Laser Power Beaming: From Concept towards Application for a Wireless Energy Future

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Abstract

Wireless energy is the future, inductive charging, and laser power beaming (LPB) are the two main technologies for this. Although both these technologies offer exciting advancements LPB is of importance as it can help tackle the global challenge of climate change by offering an efficient route for power transfer with existing renewable energy sources. Furthermore, LPB offers effective solutions for disaster relief, the development of international energy super grids and for harnessing energy from space. This paper presents all the above, while also giving detail of how these technologies work, their applications, limitations, and ultimately, their importance. From reviewing literature this work shows that there has been a constant increase in efficiency of photovoltaic (PV) cells and power in lasers ever since their inventions. Thereby enabling LPB to be feasible now, and even more so in future. With the considerations of safety limitations, atmospheric absorption, and power it is found that the best laser for a LPB set up is a 1550nm semiconductor laser with an efficiency of 40%. Emitted onto an InP-based based PV cell at a 45% efficiency giving an overall system efficiency of 18%.

Acknowledgments

I would like to thank Prof Stephen Sweeney, my dissertation supervisor, for guiding me through my entire degree and this paper, without him none of this would not of been possible. He is a great professor and a brilliant man, and I have been honoured to accept his guidance over these years. I also want to say thank you to Dr Timothy Eales, another dissertation supervisor who helped me find the right sources and papers for this work. Of course, ultimately the University of Surrey and the physics department, it has truly been a privilege to be an undergraduate here for over four years now.

List of important papers

1. Jarvis, S., 2017. *Towards High Efficiency Photovoltaics For Applications In Laser Power Beaming*. PhD. University of Surrey. [1]

2. Helrich, C., 2012. *The Classical Theory Of Fields-Electromagnetism*. 1st ed. Berlin: Springer, pp.3-15. [2]

3. Jarvis, S., Mukherjee, J., Perren, M. and Sweeney, S., 2013. *On The Fundamental Efficiency Limits Of Photovoltaic Converters For Optical Power Transfer Applications*. Undergraduate. University of Surrey. [3]

4. Arya, M., Lee, N. and Pellegrino, S., 2016. Ultralight Structures for Space Solar Power Satellites. In: *3rd AIAA Spacecraft Structures Conference*. Pasadena: California Institute of Technology. [4]

Nomenclature

LPB	Laser Power Based
PV	Photovoltaic
LIA	Laser Institute of America
BSI	British Standards Institute
UN	United Nations
EU	European Union
EMF	Electro Motive Force
AC	Alternating Current
DC	Direct Current
MPB	Microwave Power Beaming
NRL	Naval Research Laboratory
UAV	Unmanned aerial vehicles
SBSP	Space-based solar power
NASA	National Aeronautics and Space Administration
LPC	Laser Power Converter
NREL	National Renewable Energy Laboratory
MJ	Multi-junction
MPE	Maximum Permissible Exposure
LPC	Laser Power Converter

Contents

1. INTRODUCTION

Electrical power has become essential for societies, as technology advances and the global population rises, so does the demand for electrical power. The increasing demand for energy is contributing to climate change so renewable energy must be used to prevent further harm. Renewable energy however faces major challenges, being volatile, unreliable and often unable to match demand in real time. Additionally, the demand for energy means costly, dangerous and invasive power lines stretch to every corner of humanity. There are several possible solutions for these major global problems, one of them is Laser Power Beaming (LPB). This is a newly emerging technology which uses lasers to beam energy through the air as light and onto a Photovoltaic (PV) cell which transforms that light energy into electrical energy. The major benefits to this are its potential long-range energy transfer without the traditional costs and pollution of electric infrastructure. LPB can help disaster struck areas without power, it can lead the way to powering the Earth from space using the sun. This technology is evidently important, but not without its rivals for the wireless energy world. Inductive charging is a promising technique which uses the electromagnetic field to also transfer energy through the air, though it does not have the range of LPB, it does have its own useful applications. So LPB is positioned to help revolutionise power transfer across the planet, just as the internet revolutionised communication, making the phone line obsolete. Developing LPB has been challenging particularly due to the efficiency of lasers and PV cells. However, since their inception both PV cells and lasers have been increasing in efficiency and are now ready to take on this challenge. Reviewing a large range of literature sources, such as S. Jarvis's '*Towards High Efficiency Photovoltaics For Applications In Laser Power Beaming'* [50] and C. Helrich's '*The Classical Theory Of Fields-Electromagnetism'* [23] it will be shown LPB is now feasible and well positioned to tackle the issue of energy demand. The concepts, limitations, considerations to make LPB a reality will be discussed in addition to finding the most efficient lasers and PV cells for the task.

1.1 The Importance of Laser Power Beaming

The Basic Set up

Laser power beaming (LBP) transfers power wirelessly through the air using the electromagnetic spectrum. The laser turns electric energy into light energy, beams it great distances due to its power and coherent light into a Photovoltaic (PV) cell which then does the reverse, turning the light energy into electrical energy. The great advantage is the great distances this technology can send energy with no infrastructure in-between. A simple set up of this LPB system is shown below in Fig.1.

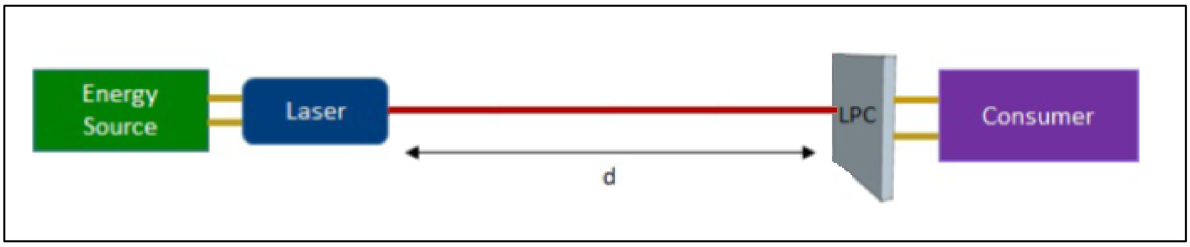


Figure 1: Diagram showing the basic set up of a laser beam powered system, yellow lines representing standard traditional power lines, and the red line the laser transmitting the power over a distance d onto the Laser Power Converter (LPC) [1].

1.1.1 Essential for Renewable Energy

The Problem

Renewable energy (biomass, solar, hydro, wind, tidal, geothermal, and more) is an amazing feat of mankind and is the future of the world's energy needs. This clean, cheap source of energy is becoming more popular with countries steering to the direction of being powered by 100% renewable sources, '75 countries pledged to deliver 2050 net zero emissions strategy by 2020' (2019 UN Report) [5]. The Kyoto agreement (1997) and the Paris agreement (2016) show countries are committed to tackling climate change demonstrating the important future of renewable energy [6].

The main issue currently facing renewable energy (solar and wind being main ones at present [7]) is that it can be unreliable and highly variable. The electric grid relies on a steady stream of power to be able to increase/decrease rapidly depending on demand.

This issue is evident with solar energy for example which peaks its energy performance at mid-day due to the position of the sun. This takes a massive demand of energy off the grid, as it is now being supplied by the solar panels, and hence the other energy sources are not needed, this dip in power demand is seen in Fig.2. As the sun goes down solar energy starts to produce less energy until It is producing none at all, this is when the alternative power sources have to be turned on or ramped up to take the load the solar energy is no longer taking. This is also the point of the day when electric power is at its highest demand due to more people being home using electric. This creates a massively increased ramp in energy demand over a short space in time, causing heavy loads and stress on the power grid, this peak in demand can be seen on the right of Fig.2. Together these two extremes cause steep change in power demand, and it is referred to as the 'duck curve' [8] as seen in Fig.2.

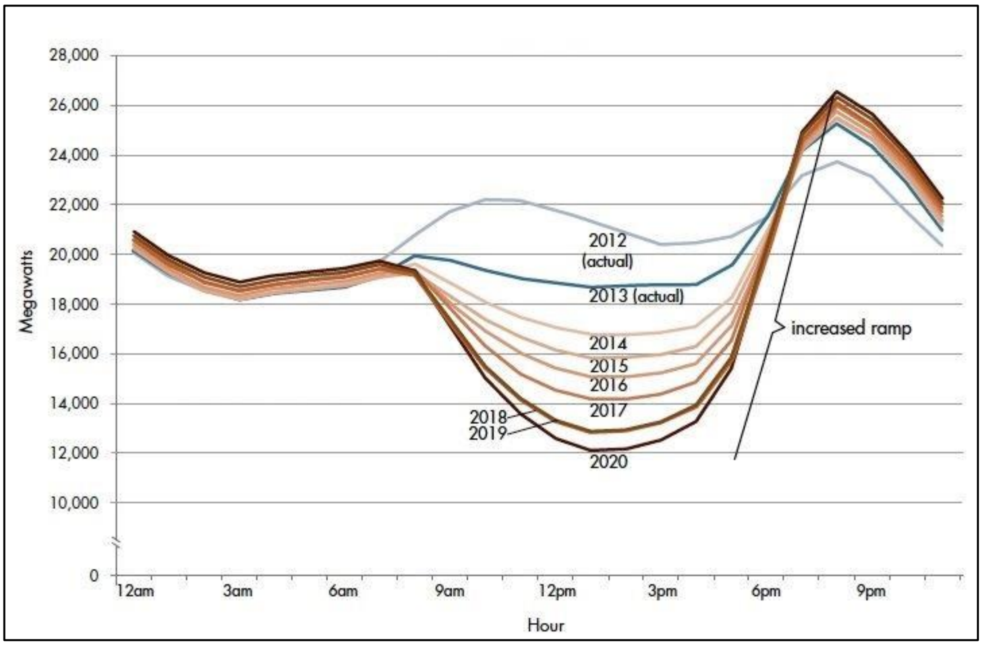


Figure 2: Diagram showing the demand of energy in megawatts over 24 hours in California, USA. The 'duck curve' is visible with a clear afternoon dip and increased ramp in the evening. Data is shown over eight years, with the duck curve becoming increasingly pronounced each year [8].

The rapidly alternating demand and stress on the power grid is not the only current issue with renewable energy, more specifically solar energy. At midday, there is too much power supply due to the solar panels, this would overload the electric grid if left alone, hence something must be done to stop the overload. Currently the best solution is temporarily turning the solar panels off, and this leads to a lot of energy being wasted. California is a great example of this issue and due to this very problem, incurred a record high curtailment of 223,195 megawatt-hours (MWh) in one month (May 2019) [9].

Various Solutions

There are three possible solutions to this, the current one in practise is using non-renewable energy sources (e.g. nuclear, natural gas, coal or oil). However, non-renewable sources present issues, many contribute to climate change, an increased cost as renewable energy is cheaper, furthermore these sources are only economic when constantly running [10]. It is not feasible to turn these power plants off and on when needed [10], there are 'Peaker plants' designed to combat this issue but they too are unsustainable for the same reasons.

A clear solution is energy storage; but this technology is not developed enough to meet the demands as such it is not feasible nor efficient to store energy on a large scale in industrial batteries. Currently lithium ion batteries are the leading technology and are unsuitable for long-term storage and gradually lose charge with time. Lithium ion batteries are expensive for large scales and possess other problems such as space, fire hazards and environmental impacts.

There are many other energy storage methods being worked on from many different companies such as pumped-hydro [11], Energy Faults new gravity-based system [12], thermal [13], and other forms of chemical storage like flow batteries [14]. These again suffer with efficiency, space, and cost issues. Even if an efficient storage system was found another challenge is that a surplus of energy would then be required; enough to store for the dark winter months for example. Therefore, more energy sources would be needed to create this surplus, requiring more costs and more space.

The third solution is electric grid interconnectivity between states and countries, transporting power to where it is needed, when it is needed. Power could be used as it is produced, no need for storage, no need for 'Peaker plants' or non-renewable sources during down periods. Essentially this creates an international market where countries can trade energy instantaneously. For example, a dark cloudy day in a solar rich Spain could be powered by a windy day in Denmark, and vice versa if conditions were different. Imagining this on an international scale, mankind's power needs could me met entirely by the sun, with one side of the earth during the day powering the other side during its night period. Though a more efficient and versatile method would be to diversify the source of renewable energies such as using all types: solar, wind, hydro and more. California's curtailment of energy (mentioned above) could be solved by this interconnectivity at a fraction of the price compared to the other possible solutions on offer. As the American Public Power Association admits it as a strong solution, the 'creation of a regional grid that would tie California's wholesale electric market with others in the Western United States' [9].

This interconnectivity does exist in many places around the globe, using the traditional method of transporting electric with power lines. An example of this is the European super grid [15], the largest connected electricity grid in the world, seen below in full detail in Fig.3. This image gives a sense of the scale of the infrastructure involved in transporting this power, showing Europe covered in and endless stream of power lines.

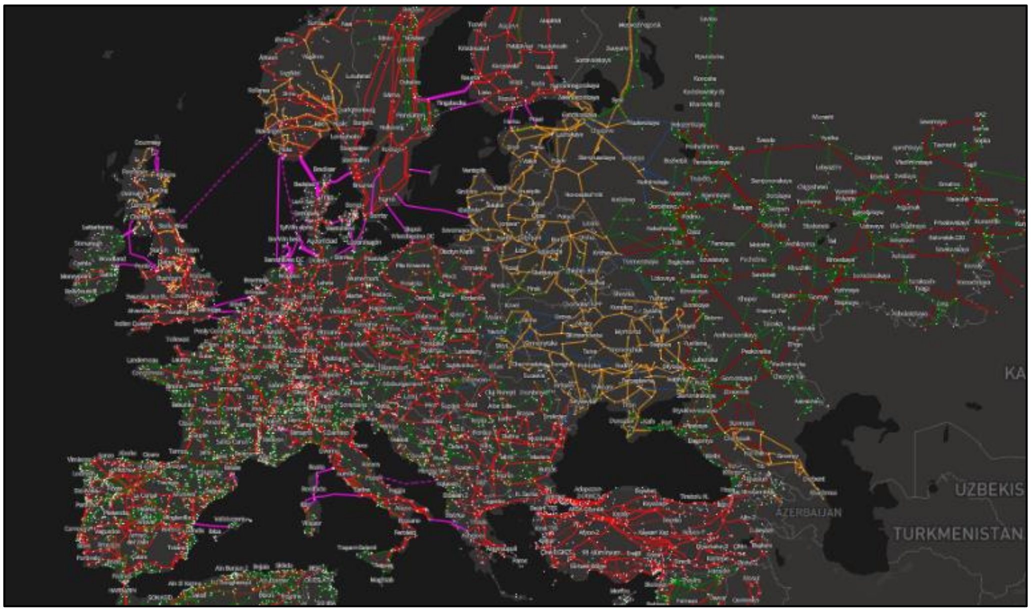


Figure 3: Diagram of the European super grid, an electric grid connecting all of Europe. This shows all national and international connections/powerlines. The bright pink lines are the international lines. Note that many more lines have been built and are in the process of being built, this data is only correct up to 01/01/2019 [16].

As renewable energy increases so too is this interconnectivity 'the European Union (EU) has set an interconnection target of at least 10% by 2020… and… 15% interconnectivity by 2030' [17]. Meaning member states/countries will have at least 10% of their total generated power connected to the grid. Countries and states will then be able to invest more money in renewable energy [17], without encountering issues such as those experienced by California.

While interconnectivity is the best solution so far, it is expensive and requires a lot of infrastructure [18]. Power demand is increasing with each passing year due to population increase and technological advancements, with a heavier reliance on power. Meaning these expensive timely projects installing infrastructure is not a permanent fix and will need upgrading at some point with more lines, bigger, and more powerful, costing more money and using more space. One power line alone is costing a total of €1 Billion, connecting Ireland and France directly for the first time, called the 'Celtic interconnector' [18], as seen in Fig.4 below. This line will have a capacity of 700MW, powering 450,000 homes, this is a major step for Ireland. Europe is set to benefit from this and the EU is committed to this strategy investing €530 million of the above total cost [18]. This is because interconnectivity as described above is a prosperous solution for all states/countries involved for many reasons, and is truly the future, many more lines like the 'Celtic interconnector' are currently under construction or being planned.

Figure 4: Diagram of the European super grid, connecting various European countries electric grids with traditional means such as wires. The red lines representing the connections, while the yellow line represents the 'Celtic Interconnector' currently still under construction [16].

The Solution: Laser Power Beaming

The important 'super grid' has massive costs, huge infrastructure, with time and distance constraints on connections, this could all be eased by LPB. In place of these power lines would be laser power beams, invisible to the human eye, with the environment unmarked by its presence. This system could transmit power from any country to another with no intermediary. Currently if Spain wants to trade energy with Denmark it must first go through countries like France, losing power via transmission. LPB could cut out these massive costs, massive infrastructure projects and increase the speed and accessibility of this power. Ultimately LPB has the potential to revolutionise this entire industry for the good. Without it, renewable energy will hit a ceiling and countries will be unable to realistically change to 100% renewable energy.

1.1.2 Essential in Disaster Relief and Remote Locations

'Natural disasters kill on average 60,000 people per year, globally' (2019) [19]. Many deaths occur after the disaster has struck during relief efforts. These areas are normally cut off from power for weeks; electric grids destroyed, power lines down with no rapid way to get it fixed. This is a major problem when even a few days without power will cost money and more importantly lives. The twenty-four hours after a disaster has struck are the most important for saving lives, so power arriving weeks later is not ideal. Power is needed for surgeries, search equipment, pumping machines, communication, and simply lighting and heating. The current solution are band aids for a bullet wound, such as portable generators able to power a building or two, but themselves needing a source of energy such as natural gas or fuel.

A laser power beam from a satellite could be sent to an offshore ship/platform which could then be sent directly to a portable station dropped into a disaster scene, an example of this is shown below in Fig.5. Powering crucial facilities with no need for roads, or electric grids or any infrastructure, all things missing and damaged in this environment. This could give immediate power to those who need it most at the most crucial time, transforming disaster relief around the globe.

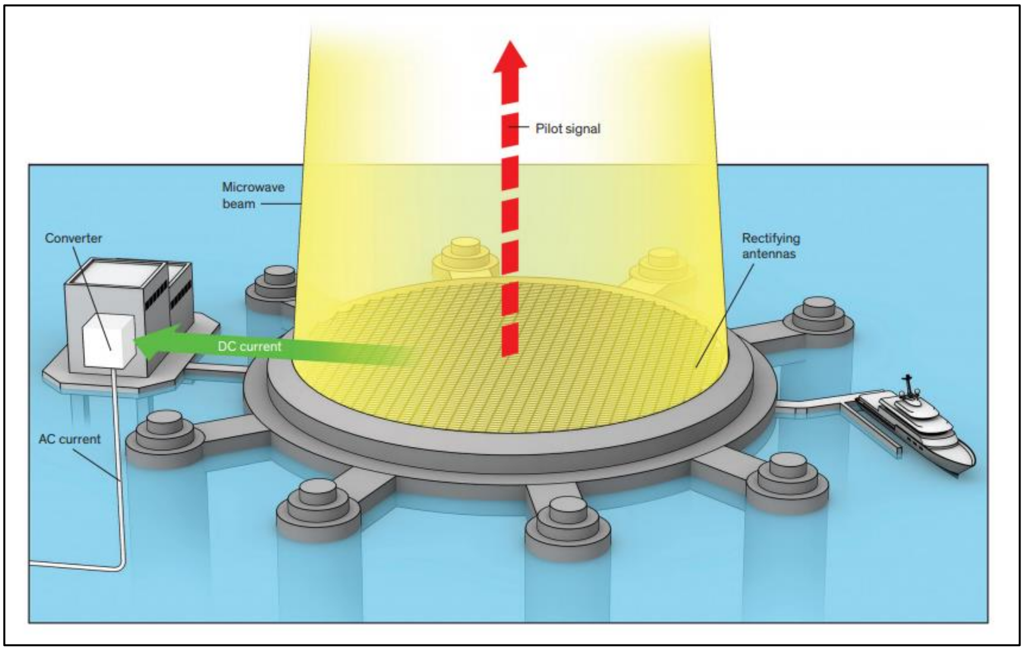


Figure 5: A diagram showing a potential portable platform which could receive laser power from space, enabling disaster areas to receive energy rapidly [20].

In disaster areas transport is a massive issue, road condition is a big obstacle, either impassable due to flooding, or destroyed by hurricanes or earthquakes. However, these obstacles can be overcome or passed around, the real problem with transport is fuel. This is due to local fuel stations being damaged either their underground tanks damaged by earthquakes, or their pumps flooded, or torn apart by hurricanes. Forcing relief efforts to bring their own fuel, a costly, timely and hazardous protocol. Electric vehicles could be used to get around this, however the inductive charging (described below) would not be possible, since that requires infrastructure with recharge points, which would be damaged along with the rest of the infrastructure. Laser power beamed vehicles, powered from satellites, drones, ships would solve this issue, enabling relief efforts so much more flexibility.

This same concept could be used for transporting power to remote villages in the third world, bringing cheap easily accessible energy to areas that would otherwise be impossible to access with power.

1.1.3 Energy From space

Laser power beaming from drones, ships, or satellites, as mentioned, is possible and has been researched now since 1971 [21]. There are many possibilities for this concept, but the most plausible method would be to get the energy as directly as possible since any conversions or distances incurs more inefficiencies and losses in energy. For example, in a disaster relief scenario the energy is collected in space, enabling it to land anywhere on the planet at any time directly from its source. The planets receiver could be a ship, or a plane designed to either reflect the beam to smaller portable platforms dropped around the disaster zone or transform the laser beam directly into electric. The plane could be landed, and the ship docked enabling it access to those in need of the power. This power could be further divided to drones powering smaller systems such as cars, lighting systems, or simply communication systems.

Although a laser beam could be powered by anything, a leading idea is having solar panels in space collecting the sun's energy, without the sunlight being lost through the earth's atmosphere and no night time would result in a constant highly efficient power source, an example of this can be seen below in Fig.6. Many companies and countries have already put money into researching this concept, China is aiming to have 'a solar farm in space by 2025' [22]. Japan has been researching since 2014 to put 'several giant solar collectors in geosynchronous orbit…beaming microwaves down to the island from 36 000 km above Earth' [20]. While America has taken strides in absorbing power in space and transmitting the energy with laser beams [4]. So, this seemingly science fiction concept, is becoming reality 'beaming solar power from space to Earth is becoming practical' [23].

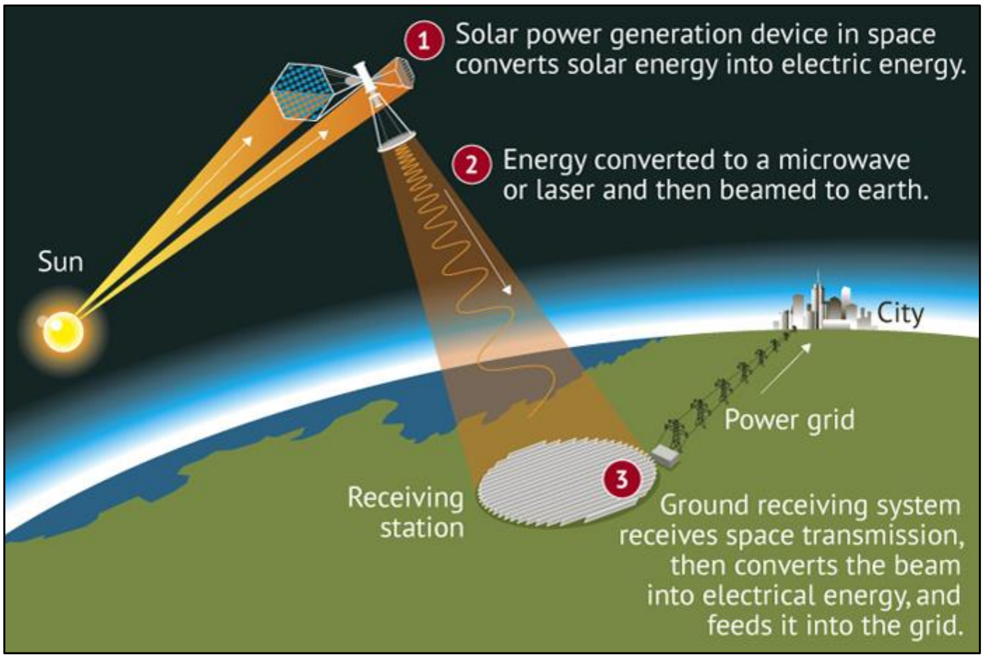


Figure 6: A diagram of a potential set up for a space based solar farm sending the suns energy down to earth via a laser or microwave [22].

This concept is not solely for the use of disaster and remote areas, as population increases, more land is needed for crops, cities, and transport etc. While solar power is a great source of energy, it does take up vital space, this above concept could solve this, having solar farms powering entire cites and countries. Only the receiving pads taking up space on the ground as represented in Fig.6 above.

1.2 Wireless Power Technologies

There are currently two main categories of wireless power transfer:

-Non-radiative methods – Using electromagnetism, and Faradays law of induction.

-Radiative methods – Using the entire electromagnetic spectrum.

To take the latter first, which is the main category of this paper, these radiative methods use lasers to transfer energy using light, received on photovoltaic (PV) cells and/or solar panels, changing it into electrical energy. Under this category is also radio frequency and microwave charging which while different to laser beaming with their own limitations, the concept of using the electromagnetic spectrum to transfer energy is still employed.

First, the former will be the focus: non-radiative methods, where an induced magnetic field is used to transfer energy wirelessly using a transmitter and a receiver. This version of wireless power has its limits, mostly in distance, but still has some promising possibilities as it will be shown.

1.2.1 Non-Radiative Methods

There is one main type of non-radiative wireless power transfer, and that is inductive charging, using the electromagnetic field. There are subcategories that derive from this technology such as capacitive charging, and resonant induction charging with their own benefits, but they are all methods that require close proximity to the power source, and hence have a disadvantage against radiative methods of power transfer. Capacitive charging with its 'simplicity, and small size makes it a very attractive solution for efficient charging' [24]. Resonant induction charging is used in electric toothbrushes with a high efficiency; however its simultaneous frequencies for can cause heat build-up in small high powered devices so for such things as mobiles this method is avoided. The main, most popular, and promising and therefore the focus in this section is inductive charging.

Inductive Charging

Inductive charging is the use of Faradays law of induction to charge such devices as mobile phones and cars. Companies such as WiTricity, and Solace Power have produced products for these purposes and the Wireless Power Consortium was founded to promote such technology (2008). Though this technology seems relatively new, the physics of it have been known and understood since Faradays discovery in 1831 [2]. Slightly before this discovery it was observed by Ørsted in 1820 that a changing electric current causes a magnetic field [2]. Faraday took it further and discovered the reverse is also true "A changing magnetic field will induce an EMF in a loop of wire" (EMF: Electro Motive Force) [2]. Batteries can be charged using this latter discovery, with no connection between the power source and the battery, so how is this possible and how does it work.

The Physics

Inductive charging is a fascinating use of the pure nature of physics, as mentioned above, an electric field causes a magnetic field and vice versa. This is why it is called the electromagnetic field; one field propagates the other. This simple innate characteristic of the universe is used to humans' advantage with the generators, transformers, rotating disk hard drives, and for inductive charging.

An alternating current (AC) is passed through a coil of wire, this creates a magnetic field as discovered by Ørsted in 1820 [2]. The direction of this magnetic field can be determined using Fleming's 'right hand rule' [59]. As seen in Fig.7 the AC is coming from L1 and L2, the red coil connected to these loads on the left is a wire of conducting material, normally made from copper. This is called the inductor or a transmission coil. The blue lines show this above induced magnetic field, and every time the AC changes direction so too does the magnetic field, further along it will be seen why this is important.

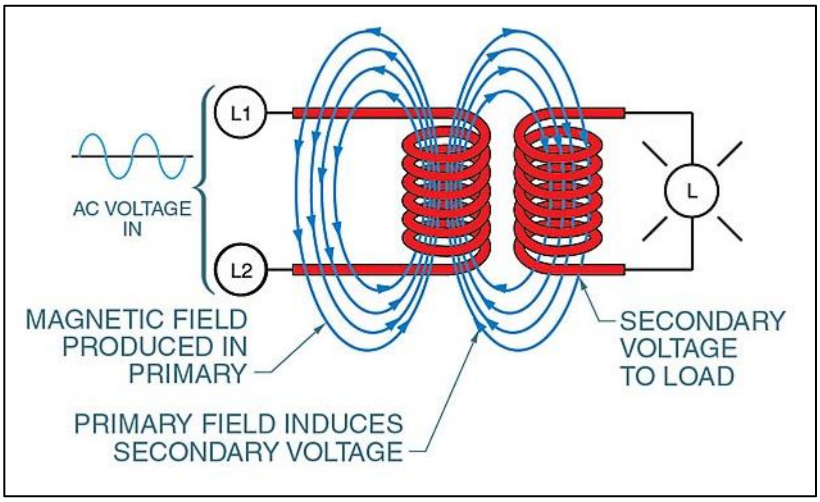


Figure 7: Diagram of electromagnetic induction, a primary coil (L1, L2) inducing an EMF in a secondary coil (L) [25].

The strength of this magnetic field running through the coil, its Magnetic flux (Φ_B), is determined by the following Eq.1 [2]. It shows that its strength can be changed by changing the magnetic field(B), changing the size of the coils (A), and changing the angle between the magnetic field and a line perpendicular to the face of the loop (θ).

$$\Phi_B = BA\cos(\theta) \tag{1}$$

This magnetic field propagates outside of the original coil as seen in Fig.7. If a secondary coil is put within this field an EMF will be induced inside it due to the changing magnetic field, as discovered by Faraday in 1831 [2]. The direction of this induced EMF is determined by Lenz's law (1834) [2], however, effectively it will be an AC, and once put through a rectifier the Direct Current (DC) can be used to power or charge anything connected to it, as indicated by (L) in Fig.7.

The strength of this induced EMF in the secondary coil ($\mathcal{E}$) is determined using Eq.2 [2] below, known as the Faraday-Lenz equation [2]. The negative sign is Lenz's contribution, and is important because it shows how the induced EMF will travel in the opposite direction of the magnetic field [2].

$$\mathcal{E} = -N\,\frac{\Delta\Phi_B}{\Delta t} \tag{2}$$

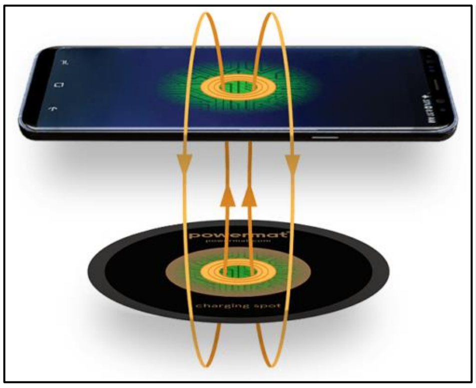
Here it can be seen why the above Eq.1 is important because the change in magnetic flux ($\Delta\Phi_B$), is a main factor in determining the strength of the EMF. Other factors as seen are the number of loops (N), and change in time (Δt).

EMF is what causes electrons to move and to form current, so the strength of the EMF directly corresponds to the amount of power transferred. These above equations (4,5) are generalized forms and would need adapting for real world non ideal situations, but the basic concept is that power can be transferred wirelessly and the above factors are what determine that power. So how is this currently put to good use, and what are its advantages and disadvantages.

Applications

In the real world the left side of Fig.7 is essentially the charging pad, and the right side is the receiver device installed in such things as mobiles or cars. The distance between these two devices can vary, and it is important to note that due to the power being transferred via the magnetic field any substance can be in between them. Meaning this power transfer can work through plastic, concrete, and many other useful substances, it will seen in the next section how this is an advantage over LPB.

Below in Fig.8 and Fig.9 these examples of this above set up can be seen, in both examples the primary coil (Inductor) is on the bottom, while the secondary coil (receiver) is on top in the mobile and in the car.



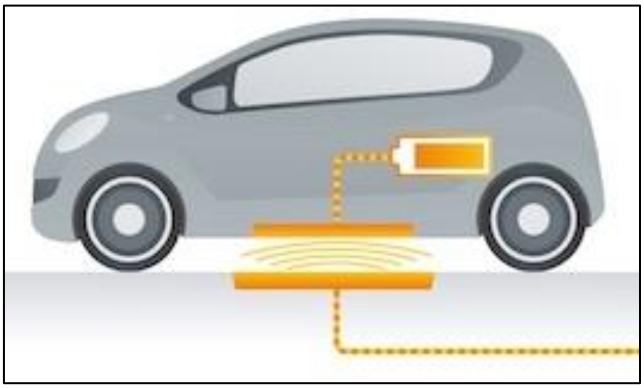


Figure 8: (Left) Diagram of an inductive charging pad for a mobile phone, showing the magnetic field transmitting power from the primary coil to the receiver in the mobile [26].

Figure 9: (Right) Diagram of inductive charging for a car, showing magnetic field transferring the energy wirelessly to charge the car battery [27].

Its Possibilities and Limitations

As discussed above a good advantage to inductive charging is its ability to transfer energy through almost any substance, this gives it a variety of uses not possible in LPB. Such as aquatic applications, where water is heavily involved, inductive charging is the answer to a safe and efficient usage of electric. A laser in this area would be dangerous and/or ineffective due to reflection and diffraction. Another positive is modern convenience, these sorts of chargers can be installed under roads to charge cars, in desks to charge mobiles, giving users less interaction and hence more convenience.

A drawback is the limitation of size, as it was shown above in Eq.1 and 2 the power transmitted depends on the physical size of the device. This means for increased power demand the transmitting inductor size must increase. This is where LPB has an edge, since more powerful lasers does not necessarily mean larger lasers, and in a world of ever-increasing power demands this could become a ceiling for inductive charging. Another major limitation is the distance, the transmitter and receiver have to be very close to each other for efficient functioning, whereas LPB has a much larger distance that it can cover.

The car industry with electric cars is where inductive charging will make its biggest impact, not only is it becoming cheaper to run electric cars, but they are more environmentally friendly making them widely popular. This inductive charging technology makes these cars even cheaper and more convenient. One of the main issues currently with electric cars is the ‘range anxiety’, consumers are worried about the lack of charging stations, and not being able to travel a long distance without worrying where the next charge station is [28]. Inductive charging can be laid into roads, charging the vehicle as it travels, solving this fear.

There is a downside to this though; stress to the electric grid, an issue that perhaps LPB and inductive charging could work together to solve. As adding an electric car to the grid is the equivalent of adding another home, meaning more and bigger power lines. In a world where space is becoming increasingly rare while power demand raises this is an exponentially increasing problem. One that will be potentially solved with LPB, less infrastructure on transporting power, while increasing power supply. In this way technologies like inductive charging and power laser beaming can and should work together in the future.

1.2.2 Radiative Methods

Laser Power Beaming

There is a mixture of applications for this type of power transfer such as: Unmanned aerial vehicles (UAV), electric cars, tether propulsion, Space-based solar power (SBSP), charging mobiles, and transferring energy. All items on this list have been successfully worked on to varying efficiencies, and much more work and money is being put into them currently. Several companies and institutions that are invested in this method are: PowerLight Technologies, LakeDiamond, University of Saskatchewan, America's Naval Research Laboratory (NRL), Lockheed Martin, NASA, helping confirm the promising future of LPB.

Why the Laser is Essential to Power Transfer?

Lasers have found many applications; surgery, astronomy, cosmetics, printers, toys, scanners, weapons, cutting and welding, fibre optics, DNA sequencing and many more. However, this paper focuses on the use of lasers for power transfer. The attractiveness of lasers for power transfer is made possible due to these numerous applications, driving down costs whilst increasing power and efficiency.

Lasers have many properties that are advantageous for power transfer, firstly light is monochromatic therefore a receiving PV cell can be specifically tuned. If the cell is tuned to the correct wavelength of the laser, the efficiency will increase because there is no loss of unused wavelengths to such things as heat. Lasers also have minimal beam divergence, therefore light emitted has a high chance of reaching its intended target PV cell, again increasing efficiency.

The Origin of the Laser

The credit for the creation of the laser, an acronym for Light Amplification by Stimulated Emission of Radiation, is a controversial topic [29]. However, the most widely accepted person awarded this honour is Charles Townes, an American physicist who shared the 1964 Nobel Prize in Physics for his contribution to the creation of the laser [30]. Townes' contribution was his paper on 'Infrared and Optical Masers' in 1958 [31], a maser using the same principle as a laser but with lower frequency microwave radiation. From Townes' work on masers the first working laser could later be produced in 1960 by Maiman [32].

It was Einstein who first realised the physics of the laser in his 1917 paper [33], showing how and why stimulated emission works using quantum physics. However, it was never shown that he saw the possible application of the amplification of light ‘Einstein did not foresee amplification but understood the quantum mechanics mechanisms’ Townes (2009) [34].

The Advantage of a Laser

Sources of light such as the sun or an incandescent light bulb emit wavelengths from across the electromagnetic spectrum, and in all directions. Three main factors separate lasers from light sources such as these. Firstly, the emitted light from a laser is monochromatic, i.e. at a single wavelength, this is due to photons and their quantized packets of energy, described in detail below in ‘Step 2’. This was made possible by Einstein’s explanation of the quantization of light in his Nobel prize winning 1905 paper [35]. Additionally, the second factor is that the monochromatic light that is emitted will be in phase. The in-phase nature of this radiation was first discovered and explained beautifully by Einstein’s 1917 paper [33] which is explained below ‘Step 3’. Finally, the third factor is the light beam originates from a point source. The combination of these factors results in a powerful coherent light beam with minimal beam divergence and scattering. This desirable combination of properties has led to much research and development with lasers becoming increasingly more powerful, efficient, and cheaper.

How a Laser Works

There are many different types of laser: semiconductor, gas, free electron, solid state and chemical. However, the focus of this work is the semiconductor laser, due to it currently being the most efficient and most powerful, so the principle of laser operation here is discussed in relation to this laser type. How a laser works is summarised below:

<u>Step 1 (Pumping- Excitation)</u>

A power source such as a battery passes electric current through a chamber with two mirrors where an element or molecule is present. This electrical power excites the atoms inside, elevating electrons from the ground state to an excited state.

<u>Step 2 (Spontaneous Emission)</u>

The excited electron will then fall to its ground state after a period of time, releasing a photon of light. This photon of light will be at a certain wavelength corresponding to the energy level difference between the excited and ground states of the electron, as seen below (Electrons and Photons in the PV cell) with Eq.3 and Eq.4 [7,8,9]. This energy level difference and hence the wavelength of the photon is determined by many factors but mainly is dependent on the choice of element in the chamber. For lasing it is important that the same element is used in this chamber and hence the same wavelength is emitted from all the excited atoms. This period of time mentioned above that the electron can spend at an excited state could theoretically be infinite, this is due to a quantum physical effect (explained below) and it is the reason that the following stimulated emission is needed.

Step 3 (Stimulated Emission)

Einstein showed that a photon passing an atom with an electron in its excited state will induce the electron to fall back to its ground state and release a second photon [33]. Not only this but the photon will be in phase with the same direction and polarization of the original photon, this is due to a quantum physical effect, all brilliantly discovered and explained by Einstein [33]. These last three essenetial steps are clearly shown in Fig.10 below.

The basics of this quantum effect falls mentioned above belongs to the simple fact that a photon relative to another photon can be in two positions, in the same state, or in a different state. There are two different ways they can be in the same state, and only one way in which it can be in different states. Hence there becomes a 66% chance they will be in the same state compared to a 33% they will not be. Hence it is probabilistic that the former will occur. Hence a photon gets emitted in symmetry with the original photon [33].

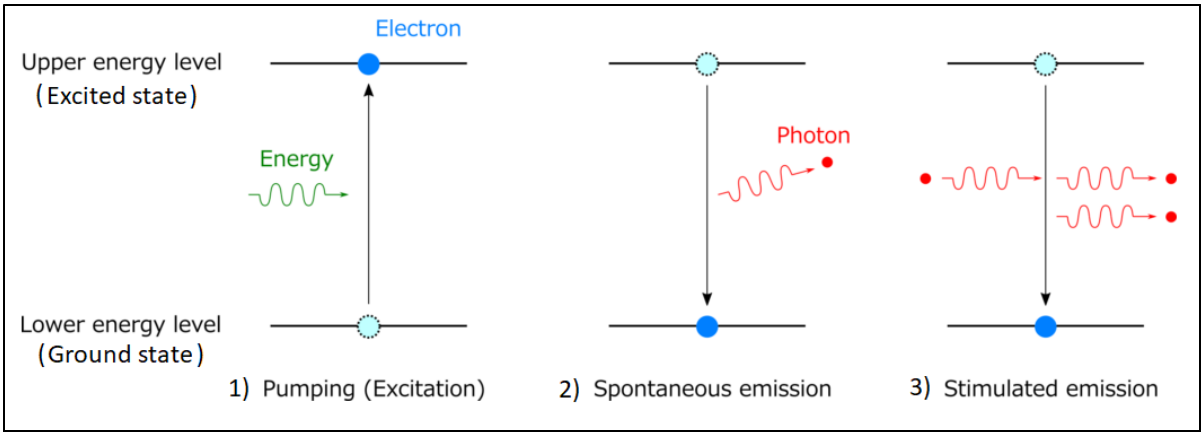


Figure 10: Diagram representing the three steps (explained in text) of the general workings of a laser, demonstrating one cycle of one photon in a laser cavity [36].

Step 4 (Chain Reaction)

This above stimulated emission can then stimulate other atoms into emitting more photons, creating a chain reaction of photon emission. In a laser this occurs with a coherent beam continually reflecting off the two mirrors within a cavity, causing the beam to increase in intensity as this chain reaction takes place. Once the beam has reached a desired intensity it escapes through a small gap in the mirrored walls.

Photovoltaic Cells

What is a Photovoltaic Cell and a Solar Panel?

The terms photovoltaic cell and solar panel are often misused or used interchangeably. Specifically, a Photovoltaic (PV) cell is the basis of any device which transfers light energy (photons) into electrical energy (moving electrons). This can be achieved with any form of light, either from the sun 150 billion meters away or from a laser 15 meters away. PV cells are typically too small to produce enough electricity for realistic needs. Therefore, many PV cells are combined in a circuit to create a solar panel. Then for further conversion to electricity, separate solar panels are then combined to create a PV system, as seen in Fig.*11*.

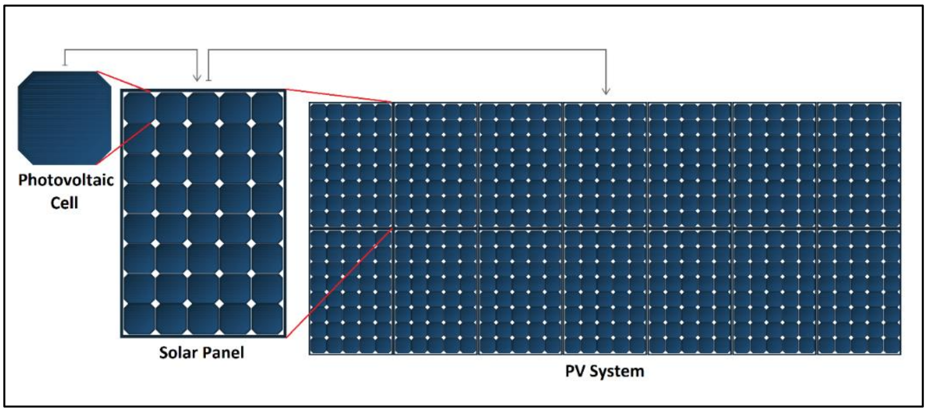


Figure 11*: Diagram showing how a photovoltaic system consists of combined solar panels that are in turn comprised of many photovoltaic cells [37].*

If a PV system is used to harness energy from the sun it is referred to as a solar array. However, when harnessing energy from lasers it is referred to as a PV array. As any form of light can be used and PV cells can be scaled to arrays, light intensity is not a factor that prevents this transfer of energy and hence distance although an obstacle can be overcome. This along with the very small divergence of light with LPB, shows that power beaming although currently limited by funding and technology, has endless scope in what can be achieved with power transfer from light incident on a PV cell.

Electrons and Photons in the PV Cell

Electrons have specific energy levels [38], when hit by a photon of the correct corresponding wavelength the electron will be raised to an excited energy level [35]. Using the Bohr model [35] and

Rydberg's formula [39] in Eq.3 below, the correct wavelength, λ, of a photon to raise an electron's energy level can be determined

$$\frac{1}{\lambda} = R_H\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right). \tag{3}$$

Where, the Rydberg constant is R_H, the initial and final energy levels of the electron are then the integer values n_i and n_f respectively. Using Einstein's theory of quantized packets of energy in photons in Eq.4 [35] below the energy of the photon, E, can be found,

$$E = \frac{hc}{\lambda}, \tag{4}$$

where, h is Planck's constant and c is the speed of light. The above equations show how the wavelength required to excite an electron of a particular element from the valence to conduction band is found.

How a Photovoltaic Cell Works "The Photovoltaic Effect"

As an overview, any light incident light on a PV cell will excite electrons in the PV cell material, typically silicon [40]. Excited electrons move freely and if in a circuit a potential difference is created resulting in a current. This current can then be used to charge batteries or transported for use elsewhere. This process is broken down in greater detail below, beginning with the transition from photon to electron.

The Absorption of the Photon

When a photon hits an atom, it can excite an electron into a higher energy state, from there three main things are possible. Although all three are important, only one is utilised in PV cells:

1. The excited electron can fall back down to its ground state, releasing a photon; this is the process used in lasers as explained above 'How a Laser Work'.

2. The energy from the photon can increase the electron to such a high energy state that it is considered emitted and detached from the atom, this is known as the photoelectric effect [35].

3. The atom being excited in a substance of similar atoms and thus the excited electron is detached from its atom as above in (2) but is not emitted from the substance. Instead the electron is raised to

its conduction band and shared with the rest of the atoms in that substance, creating a sea of electrons freely moving.

It is this last process 3 which is utilized in PV cells, this process occurs in both metals and semiconductors. Whereas process 2 occurs in only metals, this is due to the overlapping conduction band with the valence band, seen in Fig.12, this emitted electron would be wasted energy not usable in an electric circuit. This is why semiconductors are used over metals, possessing an ideal band gap size.

The Band Gap

A band gap is the amount of energy needed to increase an electron out of its valence band (ground state) and into its conduction band (excited state). If this is too small then process (2) will happen and electrons are lost [35], as seen below in Fig.12 these are metals. If it is too big then either nothing will happen, except for heat transfer and perhaps process (1). Heat transfer can damage the PV cell so this is avoided as much as possible; such substances are known as insulators. For a PV cell a semiconductor where the band gap is the correct size to allow process (3) to occur is desired.

It may be thought that metal in this case would be the most optimum material due to the electrons being easily excited, however as mentioned, if excited too high then they will be emitted from the substance. Therefore, only a small amount of energy maybe given to a metal, a rooftop amount of energy that can be absorbed while still being useful. A challenge is that a PV cells purpose is to produce electrical energy so if the material were metal there would only be a small amount of energy that could be harnessed. Hence, a semiconductor material is used with a band gap high enough to produce energy but not too large that photons from a laser or the sun cannot breach it. An interesting note however is research is being carried out on metal PV cells [41], with iron, one of the cheapest metals out there and fourth most abundant element in the earth's crust behind silicon of course [42].

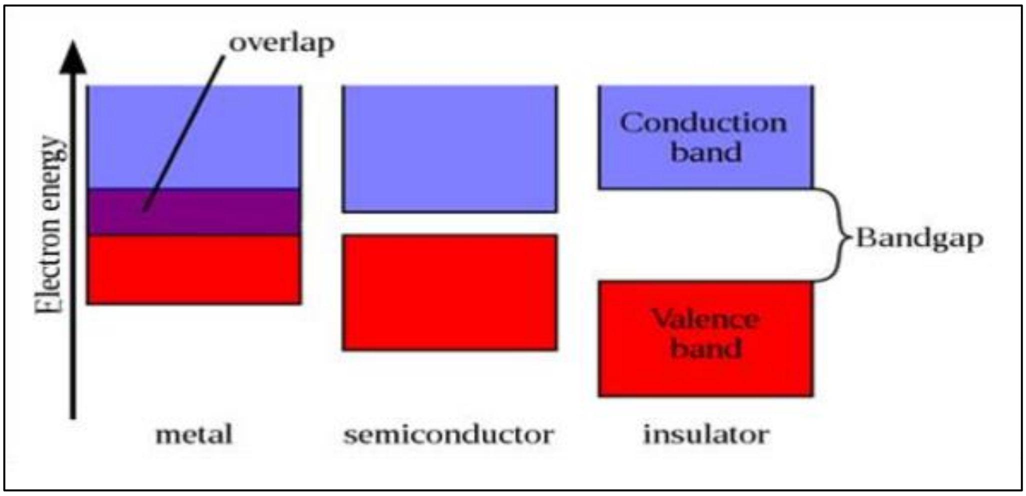


Figure 12: Diagram showing the bandgap size in different materials; metals, semiconductors, and insulators [43].

Why Silicon

Silicon is widely used as a semiconductor and is used in most PV cells; '90% of the global PV market' (2018) [40]. The major driver for silicon's popularity is cost and availability, 'Silicon makes up 27.7% of the Earth's crust by mass and is the second most abundant element' [45] (Royal Academy of Chemistry). It is found in nature as Silicon Dioxide(SiO_2), and is very easily extracted from sand using a simple process, as shown below in Eq.5 [44].

$$SiO_2 + 2C \rightarrow Si + 2CO \qquad (5)$$

There are some draw backs to silicon however, it is an 'indirect band gap semiconductor meaning that it is less optically efficient than a direct band gap semiconductor such as GaAs or InP' [1]. Also, Silicon has a band gap of 1.1eV (Electron Volts). This means that it can only absorb light with a wavelength less than ~1100nm. For a 'transmission system at 1550nm, you must use something else, e.g. an InP-based alloy known as InGaAsP' (Indium gallium arsenide phosphide) [1] [3].

These semi-conductors with their ideally sized band gaps are found in metalloids, in-between metals and non-metals as seen below in Fig.13. Silicon is one of only eight known metalloids, and of these, it is the cheapest, and can operate under a wide range of temperatures and is also easily doped, making it a great element to be used for PV cells.

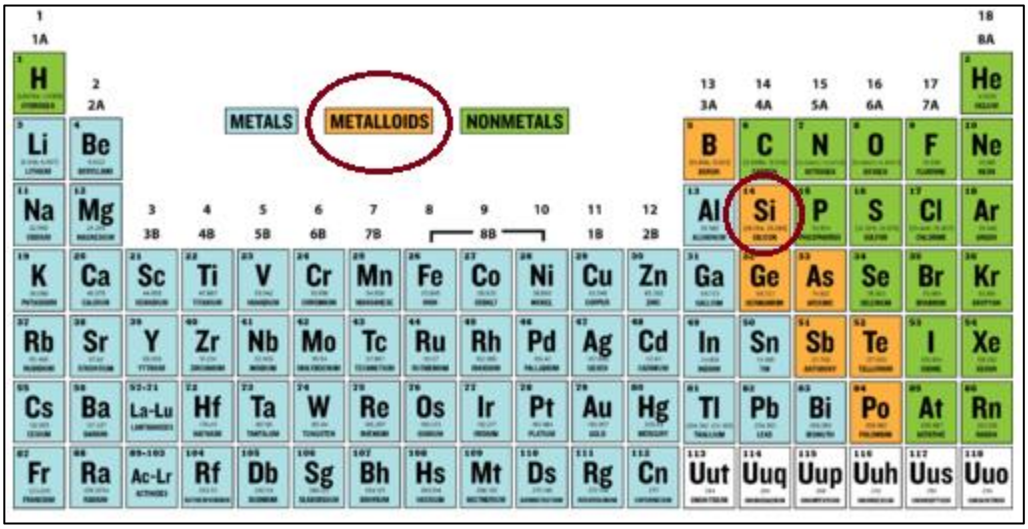


Figure 13: Picture of the periodic table, emphasizing the metals, to metalloids, to non-metals to help show why silicon is used in PV cells [46].

The reason silicon's ability to be doped is important is because, in its pure form it is an insulator. Silicon has four electrons all covalently bonded in a tetrahedral structure, making it difficult to have any free moving electrons in the conduction band, unless heated. So, to be able to take advantage of silicon's attributes it must be doped with other elements.

Doping

Doping is a complicated process with many different names assigned to the different stages and types of material, for PV cells the key point is that of electron availability. Silicon can be doped in two different ways; with an excess, or depleted number of electrons. The former is done by adding an element with spare electrons in its outer shell, this is referred to as N-type due to its net negative effect in the newly doped silicon. The latter creates a net positive effect and is classed as the P-type. This is done by adding elements with gaps in their valence band, essentially searching for electrons, these gaps are referred to as holes.

Once doped, electrons in N-type silicon exist that can be elevated to the conduction band, equally in the P-type there are holes that exist with the converse effect. Individually these types of silicon are not of benefit. But combining these two oppositely doped materials into what is known as a P-N junction, permits the flow of electrons creating a current. The importance of P-N junction cannot be overstated. It is the basic component in one of the greatest inventions of the 20th century [47], the transistor, and it is used in batteries, lasers, and most importantly here, in PV cells.

The P and N Type Doped Silicon

Doping silicon with an element that has more free electrons, such as phosphorus and sulphur, results in N-type silicon. In Fig.1*4* it can be seen why these two above elements are used, as they are immediately to the right of silicon, indicating extra electron(s) in their valence shell.

Elements further along the table such as chlorine or down the table such as arsenic, however are not used despite their increased number of spare electrons. Arsenic is a much larger atom, hence making a larger material, which means the electrons have further to travel, reducing efficiency. Elements such as chlorine are not used due to excessively large bandgaps.

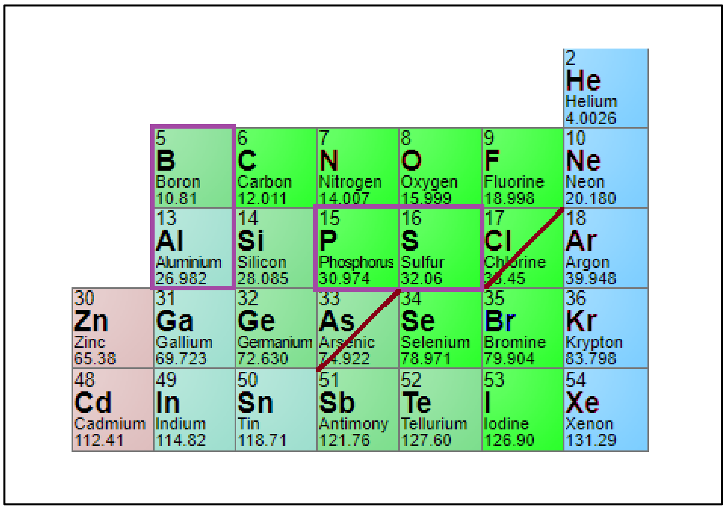


Figure 14: Picture of top right side of periodic table, showing the elements used for N and P types to help show the reason for their use over other elements [48].

The P-type is silicon doped with elements lacking in an electron in their outer shell. They are called holes since they represent a place waiting to be filled by a spare electron. These elements as seen on the periodic table, Fig.14 above, are aluminium and boron. Boron is the more preferred element mainly due to its smaller size, smaller the size the less distance an excited electron has to travel, hence a more efficient material is produced.

The P-N Junction

At first glance, this process seems simple, but like inductors as explained above, the created electric field creates a magnetic field which then interferes with the original electric field. Combining the N- and P-type silicon creates the N-P junction, where the spare electrons in the N-type are drawn to the P-type holes. This creates a temporary flow of electrons, from the N-type to the P-type side, as seen below on the left side of Fig.15. This creates a charge difference and hence and electric field between the two regions, with the N-type now having a slightly positive charge due to its migrated electrons and the P-type a slightly negative charge, as seen below on the right side of Fig.15. This creates a depletion zone between these two charges where there are no holes, and no free electrons, acting as a barrier to any further electrical conductivity.

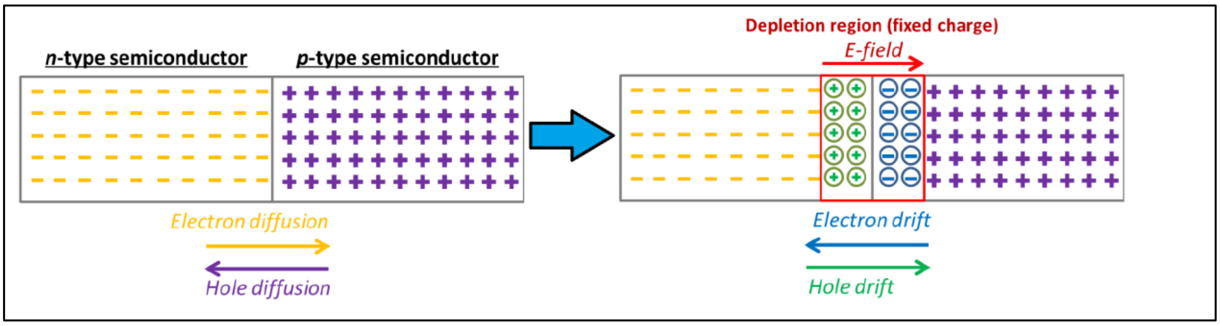


Figure 15: Diagram showing the P-N Junction with its directional charges, then creating an opposite charge with a depletion region [49].

Left alone this state would remain and nothing else would happen, however if enough energy is supplied to this depletion region to excite the electrons into their conduction band then these holes and electrons would separate from each other. At this point the electric field described above and shown on the right side of Fig.15 will now come direct these newly freed (delocalized) electrons towards the N-type region and the holes towards the P-type region. With a continuous stream of energy into the depletion region this flow will continue until there is a very large concentration of electrons in the N-type and holes in the P-type. This creates a potential difference between the two regions and by connecting to a circuit the electrons can flow through it towards the P-type region and their holes as shown in Fig.16 below.

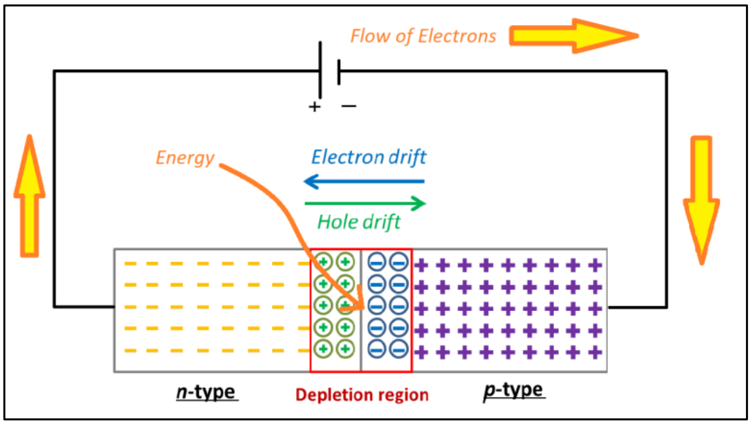


Figure 16: Diagram of the P-N Junction, with energy reaching the depletion region and creating a flow of electrons around the circuit [49] (note that it is the direction of electron flow that is illustrated and not conventional current which flows in the opposite direction from positive to negative).

This flow of electrons around the circuit is called direct current and power can be drawn from this circuit for many uses. In the case of PV cells, the energy hitting the depletion region is photons of light from either the sun or a laser. To make this system more efficient the N-type layer which is the top layer of a PV cell is made thinner than the P-type layer on the bottom, this allows for more light to get through to the depletion region. As mentioned, some photons with too much energy will be absorbed by this top layer before reaching the depletion region so it is important to optimise its size. Due to this size difference, the N-type layer is much more heavily doped then the P-type. This helps increase the depletion region which is beneficial as a this gives a larger area for the energy from photons to be used.

1.2.3 Optical Fibres

Optical fibre cables can be used to transmit energy via laser beams, just as in the air, with the only difference being the medium being travelled through is now glass. As seen in Fig.17 the energy source could be anything from nuclear power to solar energy, the power is then transferred via electric cables to the laser. The laser then shoots the beam of light through a fibre optic cable until it reaches a laser power converter (LPC), also known as a PV cell. This PV cell then transforms the light energy into electrical energy which is then transferred to the consumer.

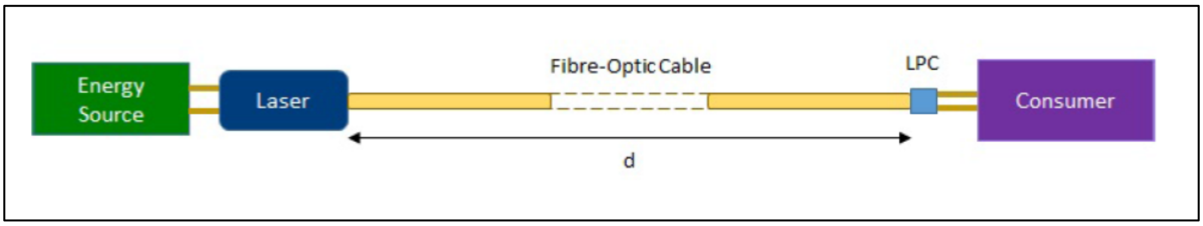


Figure 17: Diagram showing basic set up of a fibre optic power delivery system, small dark yellow lines showing traditional electric wires, main middle yellow line representing optical cable over a distance d going to the Laser Power Converter (LPC) [1].

A fibre optic power delivery system has benefits over free air LPB and conventional electrical wires:

- It is safer than electrical cables with no chance of electrocution and reduced risk of fire hazards.

- The power will be traveling at the speed of light, much faster than traditional electric traveling speed.

- Less limitations to power density and a wider range of wavelength options as there is no potential damaging exposure to organisms. However due to absorption by the cable itself and stimulated Brillouin scattering and stimulated Raman scattering there are some limitations as to the most efficient wavelength to use (850, 1064, 1310 and 1550nm) [1].

2. System Considerations

2.1 Efficiencies and Limitations

The efficiencies in all parts of the LPB system, both in the laser, the PV cell, and the transmitting beam are important. They all need to be considered and calculated to gain and overall efficiency for the system. This will help show the real applicable feasibility of this technology, as it will be shown, the efficiencies of both laser and PV cell have been rising steadily since their invention with no sign of slowing.

2.1.1 Lasers and their Efficiencies

There are many different types of lasers using different wavelengths with different efficiencies: chemical, solar pumped, free electron, gas, but two top types are solid state, and semiconductor lasers due to their power and efficiency levels. In Table.1 examples of the best performing lasers in each of these categories can be seen for comparison.

Table 1: Representing data of most efficient lasers categorised to their types, where nm is nanometres and W is watts (2017) [1].

	Wavelengths produced (nm)	Efficiency (%)	Output Power (W)
Gas	10,600	30	<10
Free-electron	1,600	2	14
Solid-state	914, 1064, 1342	25	<10
Semi-conductor	780-1064	40	40
Solar-pumped	976	10	4

Even though semiconductor lasers are the current leading type, this may not be the case in the future, as solar pumps have the potential to become more efficient overall, this is due to an energy conversion step missing. As discussed above, each energy conversion step will incur an energy drop due to innate inefficiencies in the system. When using a solar pumped laser, the energy comes straight from the sun into the PV cells and straight to powering the laser.

Table 2: Representing data of most efficient solid-state lasers [1].

Wavelength (nm)	Output Power (kW)	Efficiency (%)
974	6	>40
1070	100	>40
1550	2	>18
1940	0.2	>10

Above in Table.2 is data on the best performing solid state lasers, with a massively high efficiency of 40%, with increasing wavelength the efficiency drops. Semiconductor (Diode) lasers have an even higher efficiency rating as seen below in Table.3, again the same trend is seen, that with increasing wavelength the efficiency rating decreases. Using this data it can be seen that overall efficiency of the laser has been increasing since its creation in 1960 [32].

Table 3: Representing data of most efficient semiconductor lasers [1].

Wavelength (nm)	Output Power (kW)	Efficiency (%)
796	1	45
808	0.3	43
915-970	40	>47
1064	0.2	45
1310	0.25	>37
1470	0.25	>30
1550	0.25	>25
1650	0.75	>18

Another important factor is the power of the laser, as seen in Fig.18 below the power of laser has been increasing at a steady incline since 1985. With both these values, efficiency and power constantly increasing LPB only becomes more feasible with each passing year.

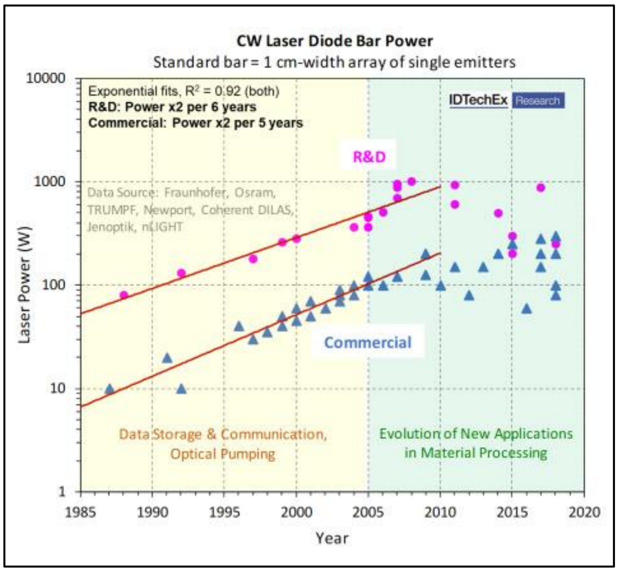


Figure 18: A graph showing laser power over time from 1985 (2020) [50].

2.1.2 PV Cells and their Efficiencies

When a solar panel is receiving light from the sun, it is receiving all wavelengths from the electromagnetic spectrum. The solar panel however cannot efficiently absorb at all wavelengths and will have a peak performance at a particular wavelength, with a lower limit and upper limit for what it can absorb. This means that the other unused wavelengths of light will be wasted through reflection or heat absorption, this heat also lowers the performance and efficiency of a solar panel. This lower limit of photon energy is due to its energy not being enough to be able to pass the bandgap. The upper limit is due to the photons being absorbed in the top layers of the PV cell before they can reach the necessary section: the 'depletion zone'.

Above in 'Electrons and Photons' Eq.3 and 2 help show us PV cells can be made to be highly efficient if both laser and PV cell are set to corresponding energy levels, unlike sunlight. Thereby, waste is minimised and a major increase in efficiency is possible, making LPB an attractive prospect. However, in future multi-junction (MJ) solar cells that are currently in development may increase the efficiency of solar panels too. MJ solar cells integrate different types of PV materials such as silicon and perovskite to capture more wavelengths of the incoming sunlight [51]. Work has been done in the labs gaining an efficiency of 28% [52] (2018).

This is why the above physics in 'Electrons and Photons' is important, because it can be used to determine the exact wavelength leaving a laser and the optimum band gap energy of the PV cell. 'It is well known that a photovoltaic cell demonstrates maximum optical to electrical conversion efficiency when illuminated by monochromatic light at a wavelength close to the absorbing material's band-gap energy' [3]. This way there will be a minimised waste and a major increase in efficiency, making LPB much more feasible in the most important terms: Efficiency.

For this reason PV cells tuned to the specific laser will be more efficient than generic solar cells. However Multi-junction (MJ) solar cells are being worked on and have the potential to change this status in the future, recently (April, 2020) the world record was broken for most efficient solar cell at 39.2% by a team at the national renewable energy laboratory (NREL) [53]. This is a major increase from 28% gained in the labs only two years ago (2018) [52]. These were both achieved using MJ cells, which integrate different types of PV materials such as silicon and perovskite to capture more wavelengths of the incoming sunlight [51]. This high efficiency is only currently in the laboratory, and the solar panels on sale to the public have efficiencies varying from 15%-23% [53], as seen below in Fig.19.

	Make	Headquarters	Manufacture	Eff%**	Warranty*
1	LG	Sth Korea	Sth Korea, USA	21.7%	25 yr
2	Sunpower	USA	USA, Mexico, China, Philippines	22.6%	25 yr
3	REC	Norway	Singapore	21.7%	20 yr
4	Solaria	USA	USA	20.5%	25 yr
5	Panasonic	Japan	Japan	19.7%	25 yr
6	Silfab	Canada	USA, Canada	19.4%	25 yr
7	Qcells	Sth Korea	Sth Korea, China, USA	20.1%	25 yr
8	Winaico	Taiwan	Taiwan	19.4%	25 yr
9	JinkoSolar	China	China, USA	20.4%	12 yr
10	Trina Solar	China	China, Vietnam	20.5%	12 yr
11	Canadian Solar	China	China, Vietnam	20.3%	12 yr
12	LONGi Solar	China	China	20.6%	12 yr

Figure 19: A table showing top PV cell efficiencies in the global public market (2020) [53].

This same team at NREL also broke the record for highest efficiency under a concentrated source of sunlight (143 suns concentration) at 47.1% [53]. This helps demonstrate using a concentrated source of light is beneficial and the efficiency can be raised using these lasers.

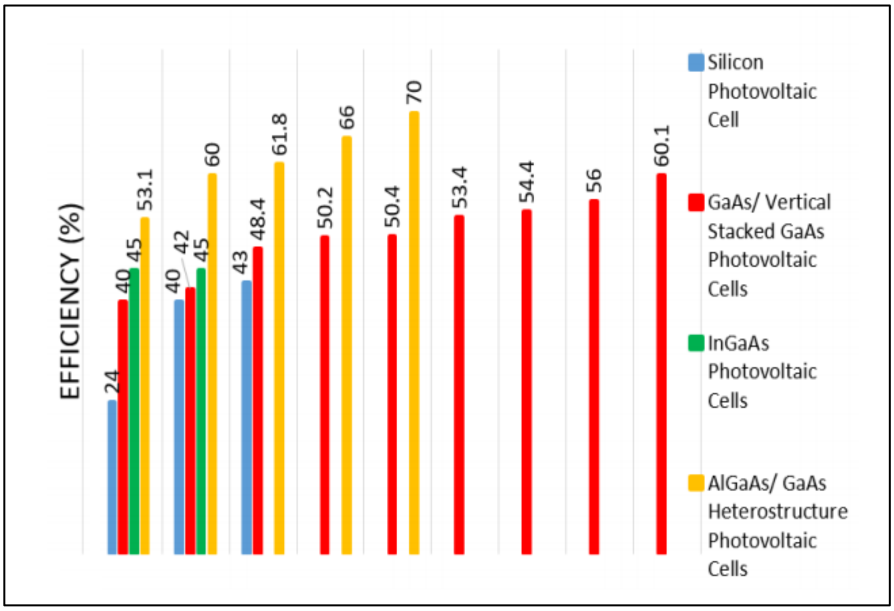


Figure 20: A graph showing different types of PV cells efficiencies (2020) [54].

Different PV cells have different efficiencies, above in Fig.20 this is demonstrated nicely, over all 'Typical photovoltaic receivers for LPB are about 45% efficient' [55]. Below in Fig.21 it can be seen that all types of PV cells have continued to increase in efficiency since their creation. This overall upward trend has not ceased in over 40 years, a great sign for the use of PV cells.

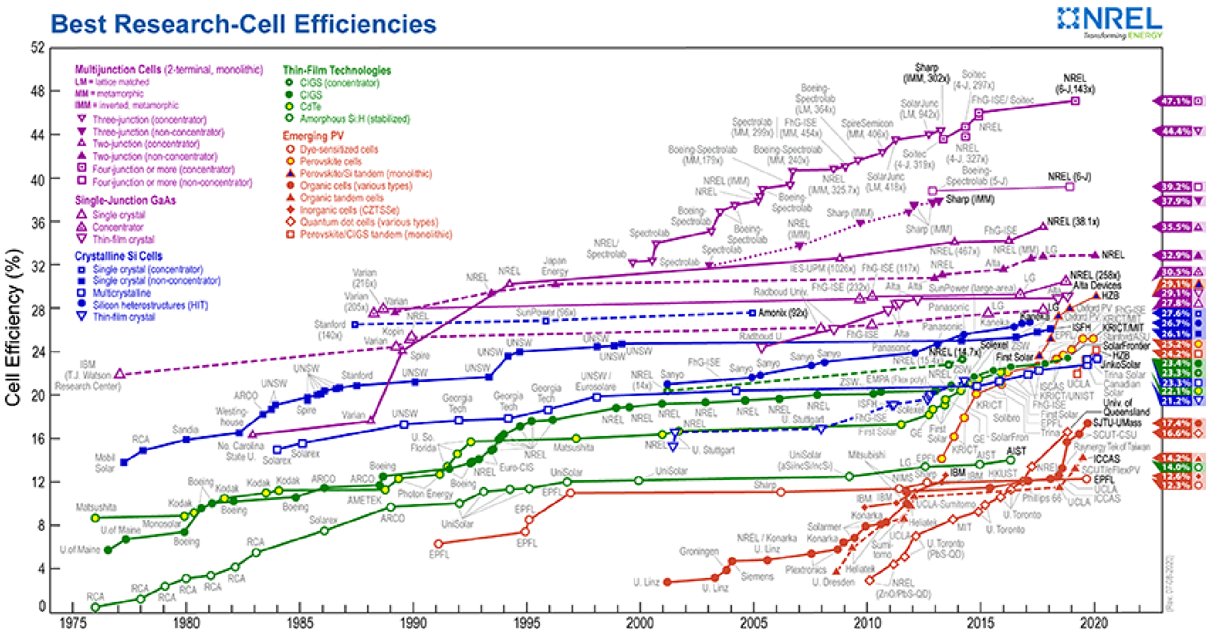


Figure 21: A table showing top PV cell efficiencies in the global public market from 1975 to present (2020) [53].

2.1.3 Safety Limitations

Lasers are powerful beams of energy, and therefore can harm organisms such as animals, plants and humans, for this reason, safety precautions must be considered. Controlling their intensity and wavelength is one such precaution, the Laser Institute of America (LIA) has set out guidelines for the purpose of 'laser safety worldwide' [56]. Among many other guidelines set down by the British Standards Institute (BSI) and the LIA they give a Maximum Permissible Exposure (MPE) for human skin and eyes under the 2005. *ANSI Z136 Standards [56]*. This is how much light intensity eyes and skin can absorb before causing biological damage.

The Skin

An example of how these limitations for skin can be viewed can be seen in Fig.22 below, the graph shows how between the wavelengths of 0.4 - 1.05µm the allowed surface irradiance is 2.5 - 10 kW/m^2, and between 1.05 – 1.40µm only 10 kW/m^2 is allowed, and wavelengths above 1.40µm can only be 0.1 kW/m^2.

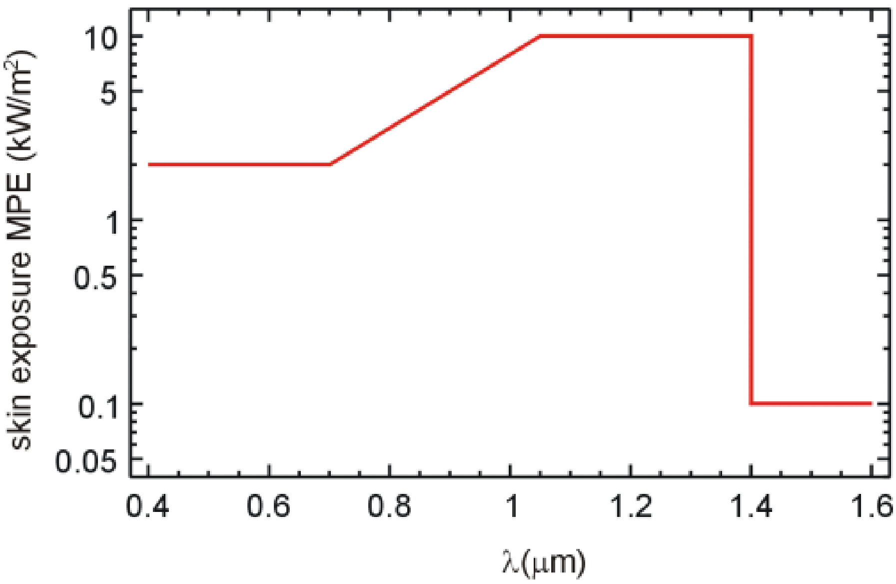


Figure 22: Graph showing the Maximum Permissible Exposure (MPE) of skin to optical illumination, in kilowatts per metre squared ($\boldsymbol{kW/m^2}$) the wavelength(λ) with a unit of micrometre(µm) [57].

The Eyes

A more complicated limitations is for eye exposure as seen below in Fig.23. For a human eye 'one blink lasts about 1/3 s' [58], the speed of light is $3x10^8$m/s which means in the time it takes a person to blink light will travel $1x10^8$m. Meaning between the point in time a laser hits a humans eyeball and the point they react by closing their eye lid a lot of light will pass. This means that any laser being used must have a wavelength and intensity safe for your eyes to observe.

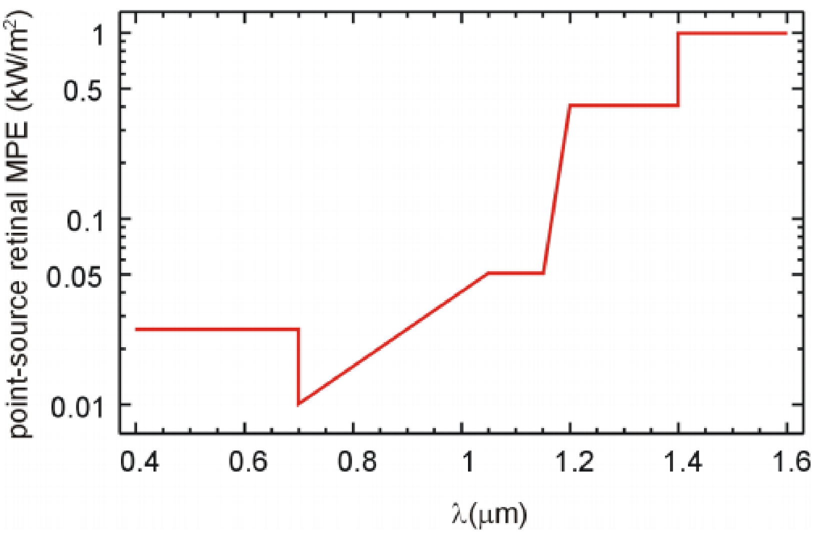


Figure 23: Graph showing the Maximum Permissible Exposure (MPE) of eye radiation from a single point source, in kilowatts per metre squared $(\boldsymbol{kW/m^2})$ *the wavelength(λ) with a unit of micrometre(μm) [57].*

The Solutions

This limits LPB greatly as only certain wavelengths can be used, this results in less powerful energy beaming, increasingly inefficiencies with a myriad of other issues. There are several solutions to this, such as using optical fibres, or Fresnel lens [1], the former being self-explanatory in that a laser beam encased inside a fibre optic cable will not be in danger of exposure to any surface. The latter is quite a simple solution, pictured in Fig.24 below the laser source directs many beams outward at different angles but all towards a Fresnel lens.

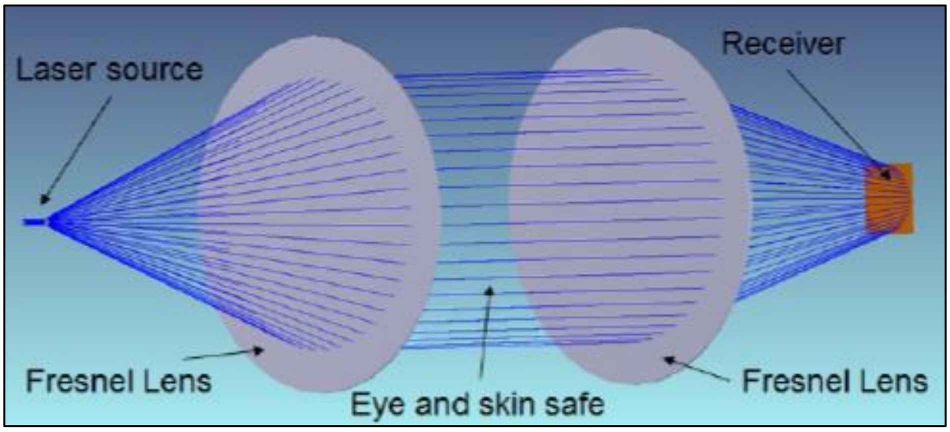


Figure 24: Diagram of a representation of what a possible laser power beaming system could look like, using a Fresnel lens to make transmitting laser beams safe for skin and eye contact [1].

This lens then collimates the laser beams, sending them to another Fresnel lens which then redirects all the beams to a single receiver. This way a large power transfer can occur via one laser, without ever having one single beam with a high enough intensity able to damage or harm any organism. The only danger would be at the lasers source and receiver, so the main distance covered, in between the Fresnel lens would be eye and skin safe.

2.1.4 Atmospheric Absorption

One factor in need of consideration when looking at LPB from space is atmospheric absorption. This is where different elements in the ozone absorb certain wavelengths, therefore reducing power and ultimately efficiency of a laser beam. These absorbed wavelengths depend on the weather as Fig.25 below shows the transmission spectrum is different depending on whether it is a clear or a hazy day. As found in S.Jarvis' thesis 'To achieve transmission above 90%, lasing wavelengths must lie between: 800nm-850nm, 1000-1100nm, 1200-1300nm, 1510-1750nm and 2100-2325nm' (2017) [1].

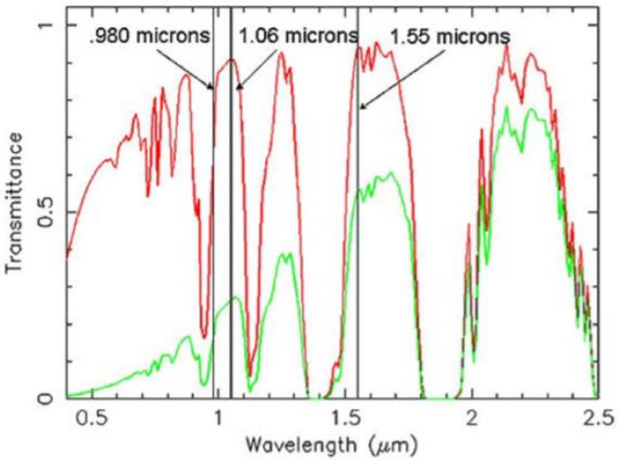


Figure 25: Graph of atmospheric transmission spectrum in the range 0.4-2.5μm (400-2500nm), red line is on a clear day and green on a hazy day [1].

This limits the wavelengths able to be used for such a task, however it is possible to disregard the above safety limitations for skin and eye exposure in these circumstances. This could be achieved if this space-based laser beam had extra safety measures such as remote receivers or a cut off system which could cut off the laser if anything were to obstruct it, though this technology has not been sufficiently developed yet to disregard these safety limitations all together.

2.2 The Wavelength

With all these above considerations; safety, atmospheric absorption, PV and laser efficiency the most ideal overall wavelength for LPB is 1550nm. It has a maximum permissible exposure limit of 1kw/m2 while having a large transmission through the atmosphere. There is a solar pump laser which has this wavelength of 1550nm with a 1W output, however its efficiency is only around 2.5%. Though as mentioned before perhaps the less conversion steps would help make this laser more feasible. As found by S.Jarvis' paper the most ideal wavelength 'for a transmission system is 1550nm, using a InP-based alloy known as InGaAsP' [1] [3].

2.3 Laser Power Beaming Feasibility

Using the most efficient silicon single junction PV cell at 45% [55] and the most efficient semiconductor laser at 40% efficiency with an output power of 10kw/m2 at a wavelength of 1550nm would be a very ideal set up giving an overall maximum efficiency of 18%. Satisfying the safety LIA and BSI limitations while having maximal transmission through the atmosphere. This would be very feasible considering other energy transferring methods are less efficient.

3. Conclusions

Climate change is an internationally recognised issue facing humanity, therefore renewable energy is vital. Fortunately, renewable energy is becoming increasingly efficient and cheaper compared to other existing energy sources. Challenges exist with renewable energy with it being unreliable and volatile. Furthermore, renewable energy struggles to meet the energy demand in real time this is evidenced by the 'duck curve' and California's plight in the curtailment of solar energy. The exchange of electrical power between regions with high or low energy production is a prime solution to this. This is seen with the EU and its large investment in 'super grids', these grids allow further investment in renewable energy and reduce energy wastage. To allow this there are several solutions, however laser power beaming is ideal for this application, with its ability to transfer power over great distances without enormous expensive infrastructure that takes years and vast investment to build. LPB has the potential to connect the entire planet, no other technology wireless or not can boast such a claim. The physics of inductive charging and LPB both showed clear cut limitations. In the case of the former it was distance and size, and the latter wavelength and power was limited due to safety and absorption. The increase in PV cell efficiency and laser power over time is proof that this technology is only going to become more feasible with time. LPB will also allow space based solar energy to be harnessed, energy could be directed anywhere on earth at any moment revolutionising energy production and changing disaster scenarios for the greater good. The internet revolutionised the world and mankind, making such things as telephone wires obsolete, LPB can do the same to electrical wires. Light is the source of life and offers the fastest speed in the universe further research into light is wholly unavoidable. Lasers have already changed society after only 60 years and with still much room for development, the future of lasers is bright and inevitable.

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