# Photovoltaic Cell Energy Conversion

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Efficient photon to charge (PTC) transfer is considered to be the cornerstone of technological improvements in the photovoltaic (PV) industry, while it constitutes the most common process in nature.

Keywords: photovoltaic cell efficiency ; thermal regulation ; energy and light harvesting ; irreversibility losses ; quantum dynamics ; nature-inspired mimicking

## 1. Introduction

Nowadays, carbon footprint awareness and the necessity of environmental protection have become significant issues in our daily activities. These considerations affect the decisions we make on energy sources and use of alternatives, as well as technological production and consumption patterns, leading to major economic and social consequences. Many efforts are being conducted to model and design efficient carbon emission systems in all industrial sectors, such as metallurgy, construction, shipping, manufacturing, transportation, to name some [1][2][3][4][5][6]. In most cases, efficient processes go together with an efficient transition to a low carbon economy, however, we have to admit that there are always cases with contradicting and competitive interactions which are worthy of investigation. In this research work, our concern refers to PV systems in order to get a deeper insight into the role of efficiency in operational mode.

Solar photovoltaic (PV) systems that directly convert sunlight into electricity are small scale and highly modular devices. They offer efficient resilience, flexibility, and adaptation to the grid energy supply. They have often been considered as the ideal distributed electricity production since they are derived from solar energy, which is a ubiquitous, inexhaustible, and renewable form of energy and is widely exploited in our society. In recent years, the value of integrated grid-connected PVs has been recognized around the world and many programs have been carried out in many countries to enhance architectural and technical quality in the built environment, storage potential, and the removal of economic and non-technical barriers in order introduce PVs as an energy-significant resource. Energy market reforms and the concept of decentralized energy systems drove research into different hybrid systems with a combined effect on energy production and consumption, therefore, analyzing both demand and supply-side management. The intensive research orientation toward efficiency [7][8][9] produced the proposal that every house could act as a net energy positive provider, taking into account combined utilizations to increase the benefits of outputs [10]. Electricity production is the main driving force for the installation of integrated PV systems, but, in recent years, installations have also been recognized which establish combined electricity and thermal energy, such as coupled photovoltaic–thermal collectors to enhance heating and cooling demand coverage, to act as refrigerator alternatives [11], or to increase thermal energy storage [12], while there are many reports of the application of standalone PV systems to solar power pumps in irrigation, livestock watering, and solar-powered water purification [13][14]. The entry of these renewable systems to the grid can also affect buildings' energy demand mixture, providing effective management of short-term buffering options in alignment with battery storage [15][16]. Many concerns regarding more efficient ways to implement energy and environmental systems lead to exploring hybrid combinations in order to optimize the path for a low carbon transition towards these systems. Renewable energy sources penetration into the grid-connected power technologies bring new contradicting issues, including the cost of the mismatch between demand and supply and intermittent and unpredictable availability [17], although in many studies they are viewed as a net provider due to the cumulative declining production costs [18][19][20]. In any case, increased renewable penetration, rational exergy management models, and reduced interaction with the utility grid are of paramount importance and delignate a robust pathway for $CO_2$ mitigation from the built environment [21], as well as effective management of grid parity [22]. Typically, a PV system depends on cell performance which in turn depends on different mechanisms regarding complex design, fabrication, and operation parameters.

## 2. Photovoltaic Cell Energy Conversion

### 2.1. Fundamental Aspects

Photovoltaic solar to energy conversion is based on the electron behavior of semiconductors which originates from the existence of two electron energy bands: the valence and conduction bands. The energy difference between the bottom of conduction and the top of the valence band is the energy gap, *E*g. It is well known that the incoming energy of a photon (h stands for Plank's constant and v for frequency), *hv*, when is greater than *E*g, is absorbed and may create bound pairs of electrons-holes, the excitons. This disruption of a covalent bond transfers electrons from the valence to conduction band, leaves a hole behind, changes the conductivity, and becomes the carrier of electricity. The doping of certain impurities within the material dominates different sites of donors and acceptors in the lattice, corresponding to positive and negative regions. Therefore, the diffusion of electron and holes develops a contact potential, about 1 V under room temperature and certain doping. The potential across the p-n junction is constant and the electric field is limited to a narrow transition region. The ability of the electrons to drift into that field immediately or with delay due to recombination depends on their distance from that field and other interactions. Thus, the separation of the excitons makes the electrons serve as an external current.

### 2.2. Photogenerated Current

The necessity of absorbing as many photons as possible obligates the use of materials with a low band gap, while the connections between cells are of utmost importance for the optimization of the solar energy yield. In PV systems, since the majority of photodiodes were exposed to photons within differentiated energy streams, the efficiency is prevailed by several mechanisms to exceed beyond certain values or approach the Shockley–Queissier (S–Q) limit [23]. The portion of the unabsorbed photons, the thermalization effect, and the time dependent recombination contribute to electricity conversion, with losses leading to the partial utilization of the spectrum and photon energy. These interactions are usually contradicted and affect the tradeoff for the critical properties of the solar cell design decisions.

Moreover, energy production is simultaneously happening with the fundamental principle of time micro-reversibility, namely that the solar photons from the sun are converted into electricity within solar cells but also reemitted as thermal radiation. The emitted radiation produced by the electro–hole excess energy in the cell is luminescent, which means that the electrochemical potential of photon differs by zero, obeying the modified Planck law, and the thermodynamic efficiency of a solar converter is limited by the Carnot efficiency between the working source (sun temperature at about 6000 K) and the heat sink at the cell temperature [24].

### 2.3. Recombination Limits

The significance of the effective lifetime of the charge carriers to generate current and their dependance on the recombination processes has already been noted. There are three reasons for this association: (a) the doping level, (b) the irradiance of the cell, and (c) the nature and quality of the semiconductor. Accordingly, we recognize the following recombination processes which are interrelated with the abovementioned reasons: the surface density recombination, the Shockley-Read-Hall (SRH) recombination through undesirable light traps, the radiative recombination, and the Auger recombination—which has to do with the probability of a conduction band electron to transfer the excess energy to a valence band hole or to another conduction band electron. The latter denotes a three-particle process of the electron hole concentration under illumination and increases with the cube of the carrier concentration, making a great contribution as a limited open voltage (*V*oc) and efficiency factor, depending on the materials used. Typical mechanisms of recombination in solar cells are related to luminescence, SRH defects, SRH on impurities, Auger, and surface. In general, the total recombination rate, *τ*total, is related to the other ones, namely the radiation (*τ*radiation), Auger (*τ*Auger), and trapping (*τ*trap) recombination by the following equation:

$$\frac{1}{\tau_{total}} = \frac{1}{\tau_{radiation}} + \frac{1}{\tau_{Auger}} + \frac{1}{\tau_{trap}} \quad (2)$$

For example, in crystalline silicon solar cells the Auger recombination dominates and the distribution is: Auger 82%, radiative 9%, SRH 7% and surface 2% [25][26].

## 3. Influence Factors

### 3.1. Impacts of Material Properties and Fabrication Processes

The main materials that impact on fabrication processes are linked to the intrinsic defects at the front and back interface of PV window layers. Such defects in these bulk materials can easily form photo-active alloys due to high defect density, thus restricting the current intensity of the device and determining the absorption of photons [88]. Subsequently, higher efficiency can be achieved according to the enhancement of the current intensity, necessitating control of fabrication methods of window layers. Besides, the increase in the carrier concentration results in challenging doping materials with different band gaps and wavelength absorption. These materials are designed with preferred band bending and reduced rear barrier heights of window layers, thus, avoiding the hole transportation resistance that limits the performance of Schottky junction [89,90]. It is noteworthy that, while the interaction of the window layer materials with the deposited and diffused doping atoms reduces the rear contact, it may also increase the potential barrier between them, restricting the photo generated charge carriers, e.g., Cadmium Telluride (CdT) cell technology, when doped with Cu/Au (Copper/Gold), interacts with gold (Au) atoms, while increasing the potential. Carbon nanotubes (CNT), nanocomposites and nanocrystals with suitable valence band edges are also materials that can be used to overcome the contradicting effects [91,92,93]. Thermal evaporation, magnetron sputtering and chemical etching [94,95,96,97,98], electrostatic spray assisted vapor deposition [99], electrospinning, and annealing indium tin oxide (ITO) processes [100,101] are preparation methods that have influential roles in the electrical and optical parameters. Enhanced operational characteristics of the examined devices, such as the short circuit current, *Isc*, the open circuit voltage, *Voc* and the fill factor, *FF*, can relate surface/layer treatment with the photoconversion efficiency, *n*, via the output power derived, P, following equation:

$$n = V_{oc} \times I_{sc} \times FF/P \quad (3)$$

Besides, it can be noted that the minimization of charge recombination can increase the Fill Factor of the PV cells, thus increasing the efficiency of organic PV. Other ways of enhancing the charge transport can be implemented by the incorporation of cascaded atom number (Z) chalcogens, namely the small molecular donors (SMD), in the solubilizing side chains of the active layers which, in turn, can both promote the intermolecular interactions of atoms and further improve the connectivity. From an elementary viewpoint, oxygen (O), sulfur (S), and Selenium (Se) atoms are capable of affecting the donor–acceptor phase aggregation. In particular, the O atoms promote tighter π–π tighter stacking and the atoms of S and Se support a greater crystalline order in thin films [27]. Research efforts are also linked to manufacturing improvements, targeting the following:

- The smaller size heteroatoms, higher electronegativity of the heteroatoms, and larger moments of furan conjugated polymers or fullerene-based heterojunctions [28][29].
- Utilization of certain physical and chemicals treatments to manipulate the active layer absorption [30].
- Thermal stability of the inverted cell structure, thus improving the exciton transportation and efficient separation [31].

### 3.2. Impact of Energy Harvesting on Energy Conversion Value

When considering the impact energy harvesting on energy conversion value it is of utmost importance to note that the excess photon energy that becomes thermal losses accounts for more than half of the losses, leading towards possible energy harvesting exploitation. There are also reports of vivid interest in devices exploiting the unlimited dissipated thermal energy regarding solar to energy processes, resulting in manufacturing of small autonomous electronic devices with no need for power supply and maintenance, as well as increased conversion efficiency. Such a conversion efficiency increase can be attributed to the broadening of recycling and exploitation of thermal energy waste in many ways that commonly follow the principles of the thermoelectric conversion.

In a similar study [32] a power synthetic inductance circuit was created from the heat generated by the bearing, while other researches [33] proceeded to optimize the figure of merit of pyroelectric materials due to the improved properties of crystallinity, density, and the reduced permittivity derived from energy harvesting. The analysis supported advanced waste to energy applications with composite materials, due to the enhanced phonon transferring properties of the conductive networks.

In another recent study [34] a day-and-night combined operation of electricity and latent energy storage was investigated. Specifically, a Bismuth telluride (Bi2Te3) based thermoelectric generator (TEG), firstly, harvests the concentrated solar energy directed from Fresnel lens, while aluminum fins and mixed nanocomposite materials PCMs are functionally charging and discharging energy. Moreover, the creation of active layers of (QDs) and lithium chloride (LiCl) on top, being sandwiched between a substate and an aluminum contact, can develop a multi-step photon absorption mechanism that enabled the so-called mid gap states mechanism of the incorporated nanocrystals, allowing for harvesting of human body radiation [35]. Another critical research consideration is the exploitation of the second order phase transition above the Curie temperature from the ferromagnetic to paramagnetic phase to increase the cooling rate [36].

### 3.3. Impacts of Light Harvesting on Photon to Charge Transfer

The enhancement of light to current conversion, correspondingly, induces a wider range of power output, and may in the future yield over 35%. Naturally occurring dipole–dipole interactions between well oriented molecular excited states, generating quantum interference effects, may drive the future research. It is reported [37] that, in lasing, the quantum coherence breaks the balance in a cavity light trap, suppressing the absorption process, and, consequently, the emission dominates. The idea behind the reverse engineered phenomenon in the photovoltaic conversion is an optical pump device which could suppress the emission rate, hence, promoting the absorption rate, e.g., at ground level. In quantum mechanics, this can be achieved by adding a two-level relative transition amplitude which can coherently result in a destructive interference of the undesirable process, namely the emission [37]. Recent research on thin films, copper indium gallium diselenide (CIGS), towards the passivation of rear surface and light trapping in a nanocavity array showed the superior behavior of aluminum oxide ($Al_2O_3$) substrate and *Voc* and *Jsc* improvements about 10% [38].

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