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ECONOMIC ANALISES OF NEW PHOTOVOLTAIC MATERIALS APPLICATION AND THEIR EFFECTS ON LANDSCAPE MANAGEMENT

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Summary: *Photovoltaic technology is one of the best ways for application of the solar energy. New photo voltaic panels are composed of silicon pn-junction photocell for converting solar radiation into electrical power. In the future other materials and concepts can be expected to come into play. Some of these are: dye sensitized cells, organic solar cells and various concentrating systems including III/V-tandem cells. Since the solar energy is coming to the Earth as a free renewable resources, it is one of the cheapest way of electric energy production. This paper contains economic analyses of photovoltaic technology application, in comparison with two other alternatives, in one specific ecology camp. Solar power plants have certain impact on the environment. Review on constructed power plants in the world and their effects on landscape management is done.*

Keywords: *solar panels, photovoltaic materials, case study, economic analyses, landscape management*.

1. INTRODUCTION

Global environmental concerns and the escalating demand for energy, coupled with steady progress in renewable energy technologies, are opening up new opportunities for utilization of renewable energy resources and new materials development and application. Solar energy is the most abundant, inexhaustible and clean of all the renewable energy resources till date. The power from sun intercepted by the earth is about 1.8 × 1011 MW, which is many times larger than the present rate of all the energy consumption. Photovoltaic technology is one of the finest ways to harness the solar power. This paper reviews the photovoltaic technology, its power generating capability, the different existing light absorbing materials used, its environmental aspect coupled with a variety of its applications and landscape management, related to the big solar power plants development, [1].
Solar photovoltaics have great promise for a low-carbon future but remain expensive relative to other technologies. Greatly increased penetration of photovoltaics into global energy markets requires an expansion in attention from designs of high-performance materials to those that can deliver significantly lower cost per kilowatt-hour (kWh). To evaluate a new set of technical and economic performance targets, it is examined material extraction costs and supply constraints for 23 promising semiconducting materials.
Twelve composite materials systems were found to have the capacity to meet or exceed the annual worldwide electricity consumption of 17 000 TWh, of which nine have the potential for a significant cost reduction over crystalline silicon. In the literature it is identified a large material extraction cost (cents/watt) gap between leading thin film materials and a number of unconventional solar cell candidates including FeS_2, CuO, and Zn_3P_2. It is developed a roadmap emphasizing low-cost alternatives that could become a dominant new approach for photovoltaics materials research and deployment, [2].

Since the photovoltaic (PV) introduction in the mid 1950s, solar cells have experienced an incredible development. Silicon PV devices were initially employed as reliable and convenient power sources for space satellites, whilst in the last two decades they have found an application on Earth, where they can provide a reliable source of electricity in isolated places, or be connected to the grid in order to produce electricity.

At the beginning of 1980, III-V semiconducotor devices, based on GaAs deposited by means of epitaxial techniques on GaAs substrates, began to be used in PV applications, and thanks to their superior physical properties and enhanced efficiency compared to Si, were soon adopted in space satellites. Several years later, more complex heterostructures based on arsenides and phosphide multijunction solar cells were developed and realised on Ge substrates, and important improvements achieved in the 1990s permitted to surpass the 20% efficiency rate and obtain a significative boost in satellite power sources. By the end of the year 2000 the 30% efficiency goal was reached, thanks to a triple junction InGaP/GaAs/Ge device. Nowadays, III-V semiconductor devices have almost completely replaced Silicon as the main component for space flat PV modules, thanks to their far greater efficiency, low weight and better radiation resistance.

Nevertheless, Si PV is probably one of the most significant examples of a space technology which has finally succeeded in finding an application on Earth, and now has great potential for changing the world-wide energy scenario, thanks to its capability of producing renewable energy. The latter is a particularly attractive characteristic, considered the importance and the necessity to develop a self-sustainable future for mankind and the problems derived from global warming and climate change.

Even if III-V semiconductors seized the role of Si in space applications, nowadays terrestrial Si PV is one of the fastest growing and profitable industry and has enormous potential for changing the lifestyle of millions of people both in emerging and in ‘civilised’ countries. It has taken almost 50 years since the birth of the first Si solar cell right through to the adoption of large arrays of Si PV modules to produce a significant amount of elecricity on Earth at convenient prices, passing through an extensive use of Si in space.

Recalling the example of Si history, it is desirable that arsenides and phosphide eventually find an application as PV devices on Earth in the coming decades, and in this article several achievements needed to reach this goal and possible future scenarios will be analysed.

The 21st century will be characterised by a huge energetic demand: world population is steadily increasing (65 billion in 2005, an estimated 75 billion in 2020 and 9 billion in 2050, [3]), and there are hundreds of millions of people in emerging countries (China and India in particular) which are rapidly reaching the welfare of Western countries.

The world’s total energy consumption for 2002 was estimated at about 121014 KWh, [4], of which about 1/10 was used as electricity. Fossil fuels, in particular coal, oil and gas, contributed with about 80% and 65% to the generation of world total energy and electricity, respectively. It is obvious that these resources on Earth are finite, and it is also clear that their use is causing great social and economical problems for the world, in relation to geopolitical instabilities in controlling energy sources and global climate: greenhouse gases, which are thought to be the main reason for global warming and climate change, are mostly produced by burning fossil fuels.

In order to preserve human civilisation and to grant social and economical development to billions of people in the third world, an answer to the ‘energetic problem’ must be found in the coming decades and should be considered as a main topic of political discussion in all countries. The data reported by the International Energy Agency, [5], suggests that transport (terrestrial, aerial, marine) and heating have the biggest role in energy consumption (about 9/10 of the total energy used in the world is different from electricity); consequently, any energy policy focused on electricity alone is misleading, and in energy-saving attention should mainly be directed towards the development of new means of transportation, rationale goods delivery and optimisation of housing and thermal insulation facilities, since electricity has just a second-order contribution to the use of energy.

Nevertheless, electricity is the basis of all civilised countries and industrialisation, and its access is a fundamental step towards achieving people welfare. As reported in [5], 65% of the World’s total electricity consumption is obtained from fossil fuels; about 20% comes from nuclear power plants and the rest is produced by means of renewable sources, such as hydropower [6], biomasses, PV, eolic and geothermal sources: these sources are seen as the most promising ways of granting electricity to the whole world, and can help to reach a self-sustaining energy system. On the other hand, conventional nuclear power poses unanswered questions such as waste handling, potential hazards of accidents and explosions, similarity with a technology for the realisation of nuclear weapons, plant site security, nuclear fuel control as well as its availability and therefore should not be considered as a reliable answer in the long-term, [7]. It should also be mentioned that the different renewable sources are not in competition as they fulfil many different needs and are suitable in extremely different environments. They all have pros and cons (identified for example, in the location of installation, suitable climatic conditions and presence of primary supply—wind or sun), can be effectively combined to provide a reliable and continuous power supply, and can be scaled from a production going from a few milliwatts to giga/megawatt power plants.

Currently, solar power plants, is still expensive (although prices per kWh have rapidly decreased fast in the past years), comparing with wind power plant, has a longer money payback rate (8–10 years even with a feed-in tariff) and poses important technological challenges, but can be directly used by the final client even in remote locations, does not necessarily require a grid connection (or work in a "net metering' buyback, if a grid is present), is noiseless, maintenance free, reliable for more than 20 years and can be integrated in consumer electronics for low-power applications, [8].

Moreover, solar irradiation in third world countries is extremely high and is seen as the most obvious way to electrify isolated communities. Since the total amount of solar energy reaching the Earth's surface has been calculated at more than 10 000 times the world's total energy consumption, it is obvious that this source, if correctly and efficiently used, can supply the substantial part or even all of our future energetic needs.

Nevertheless, markets and clients are still dubious regarding the adoption of eolic energy and PV modules, as their price is perceived as being too high compared to fossil fuels. But it has to be stressed that current energy rates do not include externalities, i.e. 'The major impact and costs originating from the production and consumption of energy related activities such as fuel cycles', [9].

These costs arise when an activity with a specified price has an impact on another activity, and imposes on the latter an additional cost that was not accounted for in the former price. Greenhouse gases, car exhaust and chemical waste are typical examples of externalities of fossil fuel use [10], because their social costs (not only monetary, but also related to global warming, cancer, illness, etc) are not considered in the market price.

If the price of electricity generated by fossil fuels included externality costs, renewable sources could become more competitive. The adoption of renewables for power generation is slow because of the existence of several development and market penetration barriers, most of which are not scientifically related, [11]. Some of these impediments are:

- economic (lack of competitiveness and internalization of external costs of energy use),
- institutional (lack of co-ordination in governments and institutions, long-term planning policy requirements),
- network (monopoly of generation, transmission and distribution of electricity),
- social (lack of interest in future energy development and sustainability, doubts about new technologies),
- financial (lack of funding for research or pilot-installation).

Only a long-term policy can aid a niche market in developing, expanding and gaining the political and economical power needed to bring a new technology out of the niche and distribute it to everyone. This road was followed by Germany, now the second world leader in the installation of PV solar panels,10 also thanks to the feed-in tariff introduced in 2000.

There are several reports and market studies that analyse the trend in PV installation all over the world, [12]. During the past 4 years Japan, Germany and USA have emerged as leaders in the total kWp installed, sharing together about 90% of the world market. Globally, in 2003 about 753 MWp PV systems were installed, and the 1 GWp barrier was exceeded in 2004. The trend in the PV market has shown an annual increase of about 30% from 2000 until now, making PVone of the fastest growing industries. Because of this, PV is attracting more and more actors, even if the 10 biggest companies alone share about 90% of the global market; according to some studies, a demand increase is expected thanks also to the introduction of feed-in tariff in more and more countries (e.g. Italy and Spain) and the fulfilment requirements of the Kyoto Protocol. In order to reduce CO_2 emission, the European Council has stated that in 2010, up to 20% of electricity should be generated by renewable energy, while in 2030 up to 4% of the World's electricity should be generated by PV.

Estimates suggest that world energy consumption in 2050 will be about 25 Gtoe, or 271014 kWh and, if the world wants to avoid social, economic and environmental problems, the largest part of this energy should be produced by renewables. Moreover, the development of emerging countries as well as their energy policy should not follow the development trend of today's civilised countries, particularly with regards to electricity generation and transport management. Concerning PV (and renewables in general), a very long policy planning period is most definitely needed, in order to support the creation of market demand, the assignment of public funding (with 'roofprogrammes' or feed-in tariffs), and in order to continue a heavy research and development process, [13].
Photovoltaic costs (referring to conventional flat Si panles) depends on the climate and latitude where the panel is installed, and are for large photovoltaic plants.

2. MATERIALS AND METHODS

2.2. Photovoltaic materials for solar power plants

Polymer solar cells (PSCs) have attracted great attention in recent years because of their advantages of easy fabrication, low cost, light weight, and potential for flexible devices. However, the power conversion efficiency (PCE) of the PSCs needs to be improved for future commercial applications. Factors limiting the PCE of the PSCs include the low exploitation of sunlight due to the narrow absorption band of conjugated polymers, and the low charge-transport efficiency in the devices due to the lower charge-carrier mobility of the polymer photovoltaic materials. In this Research News article, recent progress in new conjugated polymer photovoltaic materials fabricated by our group and others is reviewed, including polythiophene (PT) and poly (thienylene vinylene) derivatives with conjugated side chains for a broad absorption band, crosslinked PT derivatives with conjugated bridges for higher hole mobility, and low-bandgap donor–acceptor copolymers for broad, red-shifted absorption to match the solar spectrum, [14].
Organic photovoltaic solar cells bere an important potential of development in the search for low-cost modules for the production of domestic electricity. We review the principles and techniques needed for their development: organic semiconductors, their transport properties and photophysical characteristics, photovoltaic molecule and polymer structures, device technologies, electrical and optical behaviour of the cells, state of the art, limitations and perspectives. Despite some recent record efficiencies, research on organic solar cells is still in its infancy when stability and efficiency have to be compared with the performances of silicon cells. A nominal 10% solar efficiency is the research target for the next few years, [15].
This paper traces briefly the history of this photovoltaic materials and it tries to look at possible future scenarios. A large part of the paper is concerned with silicon although from solid-state physics we know that silicon is not the ideal material for photovoltaic conversion. From the first solar cell developed at Bell Laboratories in 1954 photovoltaics was dominated by silicon. The reasons for this dominating position are investigated. Crystalline silicon today has a market share of 86% which is almost equally distributed between single crystal and cast silicon. Amorphous silicon has another 13%. The main endeavor is to reduce cost. Present trends in the crystalline field are reviewed. The conventional technology still has significant potential for cost reduction but this comes only with increasing volume. A problem to be solved is the supply of solar-grade silicon material. Other future possibilities include thin film crystalline silicon on different substrates. Because of the low absorption coefficient of silicon light trapping is required. True thin film materials need only 1–2 μm of material. Amorphous silicon, copper indium diselenide (CIS) and CdTe are hopeful approaches for very cost-effective solar cells. Some other, more speculative materials and concepts are described at the end of this paper, [16].
Organic photovoltaics in a flexible wire format has potential advantages that are described in this paper. A wire format requires long-distance transport of current that can be achieved only with conventional metals, thus eliminating the use of transparent oxide semiconductors. A phase-separated, photovoltaic layer, comprising a conducting polymer and a fullerene derivative, is coated onto a thin metal wire. A second wire, coated with a silver film, serving as the counter electrode, is wrapped around the first wire. Both wires are encased in a transparent polymer cladding. Incident light is

focused by the cladding onto to the photovoltaic layer even when it is completely shadowed by the counter electrode. Efficiency values of the wires range from 2.79% to 3.27%, [17].
The removal of thin films widely used in photovoltaics (amorphous silicon, tin oxide, zinc oxide, aluminum, and molybdenum) is studied experimentally using multi-kHz Q-switched solid-state lasers at 532 nm and 1064 nm wavelengths. The processing (“scribing”) is performed through the film-supporting glass plate at scribing speeds of the order of m/s. The dependence of the film removal threshold on the laser pulse duration (8 ns to 40 ns) is investigated and the results are complemented by a multi-layer thermal model used for numerical simulations of the laser-induced spatio-temporal temperature field within the samples. Possible film removal mechanisms are discussed upon consideration of optical, geometrical, thermal and mechanical properties of the layers, [18].

Solar power plants

At the beginning of 2013 in the United Arab Emirates, a solar power plant Shams 1 was put into operation, Fig. 1. The power plant was built three years. Consisting of 258,000 mirrors arranged at 768 cilindro-directional parabolic collector reaches the electrical power of 100 MW. Occupying an area of about 285 football fields, this power plant will provide electricity for 20,000 emiratskih households and saving the emission of around 175,000 t of CO_2, which is equivalent to planting 1.5 million trees, or removing 150,000 cars from the roads of Abu Dhabi. In addition, the power plant Shams 1 has a modern system of air cooling, which will significantly reduce water consumption, which is the most valuable resource in the desert regions of the Middle East.
The development of solar thermal power plants in 2012 (712 MW) was significantly faster than in 2011 (440 MW). As a result, the cumulative installed capacity at the end of 2012 reached the electric power of 2.42 GW. The largest part of the new plant (700 MW) was installed in Spain (in the areas of Andalusia and Ekstramadura) thanks to new incentive tariffs, [13].
The most popular technology in 2012 was cilindro-parabolic, whose share was 93%. However, this relationship in the coming years significantly changed, with the construction of new solar thermal power plants with a central receiver, primarily commissioning large-scale solar power plants, Ivanpah, in the Mojave Desert in California, Fig. 1. The plant occupies an area of 1,400 hectares, was built three years ago and put into operation in early 2014. Total investment costs for solar power Ivanpah amounted to 2.2 billion USD, and it can annually supply an electric current about 140,000 California households.

Figure 1. Photovoltaic power plants: "Shams 1" in the UAE (left) and "Ivanpah" in California (right)

Unlike the developments in the market of solar cells, whose costs are declining rapidly, during the implementation of solar power plants that fall was mitigated, which is justified, having in mind the slowness of new applications for the quite bulky plant. Their construction lasts for several years. For these reasons, many companies engaged in manufacturing equipment for solar thermal power plant, stopped working or were taken over by more successful firms.
In order to lower the production cost of electricity from solar thermal power plants, exploring new ways of storing heat collected through the application of different materials and their thermodynamic reaction, a lot of investment and promotion activites are done, Fig. 2.
It encourages the opening of new markets, the most promising for solar power plants, such as Morocco (660 MW), Tunisia (1.6 GW), Egypt (100 MW), Saudi Arabia (25 GW by 2032), United Arab Emirates (100 MW), South Africa (200 MW), China (400 MW) and India (10 GW by 2017), [11].

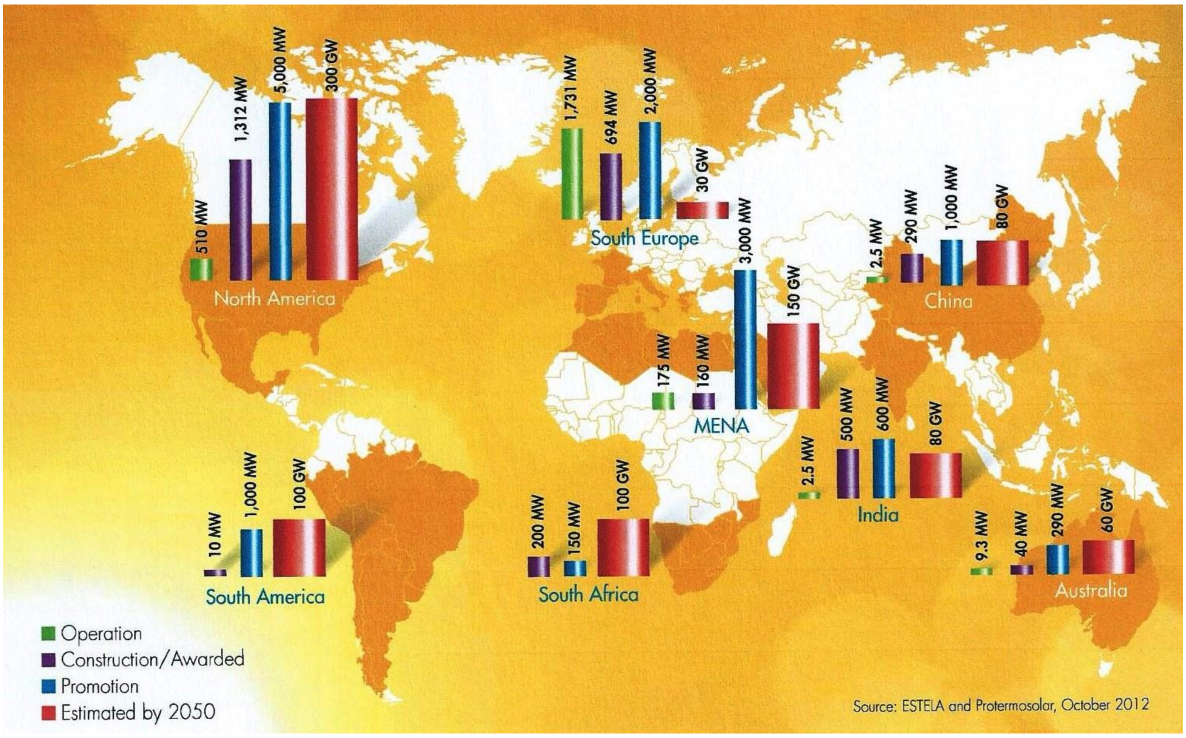

Figure 2. Distribution of solar power plants with predictions [11]

2.2. Mini solar power plant in ecology camp

Experimental mini solar power plant of 200 W was set up 12km southeast of Ulcinj in the ecological camp. Production lasted 36 days and was continuously measured. At the end the total production of electricity was calculated and techno economic analysis have been done. Solar photovoltaic panels are mounted on a wooden roof of pille dwelling, at an angle of 10˚ to the horizontal. This mini solar power plant was used as a case studi for discussion on material used, proces, period of return on equity calculation and economic analises, as wellas for environmental and landscape management discussion. This is a case study with precise techno economical results presented below.

3. RESULTS ON ECONOMIC ANALISES

3.1. Prices and period of return on equity

The prices of photovoltaic panels and complete equipment for the production of solar energy continuously falling. For example, the equipment for the solar power plant of 1 MW inverter and battery, was 7x106 € in Belgrade in 2001. The price of the same equipment, today fell 7 times and purchased for € 1x106. Causes for falling prices lies in:

- increasement of production,
- rapid development of production technology and
- entry of Chinese products into the EU market, which is almost "went to war" with China due to dumping prices.

The total investment for constructive solar power plant is 1000 €. If the electricity produced in the given system, produced kWh would, according to valid feed-in tariff was paid € 20.66 c / kWh. Measured, ie. made daily electricity production in Kite & windsurfing school, was 1 kWh / day. It follows that the solar power plant to recover the invested capital by approximately 1000 / 0.2066 hours, that is. for 3 years, in Table 1.

3.2. Techno economic and comparative analysis

Techno economic and comparative analysis are done in real time, for real-time solar power plants in the amount of 18h a day, from 8 am to 2 h after midnight, only 90 days in the season, that is. from July 1 to September 30. The assumptions with which they entered in the budget were: exploitation period lasts 90days / year, consumes 15l / day (empirical data). The benefits B is calculated, taking into account the cost of electricity and investment cost C, so the comparisons of profitability coefficient r, solar power, gasoline and diesel engine, Table 2.
Techno economic and comparative analysis - for the lifetime 20years are shown in the table below, where it is known that fotonapaonski panels can run for 20 years, and diesel and gasoline engine - hard. All computational rounding are detrimental to solutions with photovoltaic panels in favor of diesel and gasoline engine, however, the conclusion is unequivocal that solar power plants, compared to the other two alternative solutions, represents a far more functional, sustainable and cost-effective solution.

Table 1. Calculation of profitability

	Solar Power	Petrol engine	Diesel engine
Investment costs	1000€	700€	800€
The costs of maintenance and fuel (daily level)	0€/day	20€/day	16€/day
Electricity production on a daily basis	1kWh	1kWh	1kWh
The price of 1kWh in the energy market	20.66c€/kWh	7c€/kWh	7c€/kWh
Payback period of invested capital	269days (3years)	556days (6.2years)	635days (7years)
Quantified environmental impact (1min neg-5max positive)	5	1	2

Table 2. Cost benefit analises

The service life of 20 years	Solar Power (Works 20god)	Petrol engine (Hardly takes 20god)	Diesel engine (Hardly takes 20god)
Investment costs	1000€	700€	800€
Costs maintenance and fuel costs (Daily and annual)	0€/day	20€/day	16€/day
	0€/year	7300€/year	5840€/year

Electricity production on a daily basis	1kWh (working 18h/day)	1kWh (working 8h/day)	1kWh (working 8h/day)
The price of 1 kWh in the energy market	20.66c€/kWh	7c€/kWh	7c€/kWh
Benefits (B)	0.2066€/kWh x 1kWh/day x 365days/year x 20years = 1508€	0.07€/kWh x 1kWh/day x 365days/year x 20years = 511€	0.07€/kWh x 1kWh/day x 365days/year x 20years = 511€
Cost (C)	1000€	700€ + 20€/day x 365days/year x 20year = 146 700€	800€ + 16€/day x 365days/year x 20years = 116 800€
The coefficient of profitability r = B / C	1.51	0.003	0.004

4. DISCUSSION ON LANDSCAPE MANAGEMENT

Large-scale solar power plants are being developed at a rapid rate, and are setting up to use thousands or millions of acres of land globally. The environmental issues related to the installation and operation phases of such facilities have not, so far, been addressed comprehensively in the literature, [19]. It is identified 32 impacts from these phases, under the themes of land use intensity, human health and well-being, plant and animal life, geohydrological resources, and climate change. Appraisals assume that electricity generated by new solar power facilities will displace electricity from traditional generation technologies, which are not clean. Altogether in the scientific literature [19] it is find 22 of the considered 32 impacts to be beneficial. Of the remaining 10 impacts, 4 are neutral, and 6 require further research before they can be appraised. None of the impacts are negative relative to traditional power generation. In quantitative terms, large-scale solar power plants occupy the same or less land per kWh than coal power plant life cycles. Removal of forests to make space for solar power causes CO_2 emissions as high as 36 g CO_2 kW h−1, which is a significant contribution to the life cycle CO_2 emissions of solar power, but is still low compared to CO_2 emissions from coal-based electricity that are about 1100 g CO_2 kW h−1, [19].
Solar energy for the production of electric energy is one source of renewable energy which is experiencing most development in recent years. In countries with high solar radiation indices, as is the case of Spain, expectations of installation of large solar power plants are increasing. Most solar power plants are located in rural environments [20], where the landscape has remained practically unaltered ever since extensive agriculture was introduced. Because of this, one of the most significant environmental impacts of this type of installation is the visual impact derived from the alteration of the landscape. In the literature [21] an indicator is proposed for the quantification of the objective aesthetic impact, based on four criteria: visibility, color, fractality and concurrence between fixed and mobile panels, [24]. The relative importance of each variable and the corresponding value functions are calculated using expert contribution. A study of the subjective aesthetic impact is carried out using the semantic differential method [21], to obtain the perception of a sample of individuals of the initial landscapes and of the landscapes altered through the installation of a solar power plant. The combined use of objective indicator and subjective study, faithfully explains user preferences corresponding to the combined comparisons. The tools proposed for the evaluation of the aesthetic impact of solar power plants can be useful for the selection of optimal plant location and most adequate use of panel technology, to minimise aesthetic impact, [21].
Renewable energy has developed spectacularly in Spain since the European Union started a process of energy policy reform. A review of Spanish State legislation on renewable energies confirms that the

success in installing renewable energy is attributable to public aid. Andalusia is one of the autonomous communities, which has simultaneously developed the legal framework and very successfully implemented the introduction of renewable power [23]. When implementing the central government's policy, the Andalusian regional government prioritized increases in surface cover by solar plants (thermal and photovoltaic energy) and in the number of companies involved, [22]. However, this development of renewable energies took place without any proper integration into regional spatial and landscape planning. That is why it is necessary to investigate renewable power implementation through regulatory measures put in place over the last decade to develop renewable energy systems and the way they can be managed alongside planning issues. [22].

5. CONCLUSSION

III-V semiconductors, GaAs and in particular InGaP, are used in many different electronic applications. Their direct bandgap and high reliability make them ideal candidates for the realisation of high efficiency solar cells: in the past years they have been successfully used as power sources for satellites in space, where they are able to produce electricity from sunlight with an overall efficiency of around 30%. Nowadays, the use of arsenides and phosphides as photovoltaic (PV) devices is confined only to space applications since their price is much higher than conventional Si flat panel modules, the leading PV market technology.
But with the introduction of multijunction solar cells capable of operating in high concentration solar light, the area and, therefore, the cost of these cells can be reduced and will eventually find an application and market also on Earth. This article review the situation of semiconductor solar cell materials, focusing on Si, GaAs, InGaP and multijunction solar cells is reviewed and future trends and possibilities of bringing III-V technology from space to Earth is discussed.
In the future other materials and concepts can be expected to come into play. Some of these are: dye sensitized cells, organic solar cells and various concentrating systems including different III/V-tandem cells. Theoretical materials that have not yet been realized are Auger generation material and intermediate metallic band material.
Photovoltaic panels are transfering solar energy into electric energy by different size of power plants. Most solar power plants are located in rural environments, where the landscape has remained practically unaltered ever since extensive agriculture was introduced. One of the most significant environmental impacts of this type of installation is the visual impact derived from the alteration of the landscape. Furder research are recomended in the field of landscape management.
Solar energy is becoming more economically attractive as technologies improve and the cost of electricity generated by fossil fuels rises. By 2020, hundreds of billions of dollars of investment capital will probably boost global solar-generating capacity 20 to 40 times higher than its current level. As the new sector takes shape, producers of solar components must drive their costs down, utilities must place big bets despite enormous technological uncertainty, and regulators must phase out subsidies with care. The actions these players take will determine the solar sector's scale, structure, and performance for years to come.

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