries is possible. However to use the lights for 1 hour one has to cycle 34 hours to recharge the amount of power used. The calculations of the SAR show that this application perfectly complies with the limits. The economic aspects of the wireless lights are not large and will not be very important for consumers when deciding which type of light to use.

Compared to the initial ideas that are mentioned in chapter 4, the bicycle lights do not seem feasible anymore. The standby saver is less economically feasible and sustainable because it saves less energy and money than might be expected at first glance and also the technical feasibility is less trivial than first expected. If new grades were to be given on the criteria, we would come up with the values in Table 3.

Table 3: Our asssesment of the grading of the applications by the criteria initially and at the end of the project.

	Standby before	*Standby after*	*BikeLight before*	*BikeLight after*
User-friendliness	8	8	8	6
Technical feasibility	8	7	8	5
Economical feasibility	9	8	9	6
Sustainability	9	8	9	6
Health	8	8	8	8
Total Points	**42**	**39**	**42**	**31**

Summarized, the standby saver looks like the most probable application of the two studied. The bicycle lights are very difficult to realize technologically, but have no other problems, e.g. health issues. There are also some difficulties with the standby saver, for example that it needs quite a lot of power in a short time, but these might be resolved.

7.2 Recommendations

We have the following recommendations for the Standby Saver:

- It might be possible to reduce the power that the relay needs to switch.
- A separate standby saver, placed between the plug and the wall can be used for existing devices. Devices like this already exist, but they still require standby power, only less than the TV itself.
- More research could be done on the conversion of a relatively long pulse of radio waves to a shorter electrical pulse.
- It is a good idea to try to build a prototype. If this is successful, we would recommend investing in this idea and, if possible, register patents.

For the bike lights, the following recommendations are made:

- The power received by the LED lights might be increased further by increasing the transmitting antenna gain.
- A second dynamo and transmitter can be put in the back wheel to power the back lights. Otherwise, it is impossible to get any significant power there.
- It is a good idea to find out if there exist even higher efficiency, lower power LEDs.
- Since we found out that the wireless bicycle lights are not feasible, we do not recommend investing in this application.

In general, we can state that energy transfer using radiowaves is most feasible for ultra-low power applications. Both our applications have difficulties getting enough power. We recommend looking at applications that use very little power, which can possibly use the background radiation that is always present, both natural radiation and, for instance, radiation from cell phones and wireless routers. Applications to think of are fire alarms and clocks.

Appendix A: Calculation of body dielectric properties

In Table 4, the average electric conductivity σ and relative permittivity ε_r for an average 70 kg male are calculated by taking a weighed average over all types of tissue.

Table 4: The average relative permittivity ε_r and conductivity σ of an average 70 kg male, at a frequency of 5.8 GHz[71].

Tissue	percentage of weight A (%)	σ (S/m)	σ*A	ε_r	ε_r*A
Skin	18	3.717	0.66906	35.114	6.32052
Muscle	41.7	4.9615	2.068946	48.485	20.21825
Bones	15.9	1.1544	0.18355	15.394	2.447646
Brains	2	4.9865	0.09973	44.004	0.88008
Liver	2.3	4.6417	0.106759	38.13	0.87699
Heart	0.5	5.8622	0.029311	48.949	0.244745
Lungs	0.7	2.077	0.014539	18.58	0.13006
Kidneys	0.4	5.8963	0.023585	46.753	0.187012
Spleen	0.2	5.6718	0.011344	46.942	0.093884
Blood	8	6.5057	0.520456	52.539	4.20312
Bowels	1.8	6.7459	0.121426	48.672	0.876096
Fat	8.5	0.29313	0.024916	4.9549	0.421167
Average (sum)	100		3.873621		36.89956

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