Lappeenranta University of Technology

School of Energy Systems

Degree Program in Electrical Engineering

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THE COMBINATION OF QUANTUM DOTS AND OPTICAL RECTENNAS FOR SOLAR CELLS APPLICATION

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ABSTRACT

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The combination of quantum dots and optical antennas for solar cells application.

Master’s Thesis

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The modern condition of the current energy system requires significant improvements and changes to follow the zero emissions target. In practice, it requires transit from burning of fossil fuels to an application of sustainable ways of the electric energy generation. One of the most perspective energy sources for humanity is the solar energy which is unlimited in modern understanding and can cover growing energy consumption. Nevertheless, current technologies for the harvesting of the solar power have several disadvantages which restrict their development and limit the efficiency of the conversion process. In the thesis work, features of the modern photovoltaic technologies such as semiconductor devices, quantum dots, and optical rectennas were clarified and compared. Also, current energy consumption and perspectives of its feature development were described. The main purpose of the master thesis is to propose a solution for improving a solar power harvesting device. Investigation of unique properties of quantum dots and optical antennas has allowed proposing their joint use for improving the efficiency of converting process compared with using them separately. Application of a quantum dot layer as an electromagnetic wave frequency transformer could potentially overcome a drawback of optical rectennas’ low efficiency at a broad spectrum operation, decrease a negative effect for diodes of operation with unfit frequencies and make them a promising technology for photovoltaic technology with careful further research.

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1 INTRODUCTION

In the last 100 years, our society was changing a lot, the economy was developing and nowadays society can be characterized as a post-industrial society, which determined by a high development of the economy, science and increased quality of education, production, and service. Nevertheless, planetary boundaries lead to issues which required changes of current behavior and relation to the environment. Particularly, it is connected with the growth of energy consumption and required alternatives of energy generation methods. The modification of ways electric power generation requires modification of energy resources demand.

It is obvious that humanity cannot ignore the importance of solar energy which dominates above others energy resources available to earthlings. The task of replacement fossil fuel is important. Predicted effects of these changes confirm their relevance. Advantages of the solar power such as widespread, accessibility, cheapness and clearness of energy production lead to fast growth of electric power generation by facilities of solar power plants [**1**].

Future development and changes of the current energy consumption are clarified in the first chapter with an explanation of perspectives of the solar energy conversion. The relevance of the issue is confirmed according to sustainability constraints. Description of operational principles, a definition of advantages and disadvantages of current semiconductor photovoltaic devices are made in the second section. Third and fourth sections declare optical antennas’ and quantum dots’ main features and constraints of a future development. Part five introduces a concept based on the combined use of quantum dots and optical rectennas, describe advantages, disadvantages and operational principles of the perspective photovoltaic technology. Sixth section describes selection and adjustment of nano structures of the proposed photovoltaic device, describes a procedure of efficiency computation and a summary. Section seven gives the conclusion of the manuscript.

1.1 Future of the energy sector

Current electric energy system consists of three main processes which are connected with characteristics of electric power itself and features of electric power consumption. They are energy generation on power plants, transmission by air and cable transmissions lines, and transformation process. Power generation is a process of energy conversion from primary energy resources to secondary energy such as electric power or heat power.

The modern studying calls electric power as the most perspective and useful type of energy for a few reasons such as dozens of ways for electric power generation, low energy losses for transmission and a large number ways of energy utilization. Due to these advantages, electric power occupies the first place of a secondary energy resource and share of it increases rapidly. Electricity demand increased by a factor of 20 at last 60 years [**2**]. Moreover, this permanent growth was interrupted only at Global Credit Crunch at 2009 when China decreased manufacturing. When global electric power demand is predicted population growth has to be taken into account. This factor influences on the electric demand curve formation a lot. Statists predict that population growth curve will have a form of a parabolic curve with maximal point close to 9 billion people.

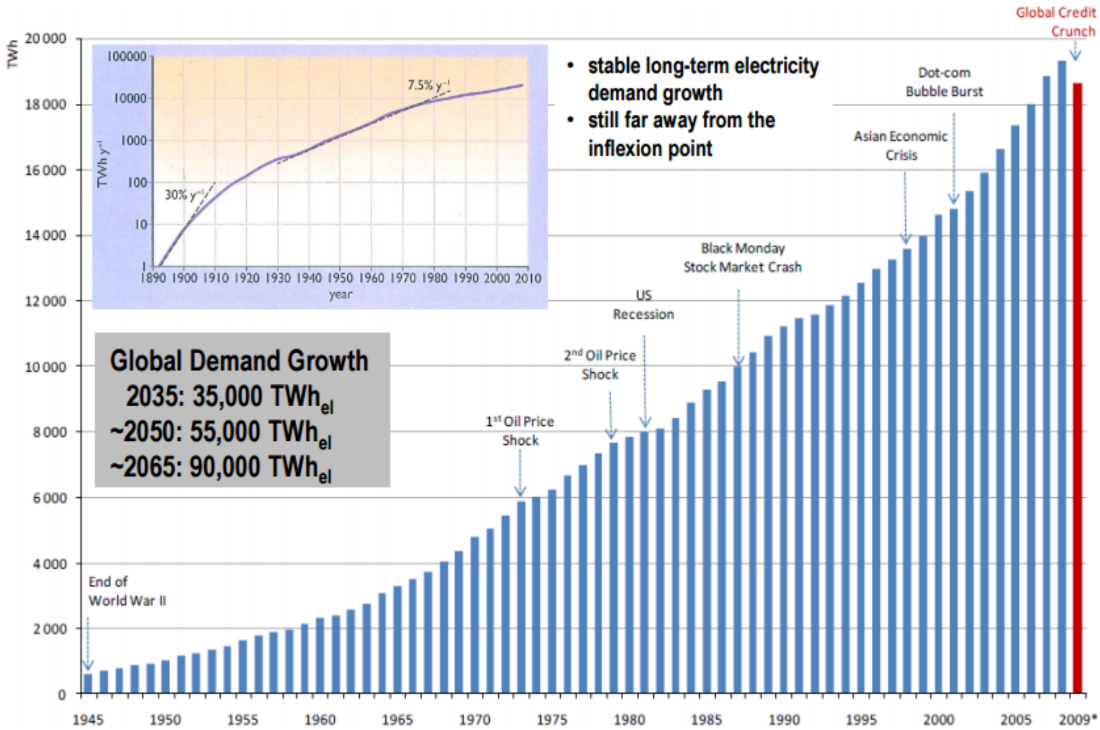


Fig. 1. The global electric power demand. [**2**]

This information helps to analyze a possible character of the electric power generation graph. The power demand graph will have similar characteristics as population growth curve but with a larger angle of gain. The predicted volume of electric power demand will be on the level of 90000 TWh at 2065, which will be by 5 more than current power generation. Follow the expectations of the main institution of the energy sector IEA (International Energy Agency) electric power consumption per capita will increase 3,5 time in the next 50 years [**2**]. The issue of rapid energy consumption increase imposes restrictions for future of the energy sector.

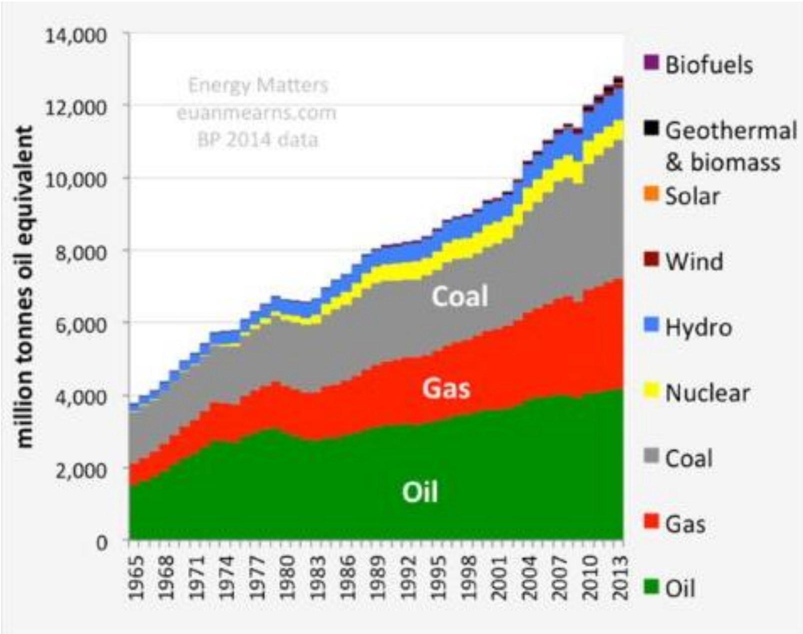


Fig. 2. The share of different energy sources in global energy demand. [**3**]

To begin with, a new energy era requires changes of electric power generation which will allow energy supplying of our new complex and developed world. Above-mentioned factors affect to worldwide carbon emissions and require dropping it to zero by 2050 [**4**].

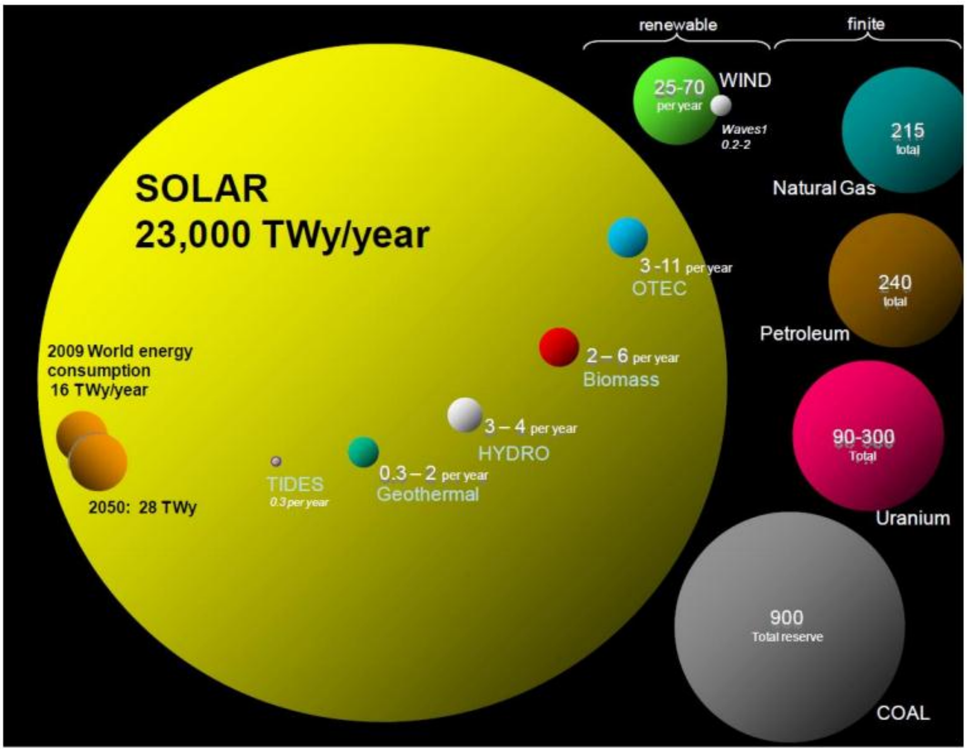


Fig. 3. The planet energy reserves. [**5**]

These constraints mean that humanity should change energy sector from burning fossil fuels to renewable energy utilization. Renewable sources of energy represent the easiest and the most perspective way to produce clean and safe energy. The cost of renewable energy becomes more and more competitive to energy generation by fossil fuels. Solar energy is widely spread energy resource which is used all over the world over 4 billion years and provides at 1400 times more energy than we consume [**5**]. Unsurprisingly, that it becomes the best decision for the sustainable world strategy. Nevertheless, solar radiation has a few major issues which will be solved if we follow the orientation to clean energy requirements.

First of all is a solar energy intermittent, but Sun is shining constantly and we just have to solve the energy storage issue. Scientists all over the world work on a creation of the best energy storage for the future energy system. The second constraint of using solar energy is a location of the highest resources. Solar power irradiance is not similar around the world and depends on latitude to a great extent. The majority of energy resources are located close to the equator. It leads to the issue that transmissions lines with low losses are needed. Researchers are carried out to solving the above-mentioned issues.

“Nanotechnology could help to solve solar energy’s obstacles and meet energy expectations without compromising the environment and human health by creating new devices that are able to generate, store and transport electricity in a clean and more efficient way and with smaller space requirements.” [**6**]

2 SEMICONDUCTOR SOLAR CELLS

The solar cell is a device for transformation of solar power to electric power [**7**]. Modern solar cells are based on several technologies and material. Nevertheless, the principle of their work is similar and limited by the same physical constraints. The most commonly used solar cells are made of silicon but might have different structures.

The principle of their operation is based on photovoltaic effect which appears when heterogeneous semiconductor structures are exposed to sunlight. Solar modules based on semiconductors represent few semiconductor cells united in series branches for achieving of the standard value of voltage and current [**7**].

Application of modern solar modules is huge and widely applicable because of their convenience. Solar cells can supply electric power to the major part of devices and consumers from house appliances and small electronics to industries and big domestic consumers. A photovoltaics system is based on plenty of the solar modules and can be the significant part of the power system. The biggest advantage of electric power production by harvesting of a solar radiation is the clearness of the produced energy. Production of the electric energy by photovoltaic devices follows the target of the zero emissions in energy sector [**5**]. It should be taken into account that semiconductor photovoltaic modules produce greenhouse gas emissions during its manufacturing. Nevertheless, the value of these emissions can be reduced by application photovoltaic devices for supplying of a manufacturer.

2.1 Introduction to semiconductor solar cells

The history of the photovoltaic effect started from 1839 when French physicist Edmond Becquerel discovered physical phenomena of appearing of the electric current and voltage in his copper plate sample immersed in a liquid under the influence of sunlight. More than 30 years later in 1873, Willoughby Smith discovered photoconductivity of selenium and 4 years later in 1877 William Adams and Richard Day discovered the photovoltaic effect in solidified selenium and called their device the selenium cell. Their studying described in a paper which calls “The action of light on selenium” [**8**]. In 1883 Charles Fritts the American inventor created a solar cell based on the plate of selenium with a thin layer of gold. The above-mentioned device had the efficiency less than 1% but produced a constant current with relation to the intensity of sunlight.

The better understanding of the physics processes inside the solar cell appeared after researching of the wave properties of light by Hertz in 1887. At 1888 Edward Weston patented the device with name “Solar cell” which worked as a converter of solar radiation to electric power. Another important push was made by Einstein during researching of quantum basics of light absorption in 1905 [**8**].

The influence of a single-crystalline structuring to an efficiency of the semiconductor solar cell was discovered only after the development of quantum mechanics in 1948 with a development of the mechanism of single germanium and silicon crystal growth by Gordon Teal and John Little. At 1954 researcher of Bell Labs Daryl Chapin created the first practical applicable silicon solar cell with efficiency in the real life conditions at 6%. A lot of individual scientists and laboratories started to research properties of solar cells and experimented with different materials [**8**]. A few years later Bell Labs announced the improving the efficiency of the solar cell up to 15%. It was a good time to develop in the area of harvesting of solar radiation because of the active development of the area of space researches, spaceships, and satellites. Solar cells represent the best way to supply satellites electric power because of their reliability, life time and solar intensity of the Earth orbit [**8**].

Till the early 1980s, the application of conventional solar cells was only as a power source for a utility which could not be supplied by the grid such as mobile housing, emergency means of communications, small portable electronics and space activities. Nevertheless, nowadays total solar electricity generation rapidly increases with the rate of 30-50% annually and doubling every few years. The global trend of generated solar electricity is represented on the picture below [**3**]. According to the report of the IEA PVPS (International Energy Agency Photovoltaic Power System Programme), more than 303 GW of installed PV power was added at the end of 2016. It means that 75 GW of new PV systems were installed in the last year. The total capacity covers almost 2% of the humanity electricity demand [**9**].

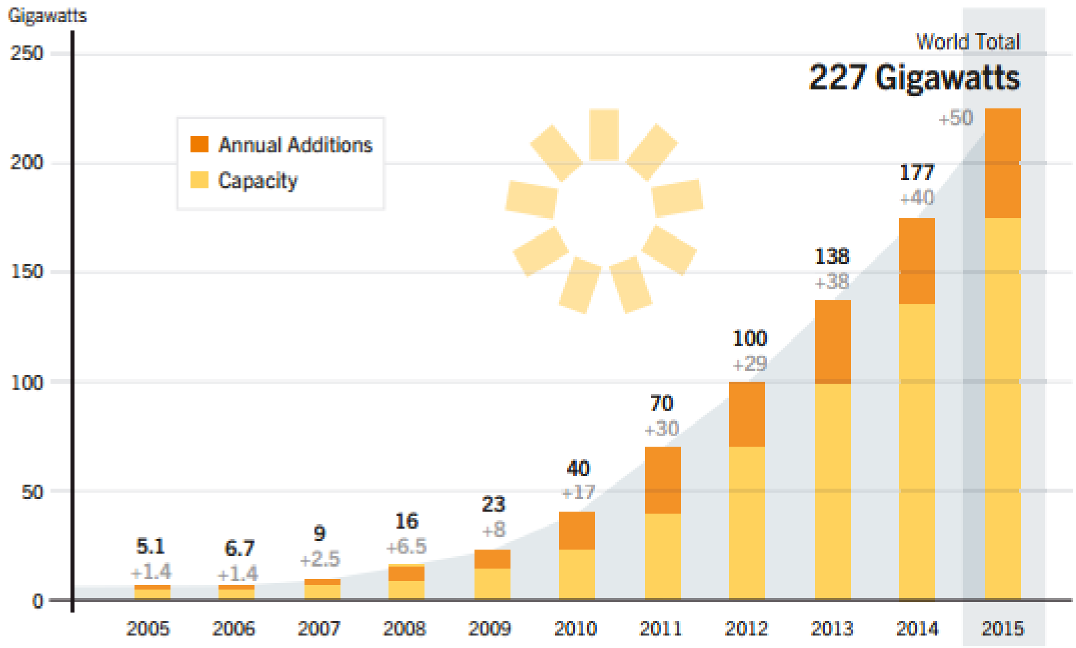


Fig. 4. Development of global solar photovoltaics power capacity. [**10**]

More and more people all over the world start using solar modules for the main electric power supplying of their houses, commercial buildings, and large-scale industrial companies. Nowadays, grid connection of roof top mounted solar cells system is a normal procedure. The creation of a solar power plant is a good business opportunity for investments. Price for solar modules, batteries, and tracking system become lower annually which influence to the development of the area of power generation based on solar modules.

2.2 Operational principle of semiconductor solar cells

The conversion process of a solar radiation to electric energy in semiconductor solar cells is based on the photovoltaic effect which appears in inhomogeneous semiconductor structures by the influence of an electromagnetic radiation. The inhomogeneous characteristic of the semiconductor requires connecting of semiconductors with different properties or using the same one but alloyed with different impurities such as the creation of p-doped and n-doped surfaces by adding atoms of boron and phosphorous to the different layers. The above-mentioned actions are connected with a need of changing the band gap energy in different layers of semiconductor which leads to a creation of p-n junction. The schematic cross-section of the photovoltaic device is represented on the picture below.

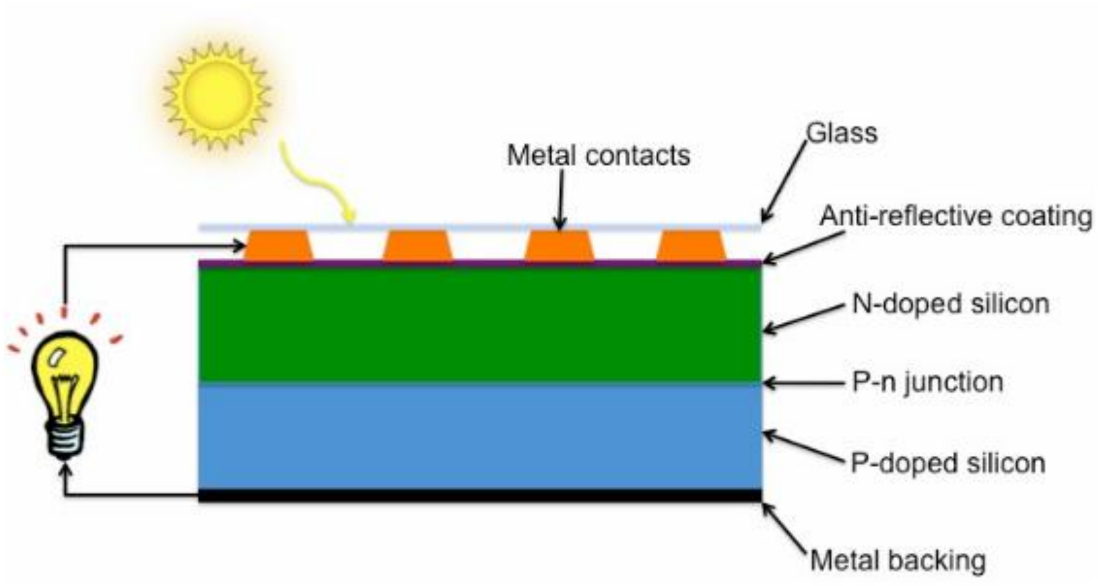


Fig. 5. The basic schematic structure of a silicon solar cell. **[**11**]**

After a creation of the semiconductor with a suitable band gap for harvesting the solar spectrum radiation, the sample should be replaced under sunlight. If the energy of photons of the solar radiation is higher than the band gap energy of the semiconductor, photons will interact with electrons of the semiconductor and will transfer energy. When electrons have enough energy to break a connection with their atom, it becomes a free charge carrier. According to the specific structure and used materials in photovoltaic devices, free electrons are able to move only in the single direction to an outer part of semiconductor and then to the load. Electrons move throw the load and create a useful work in the external load and then come back to the cell and recombine with a hole in the p-type semiconductor [**7**].

2.2 Advantages of semiconductor solar cells

Application of the device for the harvesting of the energy which value is unlimited in comprising with the modern demand for electric power is itself benefit. The value of annual solar radiation can fulfill humanity demand few times and provide enough energy for growing needs of the modern world [**5**]. Semiconductor solar cell is the first device which is used for harvesting and converting this energy to use for the modern technic in the global scale. Nevertheless, conventional solar cells based on semiconductors have more advantages than it can be noticed. First of all using of silicon as the main material is a good decision which allows production of solar modules on a large scale without tangible lack of materials. Silicon takes the second place by prevalence on the Earth after oxygen. Usually in nature silicon is in the form of silicon dioxide SiO_2 which is better known as sand, quartz, and flint [**12**].

The process of a pure silicon manufacturing is well developed and can be established in a large scale production. Of course, using a single crystal for solar modules production is a complex task which requires a high energy and time expenses. Application of a polycrystalline solar module gets less energy production per square meter, but its manufacturing is less expensive, less energy intensive, faster and simpler in comparing to the more efficient monocrystalline solar cell. The main factor which must be fulfilled for an efficient solar energy harvesting by polycrystalline solar cells is that size of an each crystal have to be bigger than the wavelength of the absorbed wave. If this rule is fulfilled, the difference in efficiency of the solar module will be not higher than 1% in comparing to monocrystalline solar modules [**7**].

Using solar cells is the way of a pollution free electric energy production, match climate change constraints and the 2^{o}C target. The end-waste and pollution during production cycle can be managed and reduced by using modern technologies. Recycling technologies for semiconductor solar cells are developing. Nevertheless, it is already understood that sustainability of a solar system is uncritical and photovoltaic devices become more and more competitive energy sources [**13**].

Another important advantage of a power plant based on semiconductor solar cells is their life time. Semiconductor photovoltaics can operate in normal conditions more than 100 years because of their solid state nature. In practice, photovoltaic systems have lifetime confirmed by a manufacturer from 20 until 30 years which prove its quality and reliability. A solar power plant requires only a little maintenance such as cleaning and rare replacement of broken elements. These procedures don't require highly-qualified employees, which effects for the installation expenses. Semiconductor solar cells don't have movable parts in their construction which means the lack of losses in friction, but also improve a reliability of the system because the lack of moving parts allows to significantly reduce maintain expenses [**7**]. It affects the operational cost of the solar power plant which is significantly low compared to power generation based on other technologies.

Another important advantage of conventional solar cells is their modularity. It means that installation of a solar power plant can be carried out at few steps with increasing installed capacity. It is a great benefit which will have a significant impact for a payback period of a power plant because as earlier the power plant starts to produce energy, as earlier investors will get their investments back and will start to make a profit. Multiplication of the above-mentioned factor to the fact that the solar power plant can be installed incredibly fast makes the solar power plant construction one of the most perspective and interesting for investors project in the energy area.

In perspective, using a large number of distributed generators such as roof top mounted solar modules can help to reduce losses in the energy sector for transmission, distribution, and transformation of electric energy. In theory, it can help to maintain existed energy system and reduce future investments for construction of new long distance transmission lines and new fossil fuels based power plants. All these plus and positive properties of semiconductor solar cells effect for their wide spread and used as the main power source all over the world.

2.3 Disadvantages of semiconductor solar cells

Nevertheless, the development of semiconductor solar cells using is restrained by some drawbacks and constraints which effect for their properties and characteristics. The first and the main drawback of the conventional solar cells is the efficiency. Basically, the most fundamental constraint of the silicon solar cell is connected with properties of silicon semiconductor. Since a semiconductor solar cell's principle of work based on the width of a band gap and creation of free charge carriers, the efficiency of the solar module will have strong limitations. In practice, it means that photons with the value of energy less than 1.12 eV cannot be absorbed by the silicon and photons with the value of energy higher than 1.12 eV lose difference of energy their energy and width of the silicon band gap to lattice vibration which leads to heating of the material. The above-mentioned constraint limits the efficiency of a silicon solar cell on the level of 29% for one junction sample [**7**]. An efficiency factor effects to the requirement of the area for production of a determine power.

In comparing to the power generation on a standard power plant, it requires a few times higher amount of area for production of the same capacity.

Another drawback of the conventional semiconductor solar cell is the fragility of the modules. Standard crystalline silicon is fragile as a normal thin plate of a solid material. Solid crystals of silicon are especially weak on flexural loads. This constraint requires using the metal or plastic frame for mounting and holding of solar cells and using glass for protection of the front side of the module. These facts influence for the weight of the module complicates manufacturing and installation procedures. Moreover, the additional elements and manufacturing expenses influence by increasing a price. Conditions of using and protection of a photovoltaic device effect to the lifetime of the module and guarantee power indicators following a manufacturer brochure [**7**].

In turn, the presence of glass and metal frame effects to reflection losses and the effective area of the panel which leads to decreasing of the modules' efficiency. A module production, transportation, and installation become more expensive, time and energy consuming which impact the final cost.

2.4 Constraints of semiconductor solar cells

Improvements of a standard photovoltaics technology become more and more important because solar cells enter in the modern life and energy sector. Nevertheless, investments in the area of the renewable energy generation are still low in comparing to the financing of the power generation based on fossil fuels or a nuclear power.

To begin with, the modern semiconductor solar cells are a decent mature technology and practical efficiency of the market samples is close enough to the maximal theoretical efficiency of the concept. This factor means that a development of the modern semiconductor solar systems has more constraints from the market side than from the physical point of view. Nevertheless, the constraint for semiconductor solar cells is efficiency and cost reduction which is connected with material selection or creation of a unique new material with properties which will be the most suitable for the harvesting of the solar radiation. A semiconductor photovoltaic utilization has the optimal relation of the positive properties such as the more suitable width of the band gap and Levelized Cost of Energy (LCOE).

The devalued calculation of Shockley–Queisser limit shows that the maximum efficiency for the maximum power point for a single junction semiconductor solar cell cannot overcome 31%. Nevertheless, the above-mentioned calculation is valid for a semiconductor with the band gap energy around 1.3-1.4 eV. In practice, the efficiency of the single junction silicon solar cell with the band gap energy of 1.1 eV is around 29%. In theory, the using of an infinite quantity of band gaps leads to efficiency improving up to 86% which correlates to the thermodynamic efficiency limit. In real life creation of three-junction solar cells is a complex task which can improve efficiency till 48% in theory but significantly increase a cost of the device [**14**].

The environmental impact of the semiconductor solar cells is a significant issue which will depend on the material and manufacturing technology to a great extent. The carbon footprint of a different type of solar cells represents on the picture below for a better understanding of environmental impact.

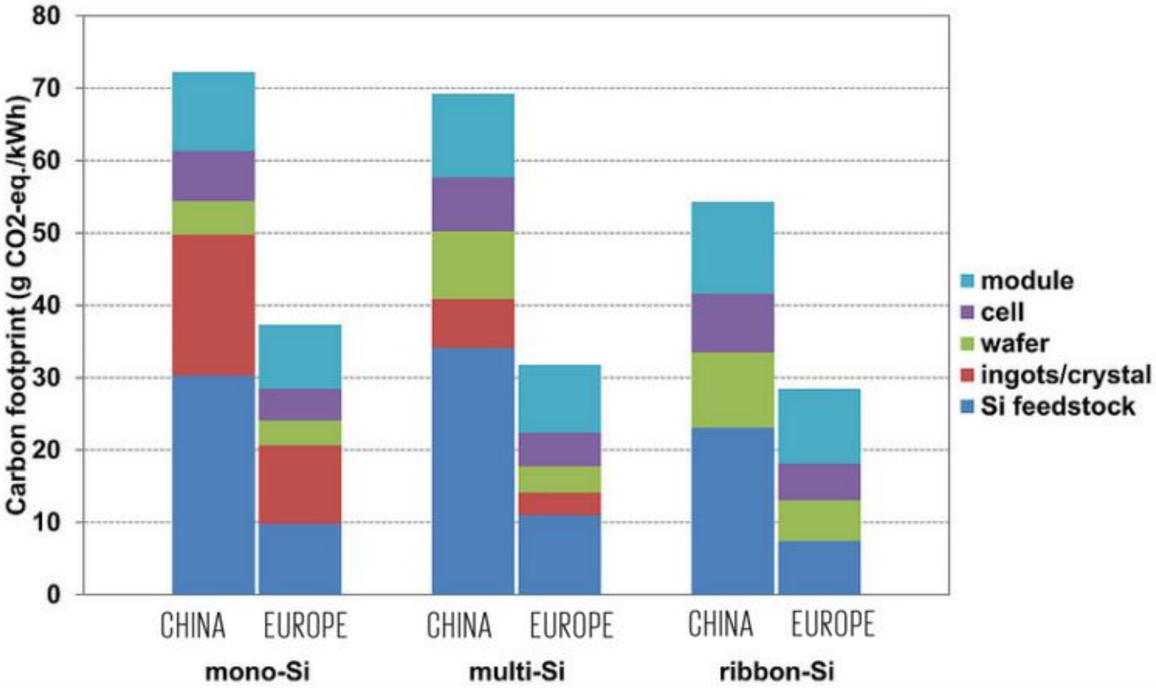


Fig. 6. The carbon footprint of photovoltaic devices. [**15**]

3 OPTICAL RECTENNAS

The basic principle of rectennas was proposed by William Brown during his activity in the Raytheon Company in the 1960s. The idea of wireless power transfer is not new and begun from Tesla's experiments in 1899 with using of radio waves [**16**]. The main purpose of Brown was to improve efficiency, increase the distance of wireless power transfer and get examples of a real-life application for a device. The simplified sample of "The Raytheon Airborne Microwave Platform" a helicopter platform flowing above 15000m high was a small platform covered of antennas array and connected to DC motor with blades. A rectifier of the 3GHz supply signal was based on a parabolic reflector with a focal point of a horn-fed reflector antenna. The system was complex and required movement of a focal point together with the movement of the device. The concept worked but the realization had a lack of technical supporting especially in the area of a rectification procedure [**17**]. A joint work of Brown and his colleague Roscoe George who worked on a microwave semiconductor diode get a result in 1963 which marked as an appearing of a rectennas concept. The first concept of a microwave antenna was constructed by George in 1963 and then patented in 1969 [**18**].

3.1 Introduction to optical rectennas

Optical rectennas is a device based on a combination of small antennas with sizes measured in nanometers and high-frequency diode. The formed circuit is able to operate with visible spectrum of sun light and transform it to direct current [**19**].

The history of an optical rectenna started at 1973 from the patient of Robert J. Fletcher of the invention which he calls "Electromagnetic wave energy converter". It was a departure point for developing an understanding of the operational principle of standard rectennas. A massive of mutually insulated electromagnetic wave absorber elements transform electromagnetic wave impinges thereon to electric power. He proposed to use artificial pyramids or cone structures similar to structures in a human eye. The device includes elements tapered in the direction of wave direction to ensure increasing of a wideband spectrum, outputs for determination of an intercepted electric field voltage. Elements are located in a way that adjusted elements affected by the electromagnetic field of an impinging wave. The difference in the value of electric field results in a voltage difference between adjacent elements which leads to impulse current flowing through a diode which rectifiers the impulse signal to a direct current [**20**]. The patient of "Devices for converting of light power to electric power" was received by Alvin Marks in 1984. The schematically presentation of a proposed structure is represented on the picture below.

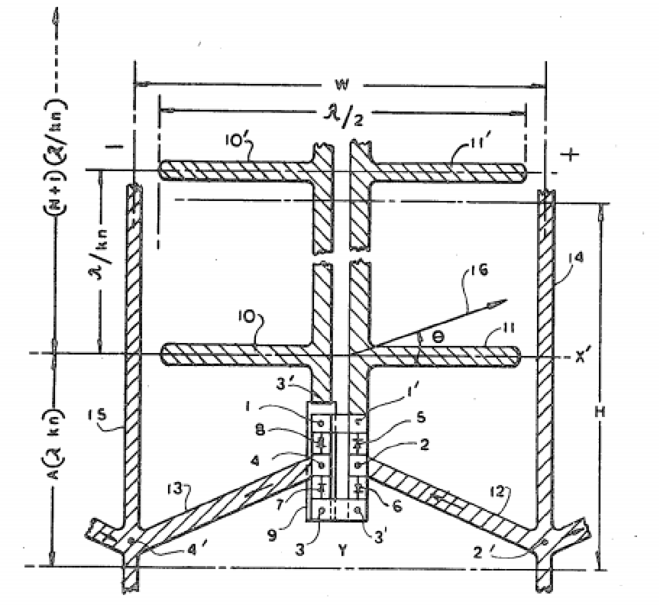
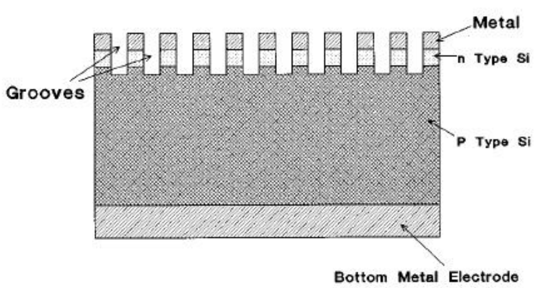


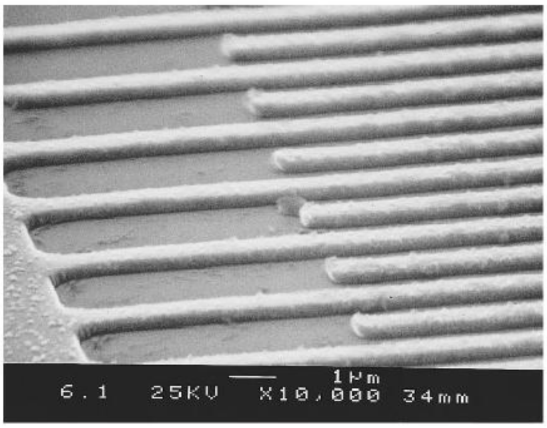
Fig. 7. The device for converting of light power to electric power**.** [**21**]

The proposed device was not the first assumption that nantennas can operate with the visible part of the solar spectrum if the high-speed diode will be used, but has shown a configuration of an optical rectenna in the conventional sense. The device represents a relatively high efficient converter of a light power to an electrical power based on a plurality of dipole antennas absorbing photons' alternating electric field to cause electron resonance in the dipole antenna and absorbing photons' energy. The efficiency of the Marks's sample is about 10% but cannot exceed this value by devices utilizing the mentioned construction [**21**].

In 1996 an article of Guang Lin was published in The Journal of Applied Physics. The article called "Investigation of resonance light absorption and rectification by sub-nanostructures" and was the first report of experimental light absorption by nanostructures. The sample consisted of a parallel dipole antennas array and highly speed diodes which are able to work at frequencies of a visible light. Guang Lin observed a resonance peak signal of a short circuit current and determined definition of a short circuit current, a wavelength, and an angle of the incident light [**22**]. The cross section of the Lins sub-nanostructured solar and fabricated cell by an electron microscope is represented on the picture below.



a)



b)

Fig. 8. The side view of the designed structure (a), lateral view of a fabricated cell (b). [**22**]

For decades interest for rectennas technologies was stable and only a few laboratories worked on their projects connected with researching of rectennas devices. The interest of rectennas and optical antenna technologies appeared again only a few years ago with a substation leap in the rectifier technologies. A plenty of laboratories all over the world work on the development of different technologies parts [**19**]. A timeline of a rectenna device researching and development is represented in the figure below.

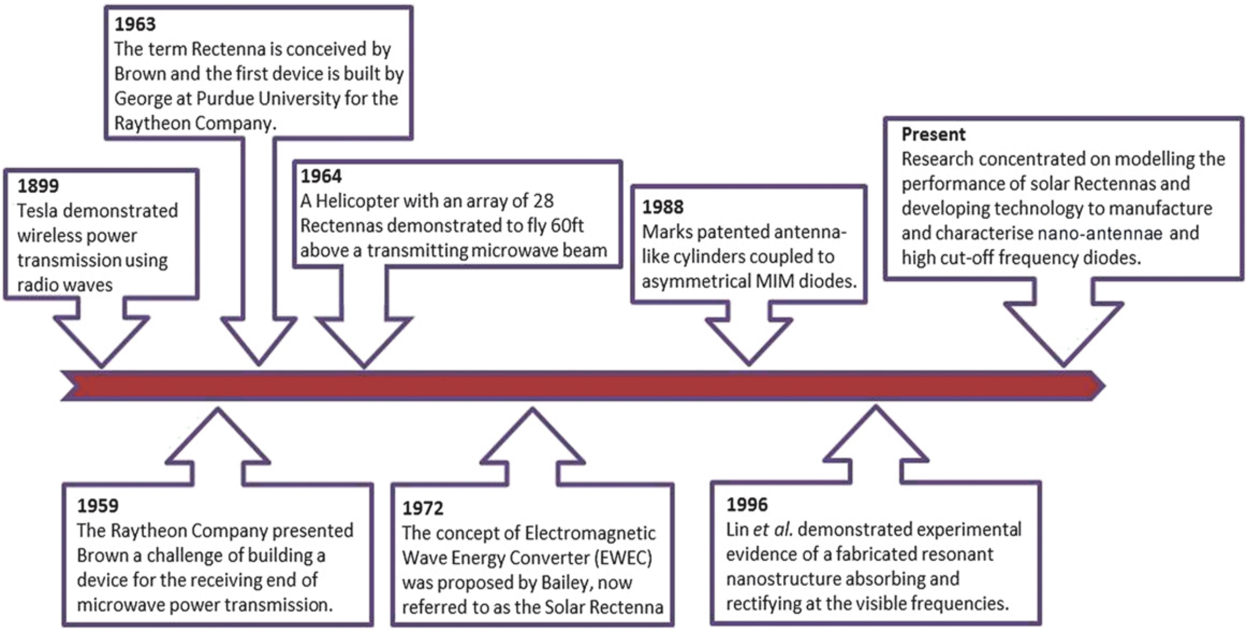


Fig. 9. A brief timeline of the rectenna device – from the concept for microwave power transmission to research focused on solar harvesting. [**23**]

After proving of the concept of the optical rectenna operation, Idaho National Laboratory created a laboratory-scale nantennas massive by electron beam lithography technology from a gold film, a thin layer of manganese, and an amorphous silicon layer. Their optical rectenna sample consists of the antenna, the optical resonance cavity, and the ground plane. This sample did not include a rectification diode [**24**].

3.2 Operational principle of optical rectennas

A rectenna is a special antenna which is used for absorption energy of electromagnetic wave and transformation it to electric energy in the form of direct current. Usually, they are used in systems of wireless power transmission and represent as a dipole antenna with a diode connected across dipole parts. An alternating magnetic field of an electromagnetic wave induces an alternating current in a dipole antenna. A rectifier diode detects alternating current to direct current absorbed by dipoles.

The major factors determining the antenna design are the antenna resonant point and the frequency range where the antenna can operate. These factors are essentially important because especially they will influence to the efficiency of a proposed device. An antenna can be represented as a form of a circuit with inductance and capacitance and can be named as an RLC circuit which has a resonant frequency. At the resonant frequency, the inductive and capacitive reactance cancel each other. At this stage, the antenna has only an active resistance which can be replaced by the losses resistance [**25**]. The loss resistance is determined by the real value of resistance of the element. The power expanding to lose resistance is lost as heat. The resistance of a circuit used AC current will be higher than for a DC-mode as a result of skin effect appearing. The resistance will be proportional to the conductor circumference and the square root of the frequency [**25**]. The picture below represents a relation of an impedance value to a frequency changing.

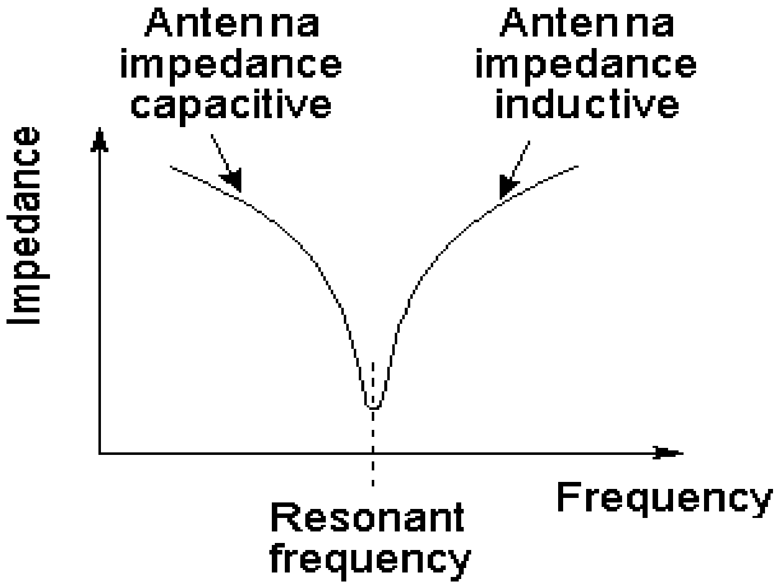


Fig. 10. The impedance relation of an antenna to frequency. [**25**]

The operational principles of optical rectennas are the same as for traditional rectennas. A quasiparticle which determines electromagnetic waves energy is a photon. A photon is the electromagnetic force carrier. Incident photons on the antenna cause to appearing of free charge carriers vacillating with the frequency of the absorbed wave. Appearing of free electrons and their movement back and forward is an alternating current. The frequency of the alternating current will be the same as the frequency of the absorbed wave.

For the efficient power of a load direct current have to be used. For rectifying alternating current have to be used diodes capable operating with absorbed wave's frequency. The effective absorption of photons appears only on the resonant frequency of the antenna is because of decreasing of impedance value. The antennas resonant frequency varies linearly with respect to changing of the physical dimension of the antenna [**26**]**.** The solar spectrum wavelengths are in the range from 0.3-2.0μm with a maximum point at the interval of the visible spectrum part. Increasing power production of optical rectennas dipoles' sizes have to be proportional to the wavelength of the visible part of the solar spectrum [**26**]. The graph of the solar radiation spectrum with a spectral irradiance is represented on the picture below.

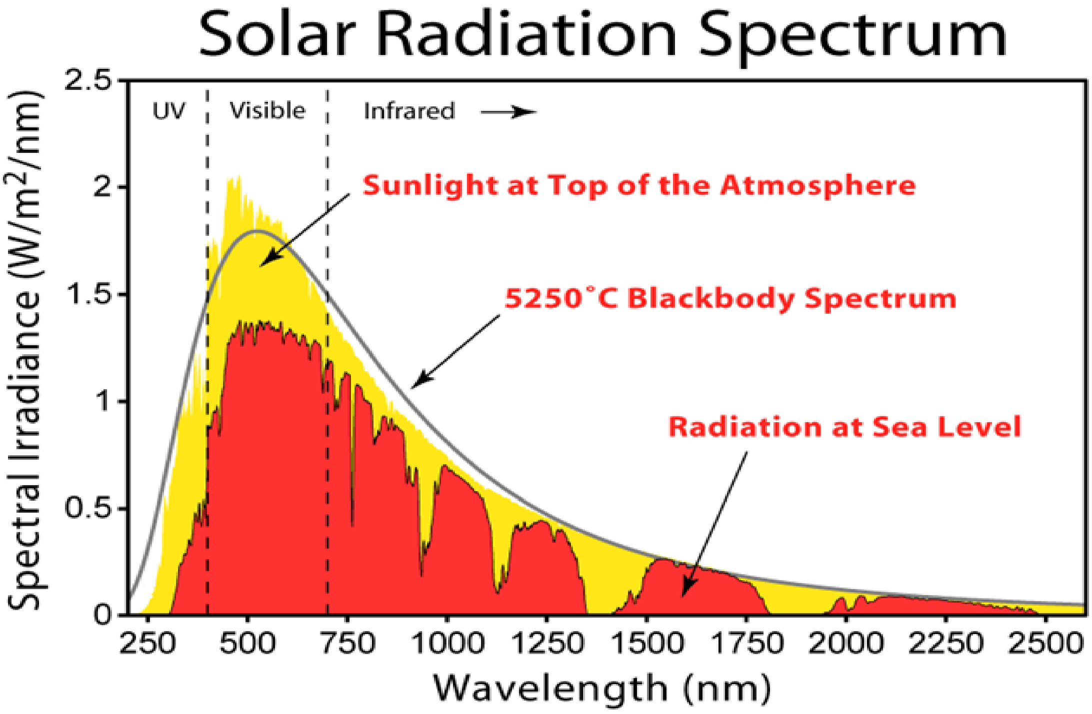


Fig. 11. The spectral irradiance of a wavelength in the solar spectrum. [**27**]

Main elements of an optical rectenna are the antenna, diode, and load which are connected in parallel. The schematic circuit is represented on the picture below. Connection schemes can vary for example by application of more sensitive diodes which allows to use more qualified scheme of rectification such as diode bridge for better rectification of output signal.

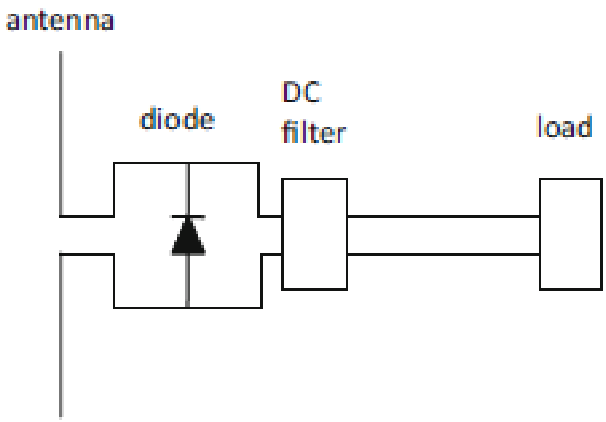


Fig. 12. The rectenna circuit. [**19**]

The antennas output signal has a frequency of the absorbed wave is rectified by the diode and going to the load throw a DC filter with filtering of low-pass frequencies. The output DC voltage will change symmetrically as the input AC voltage [**19**].

3.3 Advantages of optical rectennas

Using the optical rectennas' array as a solar cell has several benefits which can effect for their future development. In theory, the efficiency of an antenna can achieve 100%. The Carnot efficiency limit is not applicable to optical rectennas. However, the efficiency of non-laboratory sample possible can be higher than the efficiency of conventional semiconductor solar cells. For the one layer of rectenna solar cell, the ultimate efficiency will achieve the standard level of 44% as the efficiency limit for a one band gap solar cell without taking into account losses in the rectifier.

Materials for an optical rectenna solar cell creation are wide spread and low cost. Only thin films of a metal and an isolation are required. The process of fabrication can be a significantly low cost in principle by using of nanoimprint and roll-to-roll technologies [**19**]. Another benefit of rectennas for harvesting electromagnetic wave energy is that they can absorb any part of the solar spectrum or another source of electromagnetic waves. The resonant frequency of rectennas can be easily changed by variation of antennas size during manufacturing. On the other hand changing of a band gap for a standard solar cell requires changing of materials or creation of a semiconductors combination.

The "multicolored" rectenna based solar cell is an analog of a multi junction semiconductor solar cell can improve the efficiency of the above-mentioned device. For semiconductor solar cells it requires incorporating of semiconductors with different band gaps which lead to significant cost increases. The combination of layers with different antennas size is less expensive technology than a creation of multi junction solar cell. This is done in order to change the peak sensitivity of the optical rectenna.

Another important property of rectennas is an ability to absorb infrared radiation of waste heat. In comparing to optical rectennas, infrared radiation has lower frequencies and lower RC time constant, which affects for simplification of manufacturing and selection of diode technologies [**28**]. However, there will be no peak of radiation intensity according to a distribution of spontaneous radiation of a black body. In practice, it means that harvesting of waste heat by infrared antennas will have a low efficiency. The below-mentioned graph represents a definition of a radiation intensity of the emission wavelength for different temperatures.

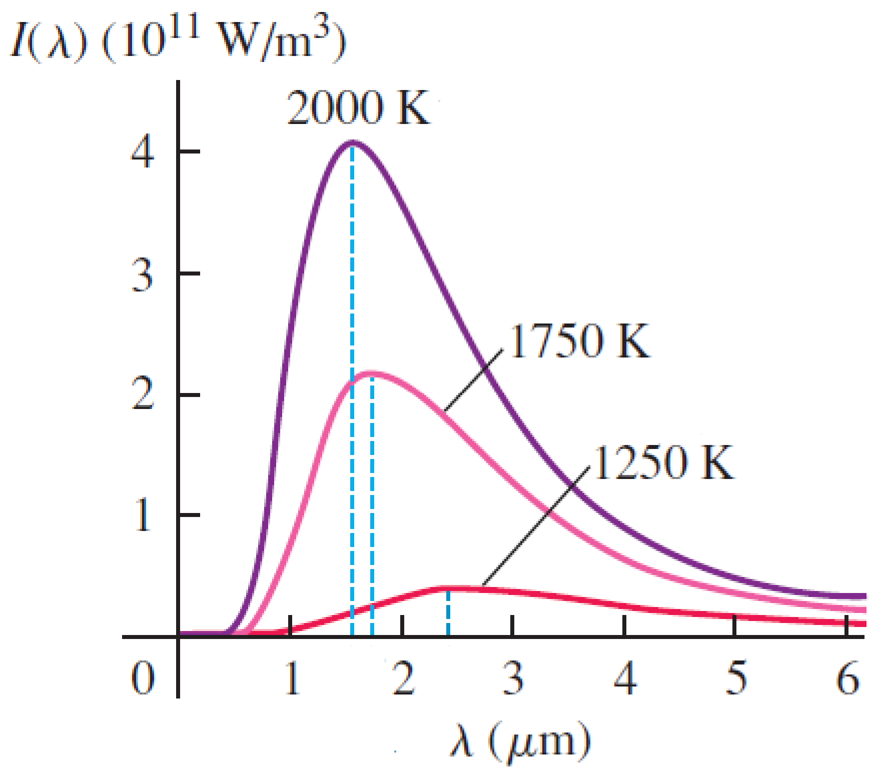


Fig. 13. The spectra emittance for radiation from a black-body at three different temperatures. **[**29**]**

The environmental issue is one of the most important questions in the modern environmental situation. The issue of pollution is still significant since the optical rectennas can be manufactured from non-toxic well-developed materials. The substrate of the optical rectenna can be replaced to any non-toxic organic surface which can maintain elements of the antenna [**19**]. Metallic elements are made from relatively easy for recycling metals such as silver, aluminum or copper. All above-mentioned factors have a significant influence on energy payback period, which can be respectively low in comparing to conventional solar cells or other technologies for the harvesting of solar radiation.

3.4 Disadvantages of optical rectennas

Using the optical rectennas' array as a solar cell has several disadvantages which can effect for their future development. First of all these disadvantages are more as constraints and limitations than a real defect. Moreover, the technology shows a lack of a parts development which is taken part in the optical rectennas creation and manufacturing.

As was mentioned before one of the strongest constraints of optical rectennas application is frequencies of a visible part of the solar spectrum. The high frequencies of a visible part of spectrum lead to high photons' energy and can be named as the ideal wavelengths range because of the higher intensity of energy. Nevertheless, using of rectennas for absorption of this range of frequencies is connected with issues of antennas design and diode selection.

The center of visible light frequencies corresponds to the RC time constant approximately of 0.1 fs. According to the requirement of efficient rectification, the rectenna time constant should be less than the time constant of absorbed wavelength. In practice, it means that diode resistance should match the antenna resistance according to the theorem of the maximum power transfer. In this case, the impedance of the whole rectenna will consist of the parallel resistance of the antennas and diode which leads to doubling the rectenna impedance. This factor makes the significant limitation of the value of the rectenna capacitance. The RC time constant influences a lot of design of optical rectennas and provides a serious research issue [**30**].

During selection procedure of the diode for optical rectennas reverse-bias leakage of the diode should be taken into account. Current-voltage curve of the optical rectenna is represented below. The diode of the nantennas should have a nonlinear relation of current to voltage in the forward and reverse operational direction according to need to avoid the reverse-bias leakage [**19**].

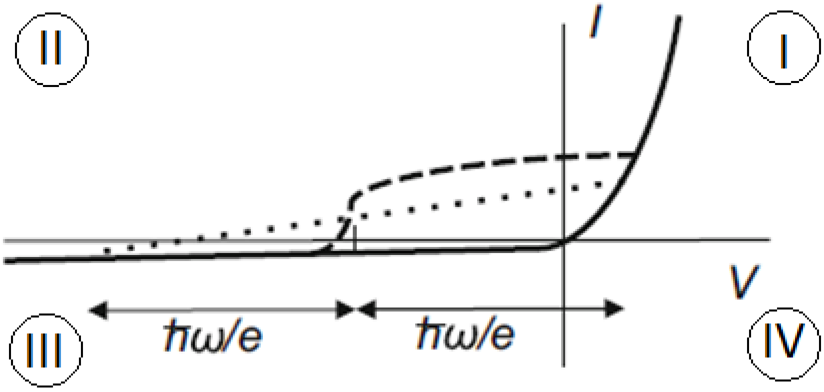


Fig. 14. Current-voltage curve for a rectenna diode. [**19**]

For the conventional semiconductor solar cells the current-voltage characteristic is decreasing when the intensity of illumination increases, the operating point is in the fourth quadrant. As can be seen from the graph above the current-voltage characteristic of the rectennas diode has a hump of the current rise in the second quadrant which will have a proportional dependence to illumination intensity and photon energy. The solid line on the graph above shows the volt-ampere characteristics of the rectenna in the dark, the dashed line demonstrate characteristic under light. Maximal power point is obtained in the second quadrant with the most suitable operating point of the rectenna based solar cell. The operating voltage is represented by a vertical hatch. The value of voltage will be negative because the maximum power will be at the voltage magnitude where full photons energy is extracted. The research of the rectenna diodes reverse-bias leakage was made by Moddel and Grover during their studying of the nantennas. According to their calculation for improving the efficiency of solar energy absorption, the diode's current should be lower than 1μA at 1V of the reverse bias [**19**].

Another substantial drawback of the optical rectennas is an issue of their manufacturing. Today's optical rectennas are produced by electron beam lithography. The technology of their production is slow, expensive and not suitable enough for mass production. Nevertheless, lithography allows creating samples with high quality and particle size about nanometers. Usually, the electron beam lithography is using for a creation of small scale laboratory samples.

3.5 Constraints of optical rectennas

Fundamental problems have to be noticed during a conversation about optical rectennas for photovoltaics systems. One of them is partial coherence. Production of electric power from fully incoherent electromagnetic wave sources is real but can be implemented by another type of generators such as Carnot engine or conventional silicon photovoltaics, which have their own limitations and constraints. The incoherence of solar radiation is a fundamental property of the sunlight. Sunlight can be characterized as partly coherent radiation according to the nature of spontaneous emission and limited solid angle subtended by the sun [**30**]. For an optical rectenna array, the current collected from dipole antennas converted at the diode means the cancellation of out-of-phase frequencies. It means that for photovoltaics systems based on optical rectennas light source should be partly coherent for efficient light absorption and rectification. In the case of lighting to the circle with a radius less a 19 μm coherence length solar spectrum more than 90% can be obtained [**28**].

Another constraint is a polarization of solar radiation. Usually, antennas work with a single linear polarization. A single polarized antenna will work effectively only with 50 percent of the solar spectrum. Cross-polarized antennas have been created to overcome the issue of polarization. Basically, it is a combination of few layers of antennas array with different polarization located orthogonally or using unidirectional conical antennas for few type of polarization. Theoretically, application of these structures can improve efficiency to 100% [**31**].

The third one is the bandwidth of solar spectrum intensity. The broadband nature of solar radiation limits absorption possibility of a single antenna. More than 60% of the solar energy is consistent to a bandwidth of 60%, but 15% is wide spread to frequencies. It creates a serious problem for optical antennas application in the aim of solar power absorber. Nevertheless, it is unnecessary to harvest the whole spectrum by a single antenna. A practical solution is in using different design antennas for the splitting of the solar spectrum and more effective absorption. If only 11 antennas have a bandwidth of 20% each of them, they will cover the wavelength range from 0.2 μm to 2 μm [**30**].

3.6 Optical rectennas based solar cell

Optical rectennas based solar cell is potentially very low-cost technology for a transformation of electromagnetic wave energy to electric power. Creation of optical rectennas array requires respectively low-cost materials and they can be few times less expensive than conventional solar cells. In fact, only thin films of aluminum and plastic are used. A substrate can be freely selected from inexpensive materials such as plastic or glass. According to statements of one of researcher of optical rectenna based solar cells Steven Novak, the current estimated cost of materials for a creation of nantennas massive is around 4-9 euros/m^2 [**24**]. On the other side, a creation of optical antennas and optical rectenna diodes requires well-adjusted complex technologies such as submicron lithography. Facility for a creation of this type structures is very expensive, slow and not suitable enough for large-scale production. However, the development of nano transfer or nano-imprint technologies in roll-to-roll fabrication methods will improve efficiency and decrease a cost of large-scale production [**24**].

According to limitations which were declared before at the current time, there are no real optical rectennas for solar radiation absorption. During last few years devices operating with frequencies of no more than few terahertz were represented. Nevertheless, it is a very young technology which is worthy of investments and future research.

4 QUANTUM DOTS

Semiconductor technologies are playing a significant role in the modern society based on electronic devices with complex technological operations. The researching of the properties of materials and realization of interconnection between atomic structure of materials and their properties marked the need of development in the area of semiconductor technologies. With a development of nanotechnologies and chemistry creating of the hetero structures with new features became possible. Better control of electrical and optical properties leads to a creation of electronics with better quality and fulfilling human needs more effectively. It was expressed in a new generation of electric devices such as quantum well lasers and resonant tunneling transistors [**32**].

The idea of hetero structures creation appears from modification of the materials band-gap by sandwiching of the thin layer of materials with different value band-gap. Creation of the quantum well became possible when two layers of material were separated by third separating layer of material with the higher energy of a band-gap, for example, AlGaAs. The quantum well structure confines free charge carriers motion. As a result, two-dimensional confinement of electron and holes were created. The next development of the area of nanomaterials was connected with the creation of quantum wires and quantum dots for one and zero-dimensional confinement respectively [**33**].

The first quantum dots were made of small semiconductor crystals of CdSe and ZnSe replaced into glass matrix. Depending on the condition of growing the result was a nearly spherical quantum dots with radius from 1 to 100 nm [**34**].

4.1 Introduction to quantum dots

Quantum dots are artificially created structures of semiconductor small enough for a demonstration of quantum properties of a particle. The size of this type of structures should be on nano scale level that leads to confining of moving of free charge carriers such as electrons and holes. As in natural atoms or quantum wells with determine depth, quantum dots have bounds and discrete electronic stages. That is why sometimes they are called as artificial atoms [**35**].

Today quantum dots are the most interesting and attractive nanotechnology with a vast number of applications. It happened because of their unique properties such as the relation of the width of the band gap and the size of quantum dot, their form, and material. The easy tunable band gap energy leads to thousands highly perspective applications such as new generation of transistors, solar cells, lasers and high-quality displays [**36**].

Alexey Ekimov discovered quantum dots while working at the Vavilov State Optical Institute. His paper titled "Quantum size effect in three-dimensional microcrystals of semiconductor" was published in 1981 [**37**]. During his work, specters of exciton absorption of micro-crystals CuCl growth in glass matrix were investigated and short-wave shift which corresponds to quantum size effect was discovered [**37**].

Louis Brus in Columbia University discovered colloidal semiconductor nanocrystals. The paper "Electron–electron and electron-hole interactions in small semiconductor crystallites: The size dependence of the lowest excited electronic state" was published in January of 1984 [**38**]. During his research at Bell Laboratory, the properties of CuCl crystals was calculated such as Schrödinger equation for determination of energy stages, effective mass, kinetic energy, potential energy, lowest excited electronic state energy and the relation of the band gap energy to size, shape, and material of quantum dots was noticed [**38**].

Nevertheless, only in 1988, Mark Reed called artificial semiconductor nanocrystals as quantum dots during his work on the paper which calls "Observation of discrete electronic states in a zero-dimensional semiconductor nanostructure" [**39**]. The effect of resonant tunneling through the quantum dot and its relation to the discrete state density of the dot was investigated.

Over the next years, hundreds of laboratories and scientists all over the world were involved in the researching of quantum dots properties and features. The potential applications of quantum dots as semiconductors with unique properties exist in the areas of quantum computing, biology, quantum electronics and energy production by quantum dots based photovoltaic devices. The researching of the potential application and features of quantum dots continue to this day. Moreover, the first commercial samples of the technique used quantum dots already exist such as display screens used quantum dots for backlight and filtration of unwanted colors for improving the represented color gamut [**40**].

4.2 Operational principle of quantum dots

Quantum dots are artificially created semiconductor crystals which confine moving of free charge carriers in three dimensions. Basically, it means that semiconductor structures with size less than two lengths of Bohr radius of hydrogen atom confinement moving of exciton (the electron-hole pair). The three dimension confined system can be characterized as a potential well.

The potential well is an existed location where the local minimum of potential energy exists. The behavior of the particle with energy less than the depth of the potential well can be characterized as a fluctuation in the well bounds. The fluctuation range of the particle will depend on particles energy. From the classical physics point of view, the particle cannot overcome bounds of the well, but according to quantum mechanics, the particle can be found elsewhere with some predictable (non-zero) probability. It calls the tunneling effect and the probability of the tunneling effect depends on the particles mass, energy and the width of the potential well [**41**].

Another important property of the quantum dots is appearing on discrete energy stages of the band gap energy. In practice, it is connected with a solution of Schrodinger equation for infinite potential well. For quantum dots, the relation of size and band gap energy exists. As stronger confinement of the particle, as the band gap will be divided into more energy levels. The result of the splitting in the strong confinement structures is the rising of the value of the emissions energy [**41**].

In practice, the specific properties of nanostructured materials can be determined by the number of dimensions of dimensions confinement. Dimensionality of a nanostructure determines the ability of free carriers to move in a material. Usually, nanostructured materials compare with the same bulk material where free carriers are able to move freely. The continuous density of energy states leads to smooth valence and conductive band. Nevertheless, there is a dependence of a separation of an energy stages within the valence and conductive band to the number density of atoms.

Basically, when the number density of atoms in lattice decreases the separation of energy states appears more and more. The confinement of a material appears in the extinction of continuous bands. Quantum dots are zero dimensional systems with confinement of charge carriers' movement in all directions. The quantum dots' density of states can be described being a mathematical delta function [**42**]. Different confinement systems and their density of states function can be observed on the picture below.

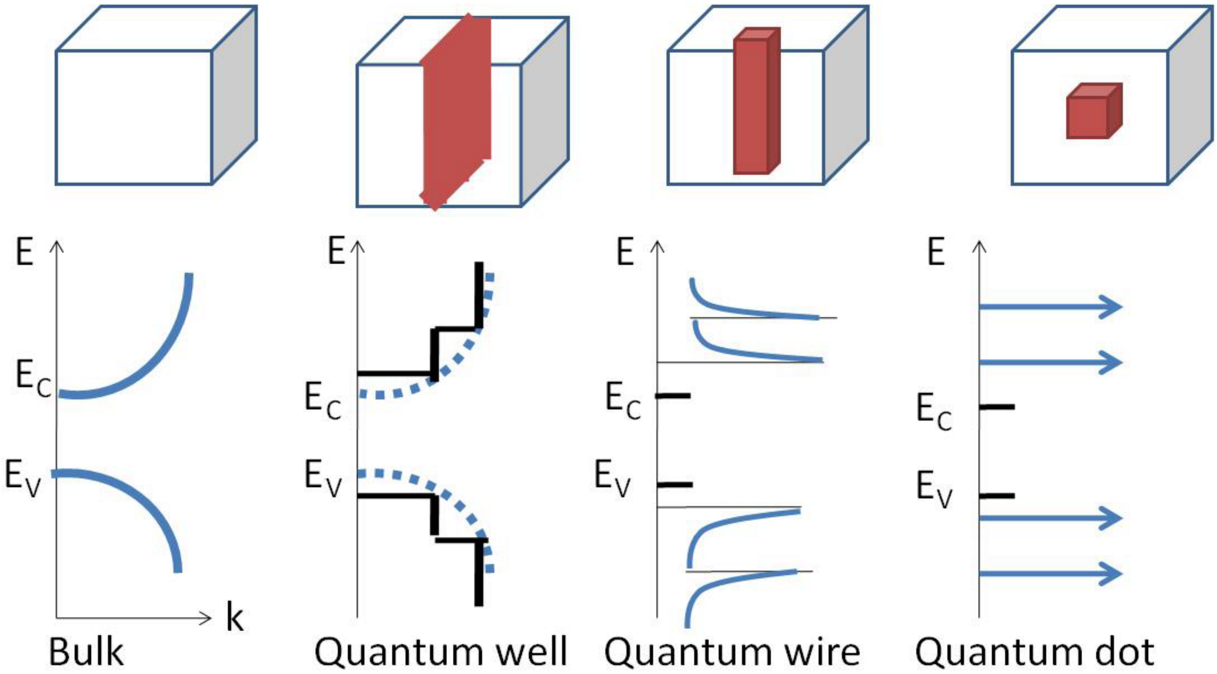


Fig. 15. The density of states in different confinement configurations: (a) bulk; (b) quantum well; (c) quantum wire; (d) quantum dot. [**42**]

The above-mentioned picture represents the order of confinement in the material which determines movement of movement of charge carriers inside a structure. The graphs below represent a schematic density of states in relation to material structure. It means that electrons and holes in the material can obtain only certain kinetic energies which depends on the physical structure of this material.

4.3 Advantages of quantum dots

To begin with, nanostructured materials demonstrate unusual features and properties which are different from natural materials. The above-mentioned changes are demonstrated in sundry features beginning from melting temperature to electric conductivity. Quantum dots as three dimensional confined systems are not an exception but confirmation of superior properties of the nanomaterials. The most important changes of the quantum dots properties are based on the fact the band gap energy depends on the size of a quantum dots. Materials with different band gap energy can be obtained from the same material by changing of a fabrication procedure or conditions of manufacturing. The effect of these changes can be noticed in changes of optical properties of the material, because changing the band gap energy leads to significant changes in absorbing and emitting properties [**42**].

The physical concept of the light absorption is based on the fact that photon absorption leads to electrons' energy increasing, after overcoming the energy of chemical bonding electron excites from the valence band to the conductive band with living a hole in the valence band. Usually, electron and hole are connected to each other and form an exciton pair. The returning of the electron to the position of hole occurs when electrons energy decreases to the ground state and calls recombination. The process of recombination is connected with the fluorescence of the photon with the energy equal to the band gap energy [**43**].

As the band gap energy depends on the size of the quantum dot, it has the major effect on the energy of the emitted. Basically, the larger a quantum dot, the lower the emitted energy will be. It means that the spectrum of the emitted wave is redshifted with the quantum dots size rising [**43**]. The emitting spectrum of quantum dots can be observed on the picture below.

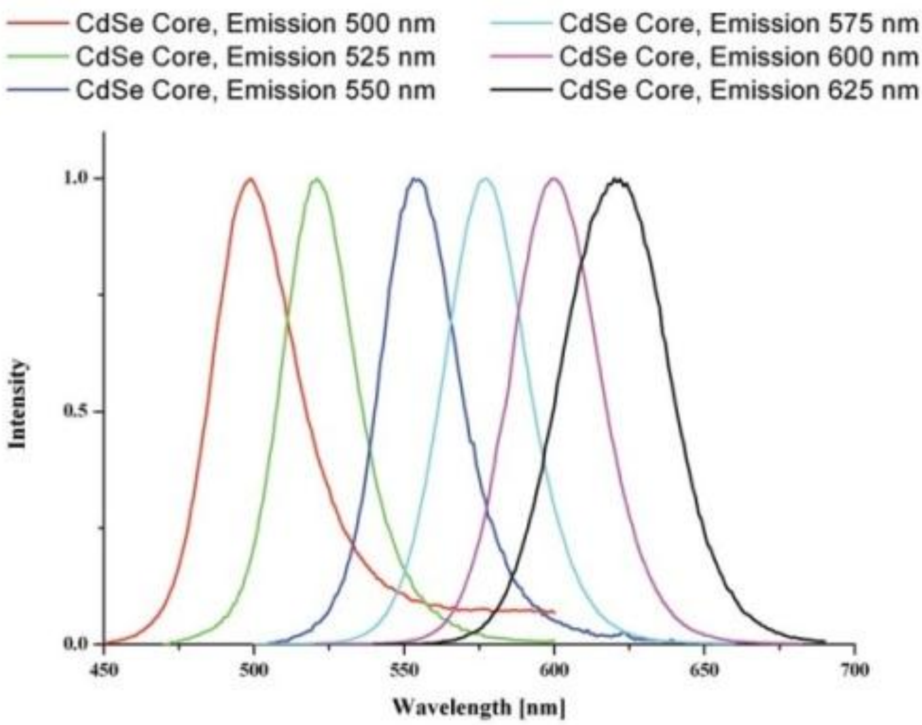


Fig. 16. CdSe quantum dots fluorescence spectrum relation to a particle size. [**44**]

On the other side of the quantum dots light emitting is the absorption features. As the quantum confinement of quantum dots is higher as the higher number of discrete energy states which leads to appearing of the absorption peaks in points of the energy matching. Moreover, the point of the energy absorption has determined energy fluctuation which leads to a not ideal delta function but to more realistic Gaussian destitution. All these facts lead to the appearing of the wide energy range of the absorption spectrum [**45**]**.**

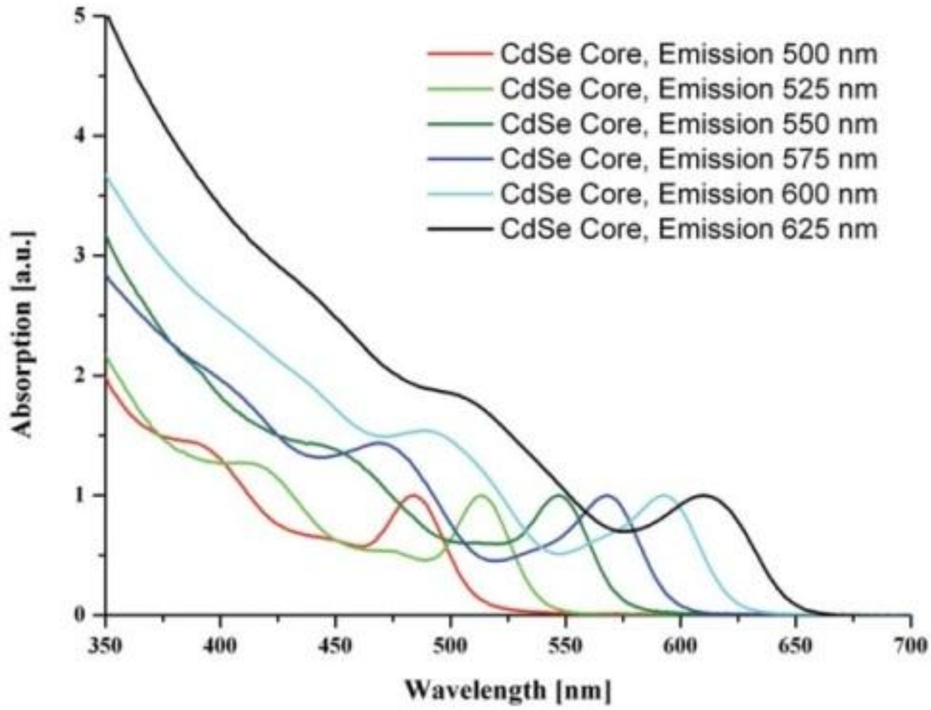


Fig. 17. CdSe quantum dots absorption spectrum relation to a particle size. [**44**]

Moreover, quantum dots have a lot of significant features which effect to the absorption and emission of electromagnetic wave procedure. One of them is multiple electron-hole pair generation. The above-mentioned phenomenon calls multiple exciton generations and is based on the fact that few excitons can be produced when the single photon was absorbed in quantum dots [**46**]. The schematic illustration of the multiple free charge carriers is represented on the picture below.

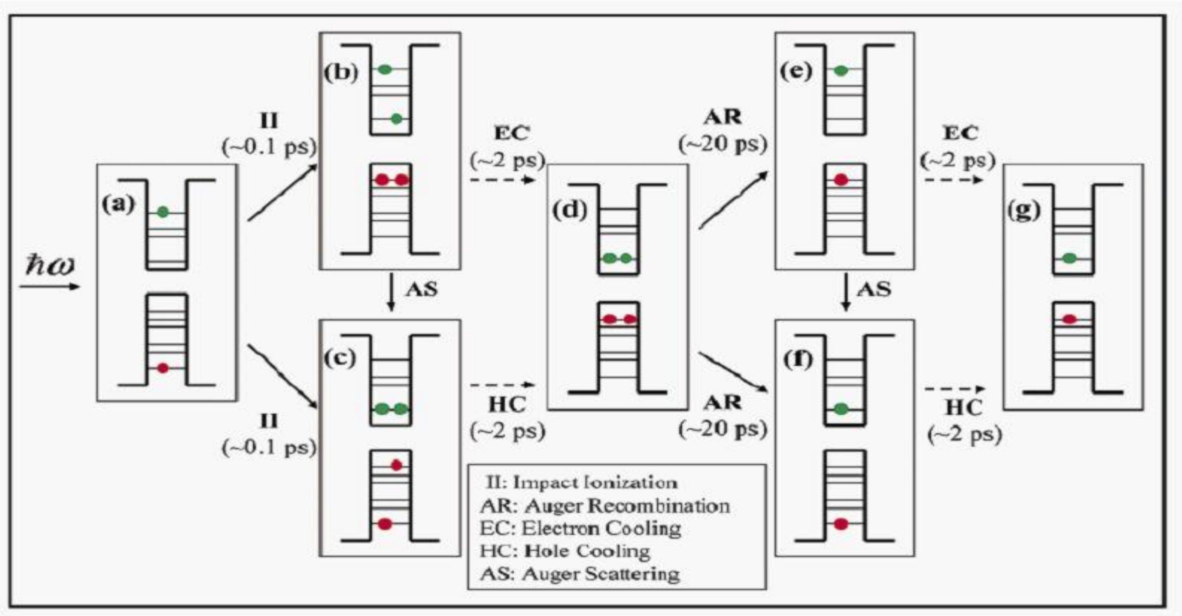


Fig. 18. Illustration of the processes leading to the generation of multiple charge carriers in a quantum dot. [**46**]

Another important point is quantum dots manufacturing. At the moment there are few main methods of quantum dots synthesis exist based on the bottom up and top down ways of nanostructures synthesis. The selection of a synthesis method depends on purposes of quantum dots and will determine properties of quantum dots. The main methods of quantum dots synthesis:

- Molecular beam epitaxy
- Metal organic chemical vapor deposition
- Electron-beam lithography
- Wet colloidal synthesis
- Spontaneous occurring in quantum well structures

The above-mentioned methods are well developed and allow creating structures with required properties of size and form.

4.4 Disadvantages of quantum dots

Despite the dozens of advantages and unusual properties of quantum dots, they have some drawbacks which impact to their development and permanent using in practice. One of them is the issue of quantum dots toxicity which became more and more important in the modern world with growing demand of nanostructures. [**47**] Some type of nanostructures and nanomaterials influence on the human health and have a probability of environmental pollution. Notably, that the major part of research in the area of the quantum dot toxicity is focused on the poisonous of the quantum dots material such as cadmium and his compounds [**47**].

Nevertheless, scientists do not reject the possibility of toxicity effect depending on the quantum dots size, shape and effects of possible compounds based on the decomposed elements. The investigation of quantum dots properties and features is continuing [**47**].

4.5 Constraints of quantum dots

The major issue of the quantum dots using is their stability which has a significant effect for possible applications of quantum dots. The main issues of the quantum dot stability are their life time and deposition. In practice, it means that researchers face the problem of how to extend the life time of quantum dots and decrease the influence of quantum dots decomposition and save its properties for a longer period of time [**48**].

Nowadays, a lot of laboratories and companies investigate and research in the area of the quantum dots life cycle. The life time depends on the quantum dots shape, form, and material which they were made. Every year scientists and researchers confirm that the life time was extended and quality was improved. Nevertheless, the life time of modern quantum dots is approximately from few days to few years which lead to competition on the further quantum dots market [**43**]. All these set of factors and issues are made quantum dots dangerous and unreliable material for real life use. In spite of it, quantum dots have needed properties and are worth the future research.

4.6 Quantum dots solar cell

Solar cells based on the effect of light absorption calls a quantum dot solar cell. The purpose of using quantum dots over the standard semiconductors is the high tunability of the material properties. The main advantage of quantum dots is highly variable characteristics of the band gap energy with the ability to use similar material but with different dots size which will effect for main characteristics [**49**].

For standard semiconductor materials, the band gap energy depends on the material and cannot be easily changed. The above-mentioned property of quantum dots gives a high potential in the development of solar cells. In practice, it means that well-selected quantum dots can improve the efficiency of solar panels and decrease the price of their manufacturing. In wet reactions of synthesis, quantum dots properties can be modified by changing the temperature and time of synthesis. Moreover, the tunable band gap energy and ability to combine dots with different size in one module make this nanostructure very attractive to the creation of multi-junction solar cells. Nowadays, a lot of quantum dots based solar cells exist. The principle of their work is dome different and use different properties of quantum dots [**50**].

5 THE PROPOSED CONCEPT

The idea of the theoretical model creation is based on the need for the good explanation and physical properties analysis of the device. The main purpose of a cooperative application of quantum dots and optical rectennas is to increase efficiency of the light absorption and conversion processes inside the structure with further ability to apply these structures as the nano based solar cell with the new prospective features and characteristics, which will effect for the development of the photovoltaic devices and renewable energy technologies.

The process .occurring in the Sun is the nucleosynthesis of helium from hydrogen which is called the fusion [**51**]. Due to the gases deposition in the process of the sun burning and properties of the atmospheric absorption, the solar radiation spectrum has a specific form which effects to the efficiency of devices for electromagnetic radiation of sun conversion to the direct current.

The solar radiation is the main source of energy for the Earth. The major part of the energy sources which are available for the humanity is the products or different forms of the solar radiated energy. The power is characterized by the solar constant which means the power emitted to the unit area which is located perpendicular to the sun light on the distance of the one astronomical unit from the solar surface. The solar constant is equal to the 1370 W/m^2. When the sun light is going through the earth's surface, the solar radiation lost approximate 370 W/m^2. Basically, for the ground surface at the equator point only 1000 W/m^2 accounts. Due to the photosynthesis process, fossil fuels were created such as oil, coal and natural gas. The scheme below represents the energy sources and their origin [**26**].

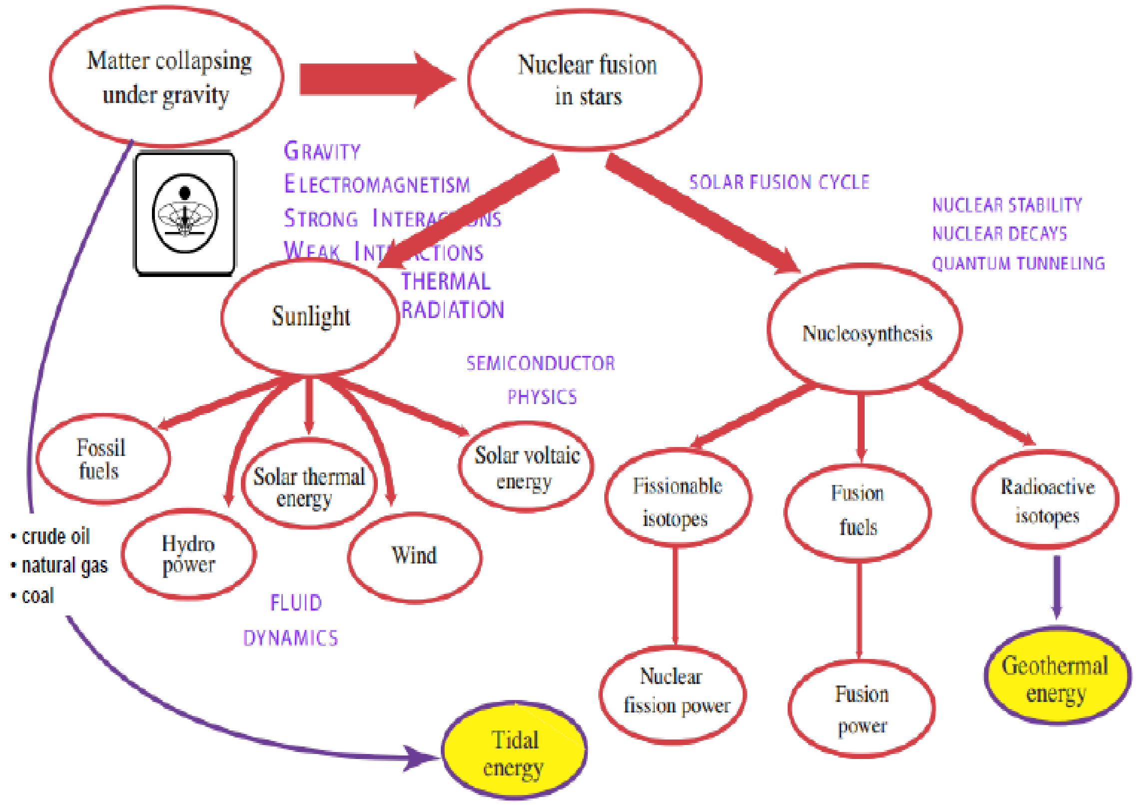


Fig. 19. The types of energy sources and their nature. [**52**]

Nevertheless, the Sun formed 4,6 billion years ago and it is considered that the Sun is roughly at the middle of its lifetime, as it will remain stable for more than five billion years. That means that the sun radiation as the energy source is an inexhaustible source of renewable energy to humanity which can cover the growing consumption of the planet few times. [**53**] The picture below represents the schematic presentation of the energy sources available to the humanity and the nature of their origin. It is obvious from the figure that the major energy source is the Sun which has the significant advantages over the other sources of energy such as:

- Highest resource availability of all renewable energy sources;
- The least cost energy sources in many regions;
- There are no significant sustainable constraints;
- Greenhouse gas emissions from the energy production match the climate change constraints;
- There is no site in the world having

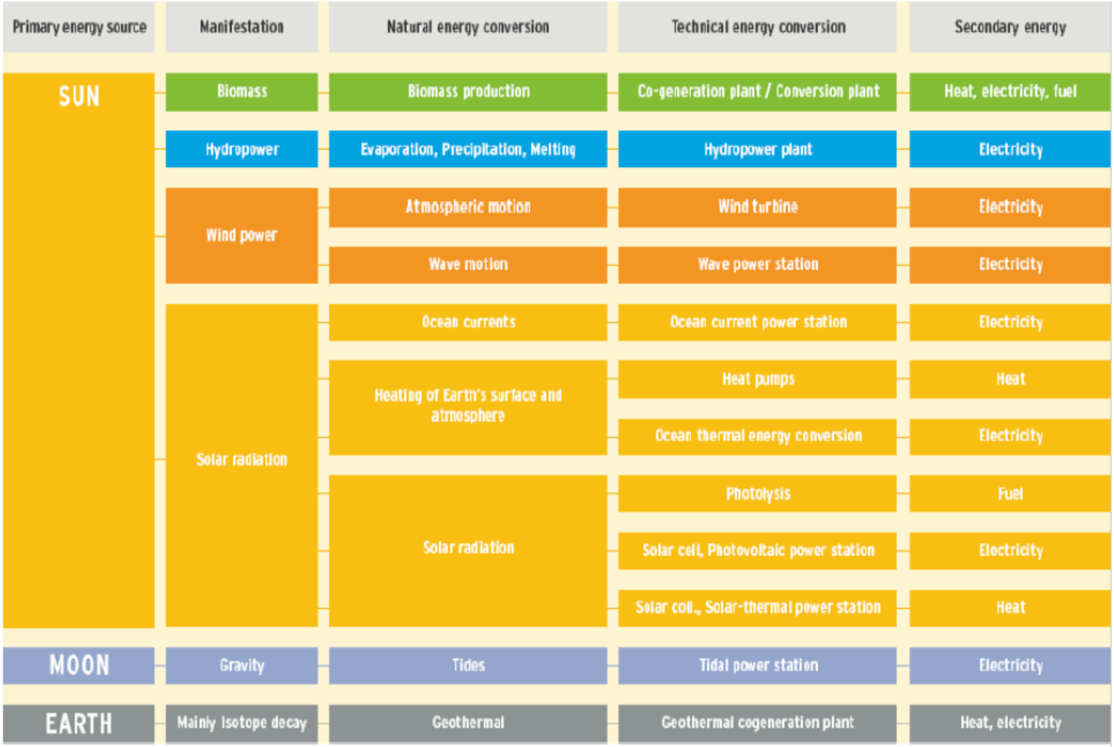


Fig. 20. The schematic presentation of the energy sources available to the humanity. [53]

5.1 Introduction to the proposed concept

The creation of the theoretical model is an important part of the research which effects for the further understanding of the processes going on the device. Due to these reasons, the theoretical model is necessary. The model creation begins from the explanation of the physical processes which are going to the device. The device is based on the combination of quantum dots and optical antennas based on nanowires and high-speed diodes. The necessity using the combination of quantum dots and optical antennas is based on the physical processes and features of the above-mentioned materials.

Separated operations in these nanomaterials have their own drawbacks and negative features which effect to the development of these materials for the purposes of the solar energy harvesting. In practice, it means, that using of these nanostructures is constrained by their properties. The major drawback of the optical antennas consists of the nanowires and high-speed diodes are the fact that the due to the operational principals of the antennas theory, the optical rectennas cannot operate effectively with the wide range of the wavelengths [**24**].

Due to the theory of the antennas operation, the antennas can work with the efficiency about 99 percent with the determine wavelength which they design for [**23**]. The efficiency of the rectenna operation corresponds to the Gaussian distribution function. Nevertheless, the optical rectennas is a decent option of the converting technology which allows effectively transform a determine range of electromagnetic wavelengths to the electric power in the form of the direct current [**23**]. This constraint is not important if the absorbed electromagnetic wave will have a high-intensity peak.

On the other side of the above-mentioned conversion technology is the layer of quantum dots which were design for the emitting of the electromagnetic wave with determine frequency. One of the most important features of the quantum dots is that the quantum dots structure can absorb a wide range of wavelengths which correspond to the photons with energies higher than the band gap of the quantum dot.

The main principle of the combination of these technologies is based on the idea of matching of the quantum dots emitting wavelengths and optical rectennas absorbed wavelengths which will effect to the efficiency of the conversion process. In practice, it means that the quantum dots emitted electromagnetic wave will be absorbed by an optical rectennas surface which will convert emitted power to the electric power in the form of the direct current.

5.2 Operational principle of a quantum dots-nantennas solar cell

The basis of the approach of the combination of quantum dots and optical rectennas is reemitting properties of quantum dots. As was clarified in paragraph 4.3 the absorption and emitting properties are unique and can help to improve efficiency characteristics of the optical rectennas based solar cell. The unique properties of quantum dots are in the absorbed and emitted spectrums which were represented in Figure 16 and Figure 17, respectively.

In practice, it means that quantum dots are used as a frequency transformer for improvement of efficiency of optical rectennas operation. The efficiency of the made solar module will depend on the quantum efficiency of quantum dots to a great extension which means what percentage of the absorbed power can be emitted at the determined frequency. The energy of the emitted photon is equal to the band gap energy of the quantum dot which means an ability of tuning of the quantum dots spectrum depending on the condition of quantum dots synthesis.

5.3 Advantages of a quantum dots-nantennas solar cell

The purpose scheme of the joint using of quantum dots as a frequency transformer and optical rectennas as a form of energy transformer has a lot of advantages which can effect to the further application of this method.

The main benefit of the above-mentioned combination is in total converting efficiency improvement. The efficiency of the converting process is an important point of the potential devices using [**54**]. In theory using this method allows to improve an efficiency of the solar power harvesting and converting it to electric power. The calculation of the total efficiency of the converting process is a complex and substantial task. It is purposed that the efficiency of using this method allows to improve efficiency and overcome some of the limits which play important role in the solar energy harvesting by the conventional solar cells [**54**].

The principle of the total efficiency improvement is based on the ideas that harvesting and converting of the solar power is going without the creation of free carriers and unique properties of quantum dots and optical rectennas. The above-mentioned method allows overcoming thermodynamic efficiency limit due to the absorption properties of quantum dots which are different from the bulk semiconductor structure [**55**]. Moreover, multiple photon absorptions play important role in the quantum efficiency improvement. In practice, the major constraint which limits the converting efficiency of this method is based on the quantum efficiency of quantum dots.

Another important reason for the method efficiency improvement is based on the concept of recombination which usually has a poor effect on the efficiency of the conventional solar cells, but the method of joint using of these technologies based on the principle of reemitting of light which implies recombination of energy carriers [**33**].

One of the most important reasons for the investigation of nanomaterials is the price related to the properties of the material. In practice, it means that the using of nanomaterials and nanostructures allow to receive unique properties of the structure and decrease expenses due to the material weight reduction and efficiency improvement [**8**].

5.4 Disadvantages of a quantum dots-nantennas solar cell

First of all, disadvantages of the joint using of quantum dots and optical rectennas are similar to the separate using these technologies. Nevertheless, the main constraint of this combination is difficulties with the manufacturing, production, and storage of these technologies at the real life.

Basically, the main problem is in the modern technology which can limit the ability of this type of structures manufacturing [**23**]. Nowadays, the manufacturing technology can produce this type of structures in a small scale which effects for the manufacturing cost and ability to use them in real life.

Nevertheless, it is expected that in the near future the roll-to-roll technology and development of quantum dots with extended lifetime will fix the issue of the nanostructure production and development [**19**]. These structures and its manufacturing are emerging technologies and required well development and better investigation of their properties.

5.5 Purpose of the concept creation

The main purpose of this manuscript is the creation of a new structure which will obtain new characteristics and features which can be more suitable for the solar energy harvesting and converting purposes than the conventional solar cells. The investigation and research of the renewable energy technologies play important role in the modern society and can help to save the planet and create the resilient future for the future generation.

The analysis of the new nanostructures and their properties has a significant impact on the development of new materials and creation of the new methods for the nanomaterials studying and further research.

6 QUANTUM DOTS-NANTENNAS SOLAR CELL CHARACTERISTICS

The calculation and assuming of the purposed model characteristics and properties are an important and significant part of studying of new structures. The characteristics determination is a complex task which requires a wide knowledge of quantum physics and understanding of nanostructures properties and processes going into them.

6.1 The proposed concept creation

The model creation begins from an understanding of the processes which will go inside the proposed solar cell. The main principle of the combination of quantum dots and optical rectennas is that the quantum dots surface absorbs the solar radiation in a wide range and emits it at the determined wavelength. The optical rectenna consists of the nanowire with the length of the quarter of the absorbed wave and high-speed diode which design for the frequency of the absorbed wave.

Nevertheless, the light emitted by quantum dots will develop in the all direction which will effect and decrease the efficiency of the absorption. For prevention of these negative consequences, the translucent mirror was applied. The main purpose of the half transparent mirror is to skip incident light from outside and reflect light emitted by the quantum dots in the direction to the layer of optical rectennas.

The optical rectennas consist of the surface of nanowires with the length of a single particle equal to the quarter of the emitted light of the quantum dots and thin-film diodes which design for rectifying of the specific frequency which is equal to the frequency of the emitted light by quantum dots.

All these surfaces are located on the dielectric substrate which prevents oxidation and contact with water what will protect the solar cell and keep it safe for a longer time.

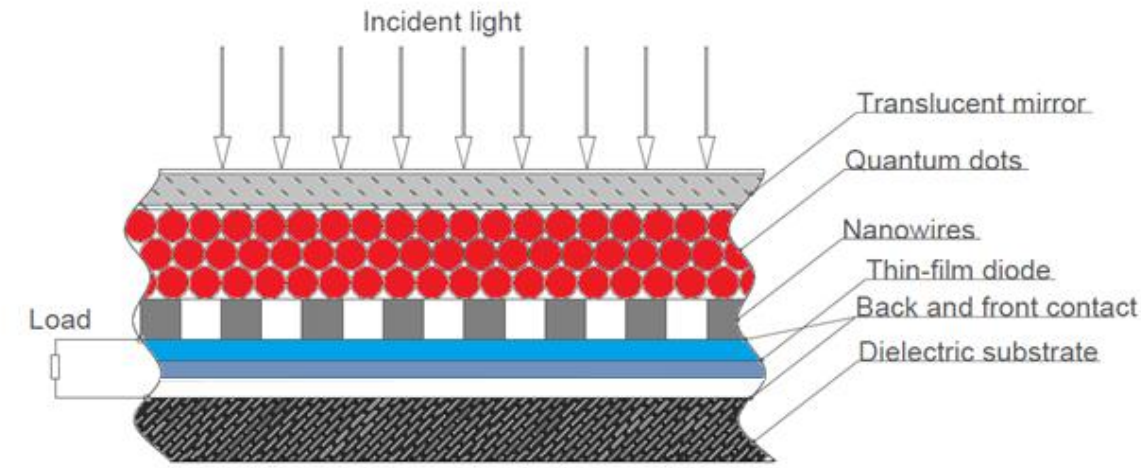


Fig. 21. The cross-section of the device.

In practice, incident light goes through the translucent mirror and absorbs by the quantum dots and then emits on the determine frequency which is equal to the quantum dots band gap energy. The emitted light is reflected from the mirror surface and goes to the optical antennas which absorb the emitted light and rectifier it to the direct current which supplies the load. The figure above represents the schematic cross-section of the device.

6.2 Efficiency assessment

The efficiency of any device and technology is one of the most important characteristics. In the modern world full of renewable energy technologies and energy saving abilities, the issue of the efficiency plays a significant role and effect for the further development of the technology. The picture below represents the efficiency of the different photovoltaics technologies and their development from 1976 to 2017. The major part of different photovoltaic technologies has analogous constraints which limit their efficiency in their principle.

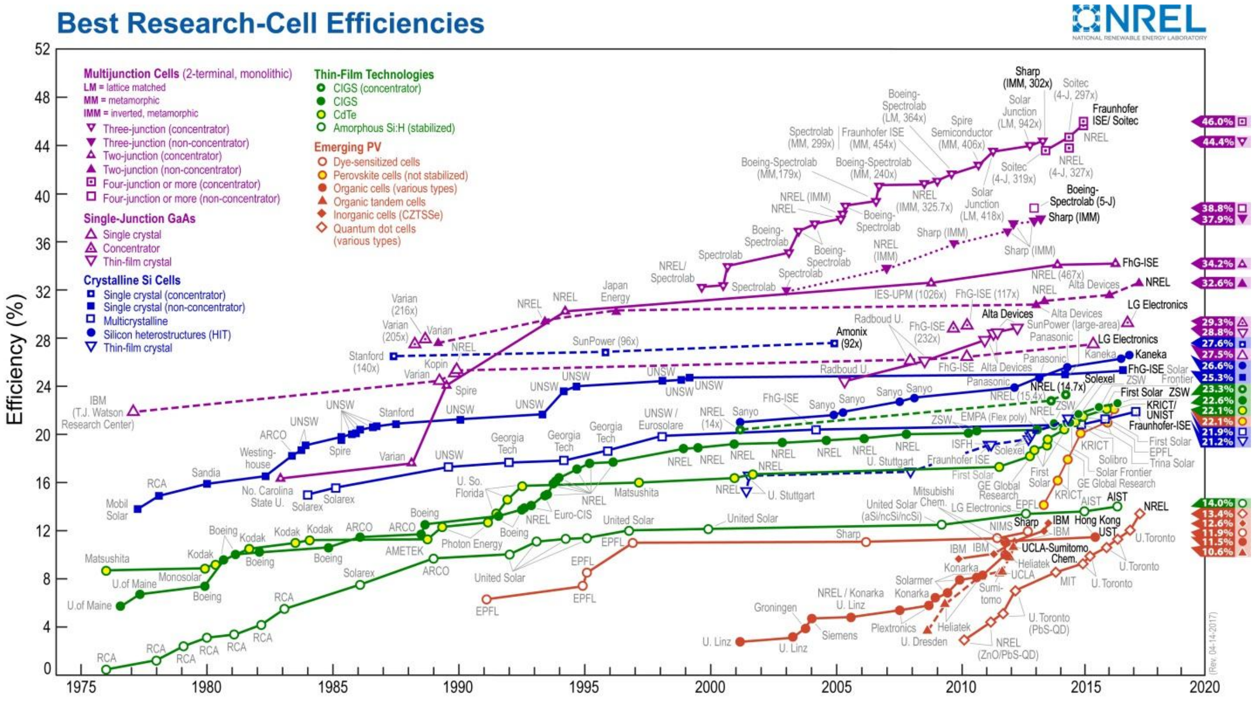


Fig. 22. Conversion efficiencies of best research solar cells worldwide from 1976 through 2017 for various photovoltaic technologies. [**56**]

The calculation of the device based on the combination of quantum dots and optical rectennas is a complex process which requires using the quantum dots absorption and emission spectrum and characteristics of the optical rectennas such as absorption and rectification efficiency and other significant values such as quantum dots quantum efficacy and reemitting efficiency which will be different for sundry materials. Different materials of quantum dots and forms of nanowires have significant effects on the efficiency and properties of the proposed device.

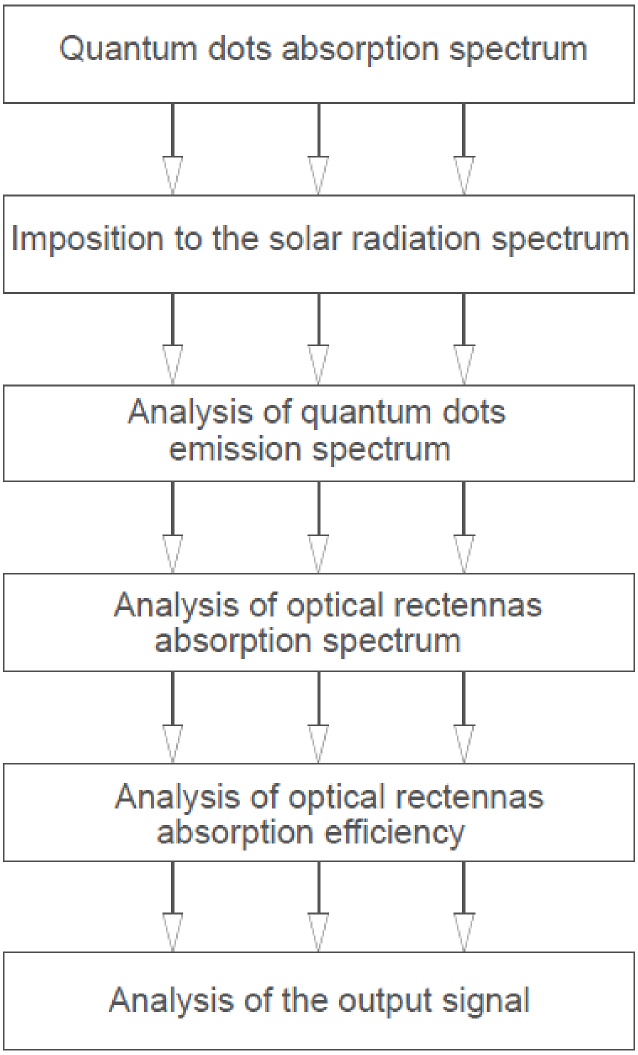


Fig. 23. The diagram of the device efficiency assessment.

The schematic presentation of the efficiency calculation process is represented on the picture above. Spectra of emission and absorption should be applied in accordance to steps in the diagram. The graphs below represent sequential overlay of absorption and emissions spectrums of different layers of the proposed device.

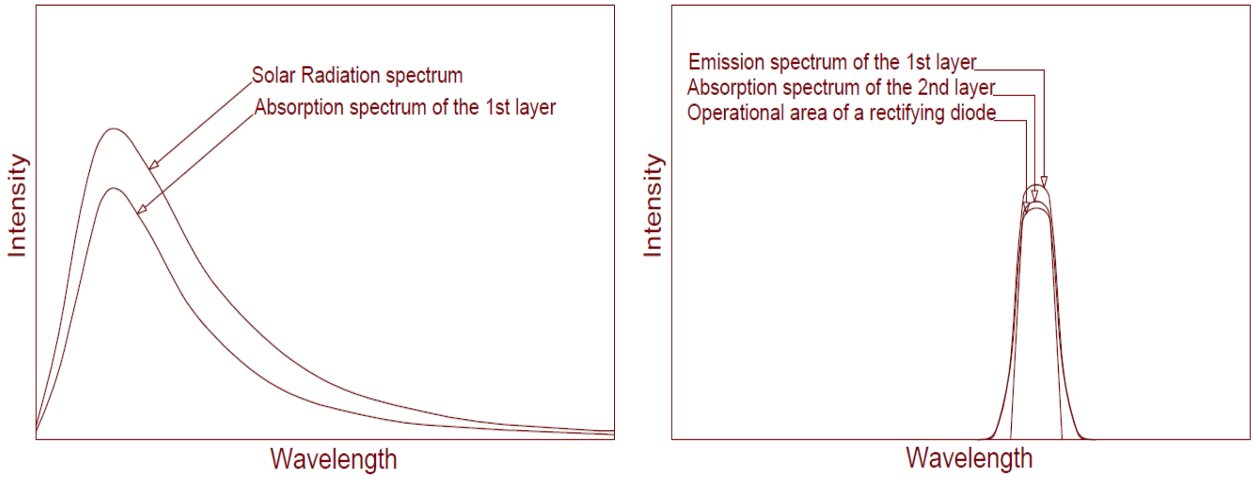


Fig. 24. The diagram of the device efficiency calculation.

The efficiency of the device depends on materials, forms, and size of nanostructures. These factors have a significant effect on the properties of the device. The calculation of these features requires wider studying of this device and explanation of its properties. Nevertheless, several values can be assumed for a rough estimation of the device efficiency. The simple downshifter model with a step absorption function should be applied for the assumption of the quantum dots absorption spectrum. Quantum dots emission spectrum represents the Gaussian distribution function. This functions and their relation in per cents are represented on the picture below.

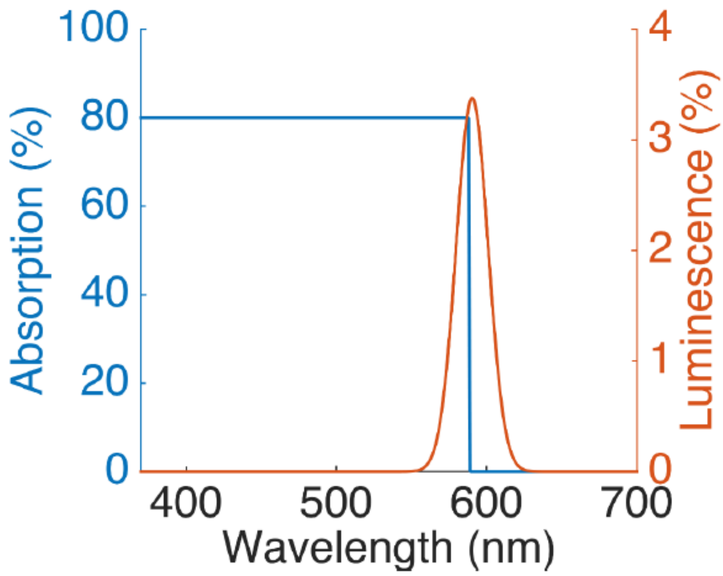


Fig. 25. The model with step absorption function and Gaussian emission function. [**57**]

For the calculation, the absorption efficiency of a quantum dot layer is assumed equal to 0.8 which means that 80% of the incident photons in the wavelength range are absorbed by the first layer. The efficiency of a light emission by quantum dots layer is assumed equal to 1. This approach is useful for seeing the general trends and help to imagine the best scenario. In addition, this approach allows adjust input parameters and compare results of the calculation.

The simplified optical rectennas consists of an antenna and a rectifier. The absorption spectrum of optical rectennas has the form of the Gaussian distribution function with the maximal point at 99%. The efficiency of the rectifier diode can be assumed as 0.7 and spectrum has a form of a step function. The efficiency of the translucent mirror assumed as 0.85 which means that 15% of light emitted by quantum dots will be lost as a reflected outside light.

The solar spectrum in a range from 400nm to 1600nm has 85% of the total solar irradiance. [**27**] The maximum of the emission spectrum of quantum dots is adjusted to 1600nm. The maximum of the absorption spectrum of optical rectennas is adjusted to 1600nm. Efficiencies of each layer and component should be multiplied for calculation of the total efficiency of the device. The total efficiency of the proposed device is approximately 40%. The data of maximum efficiency improvement collected by a researching group in the University of Maryland allows to compare results of calculation by the simple step model, results of calculation by Drude-Lorentz model and experimental data. The results of the research are represented in the picture below.

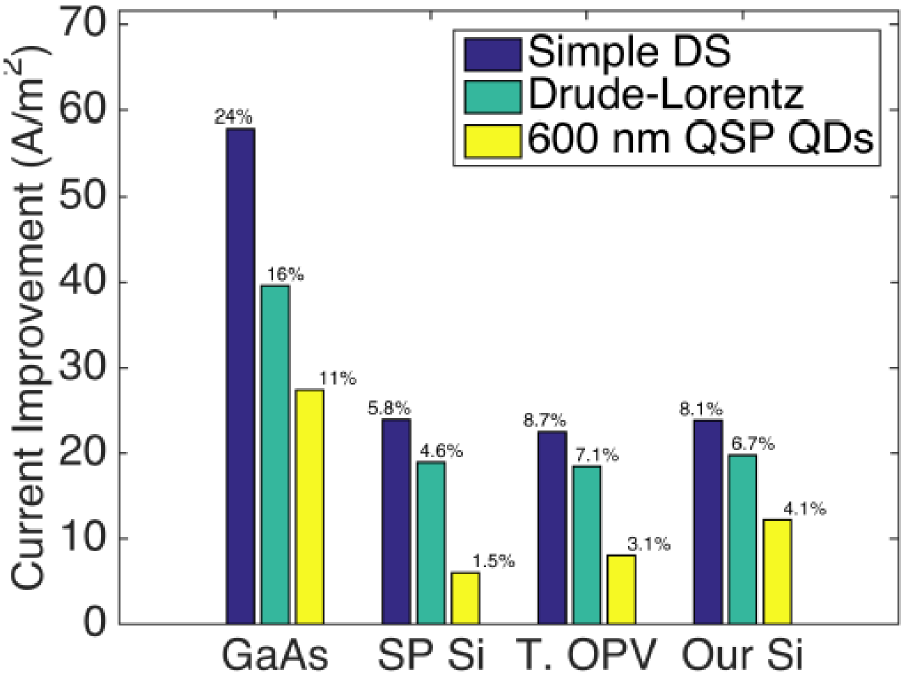


Fig. 26. The data of the maximal efficiency improvement. [**57**]

As can be seen from the graph the simple model which we used provides the highest efficiency improvement because of its inaccuracy and roundness. The relation between the simple model and the experimental data is different two times. In accordance to the above-mentioned data the total efficiency of the device based on the combination of quantum dots and optical rectennas can be assumed as 20%.

6.3 Summary of results

The feature of the energy sector was represented and compared with the modern energy sector. The relevance of the renewable energy development was clarified. Semiconductor solar cells operational principles were represented. Quantum dots operational principles and main features were represented. Optical rectennas operational principles and main features were represented. Significant disadvantages of conventional technologies were described. The device based on the combination of quantum dots and optical rectennas was proposed during the master thesis competing. The perspective photovoltaic device was proposed and the main components and structures were described. The efficiency assessment was considered and the concept of the main features was clarified.

7 CONCLUSION

During completing the master thesis the current energy consumption and perspectives of its feature development were described. Modern semiconductor devices’, quantum dots’ and optical rectennas’ basics and operational principles were described. Their advantages, disadvantages and constraints influencing to their application as photovoltaic devices were declared. The perspective solution for improvement of a solar power harvesting device based on joint using of optical antennas and quantum dots was proposed. Application of quantum dots layer as an electromagnetic wave frequency transformer allows to overcome the drawback of a low efficiency during operation on a broad spectrum of electromagnetic waves’ wavelengths and make them a promising technology for photovoltaic technology with careful further research. The main principles of operation and features were clarified. The total efficiency of the device based on the joint using of quantum dots and optical rectennas was assumed. Nevertheless, the future research and development of the proposed device require the creation of a mathematical model for calculation of the most suitable materials’ properties for adjustment of the structure and future experimental researching of the resulting device.

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