From steam engine to solar cells: can thermodynamics guide the development of future generations of photovoltaics?

Tom Markvart*

Thermodynamics has played a singular role in the development of virtually all energy technologies to-date. This review argues that it also has a role to play in the understanding and design of solar cell operation, particularly looking toward the future, high-efficiency solar cells. After a historical overview of the key developments in the ‘thermodynamics of light,’ the conversion of a monochromatic light beam is used as a starting point to analyze the conversion process, examine the fundamental losses in terms of irreversible entropy generation, and consider in detail one of the key applications: the Shockley–Queisser detailed balance. We review and compare the principal suggestions for the highest theoretical efficiency of solar energy conversion, and analyze one possible embodiment of such a third-generation structure: the hot-carrier solar cell. A somewhat different application of the statistical approach—light trapping—is reviewed at a fundamental level, and the future potential is considered for devices which combine such a ‘thermodynamic squeezing’ of light with latest developments in photonics, leading to a photonic bandgap solar cell. We argue that the widespread use of thermodynamic tools in the current photovoltaics research, especially when combined with the potential benefits to future devices, already indicates that our thinking should not be about if but how thermodynamics can guide us to make better solar cells. © 2016 The Authors. WIREs Energy and Environment published by John Wiley & Sons, Ltd.

How to cite this article:
WIREs Energy Environ 2016, 5:543–569. doi: 10.1002/wene.204

INTRODUCTION

Most of the energy forms we use today have their roots in thermodynamics. With origins dating back to the peak of the industrial revolution, classical thermodynamics has expanded beyond the immediate energy sector into a branch of science that pervades many scientific disciplines today. It is therefore no surprise that thermodynamics has been called upon to furnish the theoretical tools needed to support even one of the most recent forms of energy conversion: photovoltaics.

An early mention of thermodynamics with reference to the operation of a solar cell was the ‘Shockley paradox.’\[^1,2\] However, we shall show that many ideas behind the thermodynamic fundamentals of solar cell operation date even to a much earlier time. Perhaps it is only a coincidence that Carnot’s classical paper on the efficiency of conversion into mechanical work\[^2\] appeared some 15 years before what is now considered to be the first observation of the photovoltaic effect.\[^3\] Carnot’s work provided the
first impetus that grew into a quantitative framework now called thermodynamics. And it was the application of thermodynamic to electromagnetic radiation that gave rise to quantum mechanics at the turn of the 20th century laying down, as we shall see, the foundation stones for the understanding of modern photovoltaics in thermodynamic terms.

Our review starts with a brief historical perspective in the section The Foundation Pillars of several key concepts that underpin what is now sometimes called the ‘thermodynamics of light.’ Building on this foundation, we shall chart the progress toward the current understanding by using examples of ideas, concepts, strategies, and views that contributed to the field. We shall not aim to provide a complete list of efficiencies but, in section Light, Heat, and Work, we shall take a look at a range of classical theories aiming to determine the limits to solar energy conversion and the related process of light emission. The following sections then introduce the quantum nature of light into the conversion process. In section Quantum Solar Energy Conversion, we examine the kinetics and current considerations of the celebrated detailed balance theory of Shockley and Queisser. Thermodynamics of Photovoltaic Conversion section then revisits this subject on the basis of thermodynamics, bringing in new perspectives on the conversion process and fundamental energy losses.

A key objective of this review is to consider new avenues and opportunities for research. Two examples have been chosen in the section Future Directions: Beyond the Shockley-Queisser Limit to illustrate the potential of thermodynamics to achieve very high conversion efficiencies: the maximum limit to the efficiency of solar energy conversion and the hot-carrier solar cells. Light Trapping section examines a somewhat different application of statistical techniques to the capture of solar radiation, without reference to temperature or heat.

THE FOUNDATION PILLARS

Current photovoltaic technologies—the principal focus of this paper—are the product of modern materials science, underpinned by the quantum theory. They have emerged from developments in solid state electronics and have close relationships with other solid state devices such as microelectronic circuits. However, we shall see that the roots of their operation have deeper and more ancient origins, and the understanding of the theoretical foundations will bring us to the early days of quantum theory and thermodynamics. Not surprisingly, what many consider to be the first paper which kick-started the quantum theory combined thermodynamics with electromagnetism, in the concept of black-body radiation. Here, we review briefly four areas that can be considered as the foundation stones for a satisfactory understanding of solar energy conversion in thermodynamic terms.

The Size of a Beam of Light

Thermodynamics deals with the energy attributes of substance confined in a well-defined volume. Our aim here is to find corresponding characteristics for a beam of light. In contrast with geometrical optics which describes light propagation in terms of light rays, energy conversion requires to define bundles of rays (light beams) that have finite dimensions and are able to carry macroscopic amounts of energy. This distinction first became apparent in the analysis of concentration of light which requires optimum illumination of the receiver (a solar cell or heated fluid), without necessitating image formation. The new field of nonimaging optics therefore defined a new characteristic of the light beam: the étendue.

A key feature of the étendue which underpins its importance in optics to its invariance: the étendue of a beam propagating in a clear and transparent medium is conserved (see for e.g., Ref 5 where a proof of this theorem can be found).

The element of étendue of a narrow beam of angular spread $\delta \omega$ passing through an area $\delta A$ is defined as

$$\delta \mathcal{E} = n^2 \delta A \delta \omega \cos \theta$$

where $n$ is the refractive index of the medium and $\theta$ is the angle between the normal to $\delta A$ and the direction of the wave vector $\mathbf{k}$. For an extended beam, the total étendue is obtained by an integration of Eq. (1) giving the étendue of diffuse sunlight propagating in vacuum or air with directions extending over a complete hemisphere as $\mathcal{E} = \pi A$.

The étendue has yet another facet of fundamental significance for the thermodynamics of light: it is proportional to a volume element in the phase space of coordinate variables $x$, $y$ and wave vector components $k_x$, and $k_y$. By analogy with the early quantum mechanics, the étendue $\mathcal{E}$ can thus be considered as a measure of the number of quantum states in the beam available for photon occupation. The conservation of étendue in a clear medium can then be interpreted as the invariance of the volume of a beam in the phase space of its transverse coordinates.
Black-Body Radiation

Radiation emitted by heated objects—the subject of an intense research activity in the second half of the 19th century—gradually evolved into a universal concept which we now call black-body radiation: electromagnetic energy in thermal equilibrium with matter, characterized by the usual thermodynamic quantities such as temperature, pressure, and volume. The key formula that eventually emerged is the Planck’s distribution law, usually written in terms the energy density of black-body radiation at a certain temperature $T$. Planck never fully accepted the implication of his theory and the existence of light quanta that we now call photons.9 Having photovoltaics in mind, however, it will be more convenient to work with quantities relating to photons rather than with the energy of electromagnetic radiation, and we shall write Planck’s law in the form

$$n_{ph} = \frac{8\pi n^3 \nu^2}{c^3} \rho_\nu(T)$$

where $n_{ph}$ is the number of photons per unit frequency per unit volume, $\nu$ is the frequency, $c$ is the speed of light, $h$ is the Planck constant, $k_B$ is the Boltzmann constant, $n$ is the refractive index of the medium, and $\rho_\nu(T)$—what we now call the occupation probability of a quantum state—is given by

$$\rho_\nu(T) = \frac{1}{e^{\hbar \nu/k_B T} - 1}$$

When examined in a modern context, several features of Plank’s formulae (2), (3) deserve a special attention. The occupation probability (3) can be viewed as a special case of Bose–Einstein distribution with the chemical potential equal to zero. In thermodynamic terms this means that photons which form black-body radiation represent pure heat, and have no capacity to perform work in an isothermal process. This point will be taken up again in the sections Quantum Solar Energy Conversion, Thermodynamics of Photovoltaic Conversion, and Future Directions.

A further point of note is that the formula for photon density Eq. (2) implies the existence of not one but two forms of equilibria: an equilibrium between levels at different energy, as expressed by the occupation probability (3), and an equilibrium between different directions of propagation, as expressed by the multiplicity factor for each energy level. This latter aspect of Planck’s statistics will be discussed in more detail in the section Light Trapping.

The statistical nature of Eq. (2), with origins close to the kinetic theory of gases, required Planck to build bridges between the work of Maxwell, Kirchhoff, and particularly Boltzmann10,11 by bringing into play a relation linking $n_{ph}$ with the photon flux density $\phi_\nu$—the number of photons passing through a unit perpendicular area per unit solid angle per unit time:

$$\phi_\nu(T) = \frac{c n_{ph}(T)}{4\pi} = 2\left(\frac{\nu}{c}\right)^2 \rho_\nu(T)$$

The existence of the universal function of temperature $\phi_\nu(T)$ was already stipulated by Kirchhoff but it was determined, in the form (4), only later by Planck, as part of his theory of black-body radiation. The number of photons that propagate in a monochromatic beam of frequency width $\delta \nu$ with étendue $\mathcal{E}$ emitted by a black body at temperature $T$ and passing through area $A$ per unit time is then, by (1)

$$\Phi = \frac{\mathcal{E} \phi_\nu(T)}{n^2 \delta \nu} = \frac{\mathcal{E}}{\pi A} \Phi_o(T)$$

where $\Phi_o(T)$ refers to the photon flux emitted by a black body into a full hemisphere in vacuum. As the photon flux and the étendue are both conserved, so must be the ratio $\phi_\nu/n^2$, as already evident from the second equation (4). This is the photon flux analogue of the brightness theorem.12

The concept of black body, as a perfect absorber and emitter of radiation, is of a special significance for solar energy conversion as it represents a good approximation for the radiation emitted by the Sun. This similarity provides a powerful basis for a theoretical understanding: representing the Sun’s radiation as a black body affords a valuable tool that has been developed over many years, and is available in a standard form in most textbooks on thermodynamics and statistical physics (see e.g., Refs 13 and 14).
Heat and Work

Bringing together the words ‘work’ and ‘thermodynamics’ immediately evokes the notion of Carnot efficiency. Carnot’s result, although resting firmly on the ‘caloric’ concept, marked the birth of a new field: thermodynamics. With a remarkable insight, Carnot predicted that a quantity $Q_H$ of heat, extracted from a high-temperature reservoir can be converted to work with an efficiency at most

$$\eta_C = 1 - \frac{T_o}{T_S}$$

whilst heat $Q_L$ must be rejected into a low-temperature reservoir (Figure 2(a)). Anticipating the application to solar radiation, the temperatures of the high- and low-temperature reservoirs have (6) been set equal at the solar temperature $T_S$ and the ambient temperature $T_o$. Carnot’s efficiency proved to be an inspired foundation for what was to become the second law of thermodynamics. Since an ideal heat engine operates in a cyclical manner, the working medium returns to the same point at the beginning of the cycle. Neither the properties of the working medium nor the properties of the surroundings thus enter the argument.

We shall see that—perhaps surprisingly—Carnot efficiency appears profusely in the numerous formulae that have been suggested for solar energy conversion and that will be discussed in the sections that follow. Equally important, however, is to examine the subtle but important differences between the operation of a solar energy converter and the Carnot engine which—as we shall see—cause the efficiencies achievable in solar energy conversion to be lower than the value (6). The analysis of different models and reasons to explain this difference are among the key objectives of this paper.

Detailed Balance between Absorption and Emission of Radiation

The relationship between the absorption and emission of radiation is a key characteristic of the energy exchange between matter and the radiation field. The intense research effort in this field has brought about several different expressions of what we may now call detailed balance between absorption and emission of radiation. Indeed, some of this work paved the way to the discovery of Planck’s radiation formula.\(^\text{20}\)

The three different relations between absorption and emission by matter are summarized in Figure 1. The first general relationship between absorption and emission was formulated by Kirchhoff for radiation emitted by the surface of a heated body.\(^\text{21}\) Paraphrased in terms of photons rather than energies, Kirchhoff surmised that the ratio of the rate at which photons are emitted by a unit area to the absorbing power $a$ is equal to a universal function of only the temperature of the substance and the wavelength or frequency of emission\(^\text{21}\)—our photon flux density (Eq. (4), Figure 1(a)).

Planck elaborated on Kirchhoff’s ideas by noting that radiation can only be absorbed or generated in a volume element of a body rather than on the surface.\(^\text{22}\) He expressed this balance in terms of the absorption coefficient $\alpha_V$ and the coefficient of emission $\varepsilon_V$ (emission rate by a small interior volume into a unit solid angle, per unit volume and unit frequency interval, Figure 1(b); see also Ref 23). A further historic contribution was made by Einstein who, in his theory of radiation paper,\(^\text{24}\) extended Planck’s photon balance to describe transitions between the quantum states of matter and showed that a consistency with the Planck radiation law required the existence of stimulated emission (Figure 1(c)). Einstein’s detailed balance, initially developed for atomic lines, was later generalized to molecules by Kennard\(^\text{25,26}\) and Stepanov.\(^\text{27,28}\)

Although discussed for more than 100 years, the thermodynamic issues highlighted in this section and the underpinning assumptions continue to come under scrutiny to this day. Questions relating to entropy associated with absorption and emission of radiation\(^\text{29,30}\) and the associated assumption of reciprocity\(^\text{31}\) retain the attention of the research community, and will only be resolved with further research. Other relations between absorption and emission of light, including a geometrical interpretation, will be examined when we investigate the foundations of light trapping.

LIGHT, HEAT, AND WORK

The Foundation Pillars section has set the scene by an outline of several scientific disciplines which connect light with thermodynamics. However, little has been said how these tools can be applied to the actual conversion processes, and what constraints apply when light is transformed into other useful energy forms such as mechanical work, electricity, or chemical energy. This section takes the first step in this direction with a snapshot of several early theories which use thermodynamics to describe solar energy conversion. The conversion process is usually considered without making any significant assumptions about the conversion device. The ideas in this
Different facets of the balance and reversibility between absorption and emission of radiation. (a) Kirchhoff’s law relating the photon emission rate $\Phi_{\text{out}}$ to the absorptivity $a$ and the photon emission rate $\Phi_{\text{in}}$ of a black body. Kirchhoff’s law holds for the total emission as well as for its spectral components. (b) Planck’s relation between the emission ($\alpha_v$) and absorption ($\epsilon_v$) coefficients at frequency $v$ for a small volume element in the interior of a body. (c) Einstein’s relation, linking the photon absorption and emission rates to transitions between quantum levels of the medium. $N_o$ and $N_{\text{exc}}$ denote the numbers of atoms in the ground and excited states, respectively.

A similar problem in a more general setting has been to estimate for the maximum efficiency of a useful solar energy converter is invariably proportional to the difference of temperatures of the low-temperature reservoir as the surroundings at ambient temperature of $300 \, \text{K}$ (these numbers will be used throughout this review), a ready reference for the maximum efficiency of a solar energy converter using the Carnot efficiency (6) gives a limit of 95%. It soon becomes apparent, however, that this limit is too generous and cannot be reached even by an ideal theoretical device. Clearly, a number of features and facets of the conversion processes should be taken into account if the efficiency limit is to have at least a semblance of reality.

Energy and Power. The Photothermal and Endoreversible Engines

The first concern that comes to mind is of the Carnot efficiency as an energy efficiency: a ratio of two numbers, each with the dimension of energy. The efficiency of a useful solar energy converter is invariably understood to mean the power output divided by power incident on the device: it is therefore a power efficiency. As the argument behind Carnot efficiency rests on equilibrium thermodynamics, it is clear that the power efficiency of the Carnot engine is zero. A similar problem in a more general setting has been the subject of research for many years and is often grouped under a heading of “finite time thermodynamics”. This section takes a brief look at two examples in application to solar energy conversion.

An early model based on the conversion of solar power was proposed by Castañs and colleagues and by Jeter for what is now referred to as photothermal efficiency. The heat input to the engine is taken as the difference between the black-body energy flux received from the Sun at temperature $T_S$ and the black-body flux emitted by the converter at a temperature $T_c$. This heat is then converted with the Carnot efficiency for a converter operating between the temperatures $T_c$ and the ambient temperature $T_o$. The resulting power efficiency can then be written as

$$\eta_{PT} = \left(1 - \frac{T_o}{T_S}\right)^4 \left(1 - \frac{T_o}{T_c}\right)$$

The value of $\eta_{PT}$ usually quoted represents the maximum with respect to the converter temperature $T_c$; for $T_S = 6000 \, \text{K}$ and $T_o = 300 \, \text{K}$, the optimum $T_c$ is equal to 2544 K.

A different approach to model the dynamic (rather than static) operation of the engine is to ascribe the resulting losses to the heat flow which supplies and takes away energy to and from the engine (Figure 2(b)). As these losses (which are proportional to the difference of temperatures of the reservoirs and the inlet and outlet to the heat engine) occur outside the ideal heat engine/converter, this
The type of engine is usually called endoreversible. The resulting energy efficiency at the maximum power output then comes out as \( \eta_{CA} = 1 - \left( \frac{T_o}{T_S} \right)^{1/2} \) (8).

The power and energy efficiencies of the photothermal and Curzon–Ahlborn engines are compared in Figure 3, highlighting the losses due to a finite rate of turnover of the engine. A notable feature of these graphs is the existence of a maximum turnover rate \( Q_{max} \) for each engine where the dynamic losses match the work produced by the engine, and the net output of both energy and power is zero.

The Available Work. Landsberg Efficiency

At the fundamental level, the nature of energy supply to the engine is at the heart of a different model for solar energy conversion. The photothermal and
Endoreversible engines consider the energy delivery as a continuous process. One can consider an alternative picture where solar radiation arrives in the form of finite energy packets which are consumed when converted to useful work. Photons are transported to Earth from the Sun as light beams, in a process akin to convection or ballistic transport, which could be compared to particle motion as described by classical mechanics, without the need to employ the laws of thermodynamics. It can therefore be argued that statistical concepts such as entropy play no part in photon transport in a clear medium, and that the absorption of light differs from the absorption of heat by a heat engine which is associated with a change in entropy.

A model can thus be perceived where, instead of absorbing heat, a hot working medium in the form of solar radiation at temperature \( T_S \), is injected into the engine. Work can then be carried out by cooling the medium inside the engine to a state of equilibrium with its surroundings at temperature \( T_o \) and pressure \( p_o \). The maximum amount of available work \( W_{\text{max}} \) can be determined by the method of thermodynamics in terms of the availability or exergy:

\[
W_{\text{max}} = U_S - T_o S_S + p_o V_S \left( 1 - \frac{T_S}{T_o} \right) U_S - \left( \frac{p_S}{T_S} - \frac{p_o}{T_o} \right) T_o V_S
\]

where \( U_S \) and \( S_S \) are the internal energy and entropy of a radiant energy packet at temperature \( T_S \) with volume \( V_S \). Equation (9) has been adapted for equilibrium black-body radiation with chemical potential equal to zero.

It is instructive to consider the different processes leading to the Carnot and Landsberg efficiencies in more detail. The Carnot engine receives heat from a high temperature source (the Sun, at temperature \( T_S \)) and rejects heat into the surroundings at temperature \( T_o \). Unlike the Carnot cycle, however, the availability process is not cyclical, and the work done by and on the engine must include the work on or by the surroundings at pressure \( p_o \). We note that the input energy to the Carnot engine is heat.
exchanged at temperature $T_S$ (equal to $T_S \Delta S = T_S S_0$) but the initial energy for the conversion process described by availability (9) is the internal energy $U_S$ at temperature $T_S$ and volume $V_S$. Accordingly, the conversion efficiency is thus defined as $W_{\text{max}}/UT_S$. In mathematical terms, the efficiencies of the two processes differ in the second term of the second equation (9). This term (which is always negative) will be the subject of discussion in several parts of this review; for brevity, it will be denoted by $-\Delta p$ and referred to simply as the pressure correction.

The notion of solar energy conversion leading to available work was followed by Petela,41 Press,42 and Landsberg and Mallinson43 who determined the maximum work that can be carried out by a volume of black-body radiation at temperature $T_S$ if cooled to temperature $T_o$, leading to what is now usually called the Landsberg efficiency

$$\eta_L = \frac{W_{\text{max}}}{U_S} = 1 - \frac{4}{3} \frac{T_o}{T_S} + \frac{1}{3} \left( \frac{T_o}{T_S} \right)^4$$  \hspace{1cm} (10)

The use of Carnot and Landsberg efficiencies has been discussed in detail in Refs 44-46. All three efficiencies discussed above as functions of the ratio $T_o/T_S$ are compared in Figure 8.

As presented in this review, Eq. (10) is considered as energy efficiency. In the literature, in contrast, the Landsberg efficiency is usually portrayed as power efficiency—either as a result of a derivation based on energy flows (see the section Energy and Entropy Flows) or simply by changing the work $W_{\text{max}}$ into power or energy flow. Notwithstanding, the emphasis placed in this review on the distinction between energy and power efficiency requires that a more rigorous argument is sought to justify the notion of Landsberg efficiency as power efficiency. Indeed, we shall show in the section The Maximum Efficiency of Solar Energy Conversion on fundamental grounds that this notion may require a reappraisal.

Energy and Entropy Flows

One can simply brush aside the difficult process to justify the difference between power and conversion efficiencies (which bears many similarities to the differences between the transition from classical to irreversible thermodynamics) and apply the laws of equilibrium thermodynamics directly to energy rates rather than to energy quantities themselves. This was the approach taken by Landsberg and Tonge47 who used rate equations for a system not dissimilar to the Carnot heat engine, to describe the balance between incident and emitted photon fluxes as well as the production of useful work (Figure 2(c)) by an incident energy (solar) flux $U_{\text{in}}$:

$$U_{\text{in}} = U_{\text{out}} + Q + W$$
$$S_{\text{m}} = S_{\text{out}} + Q/T_o - \dot{S}_i$$  \hspace{1cm} (11)

where $U_{\text{out}}$ and $S_{\text{m}}$ denote the energy and entropy fluxes of the emitted photons, $Q$ is the heat flux rejected into a low-temperature reservoir at temperature $T_o$, $W$ is the rate of work (electrical energy) done by the converter, and $\dot{S}_i$ is the rate of irreversible entropy generation. Interestingly, the application of Eq. (11) to the conversion of black-body radiation at temperature $T_S$ by a converter at $T_o$ under reversible operation with $\dot{S}_i = 0$, leads again to the Landsberg efficiency (10). As already noted at the end of the previous section, however, the energy input is now the energy flux $U$ rather than the energy $U$ of a volume $V$ of black-body radiation.

Landsberg and Tonge47 showed that the determination of an upper bound on the efficiencies or coefficients of performance reduces to the determination of the appropriate temperatures $T_{\text{out}}$ and $T_{\text{exc}}$ of the emitted and exciting radiation. This is a simple matter for monochromatic radiation where a suitable definition had already been provided previously by Landau.48 For broadband radiation, the situation is more complex as it is impossible to correctly match the spectrum as well as the total radiance/energy flux by using a single temperature. We shall see in Quantum Solar Energy Conversion section that a satisfactory resolution of this issue had to await a later development: the introduction of a finite chemical potential of radiation.

The definition of a satisfactory effective temperature becomes particularly acute for solar radiation on the ground where the spectrum resembles the black-body spectrum but the total energy flux is, of course, much lower. This led Landsberg and Tonge to introduce the concept of diluted black-body radiation16 where the energy flux is reduced by a factor of

$$\varepsilon = \mathcal{E}_{\text{in}}/\mathcal{E}_{\text{out}} = \cos \theta / \pi$$  \hspace{1cm} (12)

with respect to the full black-body flux, where $\mathcal{E}_{\text{in}}$ and $\mathcal{E}_{\text{out}}$ are the étendues of the incident and emitted beams and $C$ is the concentration ratio. Landsberg and Tonge show that the formalism allows the determination of the appropriate entropy, and hence, gives an effective temperature of the diluted black-body radiation which can be used to obtain an upper
bound on the conversion efficiency with the use of (10).

The model of Landsberg and Tonge built on the previous work by Weinstein\textsuperscript{17} who used rate equations to study the conversion of work into optical emission excited by the injection of electrical current where the energy of the emitted photon can exceed the electrostatic energy of the applied bias,\textsuperscript{49} in a model based on a heat engine (Figure 2(d)). Chukova\textsuperscript{18} later extended Weinstein’s result to photoluminescence (Figure 2(e)). More recently, a similar line of work has been pursued in connection with laser cooling.\textsuperscript{50}

**QUANTUM SOLAR ENERGY CONVERSION. KINETIC ASPECTS**

The focus of our review so far has been what could be called the classical approach to the thermodynamics of solar energy conversion: the conversion of the incident energy flux in terms of equilibrium thermodynamics, with no attempt to describe the quantum nature of solar radiation as a stream of photons. The theoretical foundations of modern photovoltaics, accompanied by an improved understanding of photochemical energy conversion in photosynthesis, are underpinned by the quantum nature of solar energy conversion where photons play a primary role.

A brief glance at the output of a solar cell along the current voltage characteristic will illustrate the main features of the conversion process. The energy generated by a photon is directly related to the voltage at the solar cell terminals, or to energy content of the molecular product. Near the open circuit, the solar cell is an energy converter where each photon produces energy $qV$, under conditions similar to classical thermodynamics because the ‘turnover rate’ $I/q$ (represented here by the extraction of charge carriers) is low. Near the short circuit, on the other hand, the solar cell resembles a kinetic device, converting photons into electrons in an electrical circuit, at a rate given by the turnover rate $I/q$. When extended to produce the complete current–voltage characteristic both viewpoints are, of course, equivalent. As we shall see in the next sections, each aspect provides a different aspect on the device operation and a different description of losses in conversion. We begin our discussion with a review of the more traditional approach, the kinetics, based on currents and photon flows. We will return to consider the energy aspects and thermodynamics in the section *Thermodynamics of Photovoltaic Conversion*.

**The Shockley—Queisser Model of Detailed Balance**

We have already noted that the origins of modern photovoltaics are anchored in semiconductor technology. A satisfactory understanding of the fundamental limits on solar cell operation, however, relies on an insight from a different branch of science. This came with a description of the solar cell solely in terms of the characteristics of the incident and emitted energy beams of light, in a breakthrough paper by William Shockley and Hans-Joachim Queisser\textsuperscript{51} in the early 1960’s.

Based on what might now seem a simple strategy, Shockley and Queisser called their method ‘detailed balance’. Indeed, certain similarities will be recognized with the balance between absorption and emission as summarized in Kirchhoff’s law in the *Foundation Pillars* section. What Shockley and Queisser had in mind was to equate the incident (and completely absorbed) flux $\Phi_{in}$ of photons with energy above the bandgap $E_g$ at temperature $T_S$ to the flux $\Phi_{out}$ in the same energy range at temperature $T_o$ emitted by the cell, allowing for a fraction of photons which are used for conversion to electrical current $I$:

$$\Phi_{in} = \Phi_{out} + \frac{1}{q}$$

A model for the incident flux was at hand in the form of black-body radiation emitted by the Sun (see the *Foundation Pillars* section) but no universally accepted view was available to describe the photon flux emitted by a semiconductor under electrical excitation. Shockley and Queisser made an approximation which turned out to be surprisingly accurate: to multiply the equilibrium photon flux at the ambient temperature by a factor equal to the rate of increase of radiative recombination at a semiconductor junction under applied voltage $V$:

$$\Phi_{in} = C \frac{\omega_S}{\pi} \Phi_0(T_S)$$

$$\Phi_{out} = e^{qV/kT_o} \Phi_0(T_o)$$

where $\omega_S$ is the solid angle subtended by the Sun, $C$ is the concentration ratio ($C = 1$ for one sun illumination and $C = \pi/\omega_S$ for maximum concentration), and the photon fluxes refer to the range of photon energies $h\nu > E_g$ where $E_g$ is the bandgap of the semiconductor. Combining Eqs. (13) and (14) gives the current voltage characteristic of an ideal solar cell:

$$I = I_t - I_o \left( e^{qV/kT_o} - 1 \right)$$
The Shockley–Queisser ideal efficiency of a single-junction solar cell as a function of the semiconductor bandgap, together with the bandgaps of a number semiconductor with photovoltaic applications. The incident and emitted light beams have the black-body spectrum at temperatures 6000 and 300 K, respectively.

![Figure 4](image)

**FIGURE 4** The Shockley–Queisser ideal efficiency of a single-junction solar cell as a function of the semiconductor bandgap, together with the bandgaps of a number semiconductor with photovoltaic applications. The incident and emitted light beams have the black-body spectrum at temperatures 6000 and 300 K, respectively.

where $I_t$ and $I_o$ are the photogenerated and dark saturation currents,

$$I_o = q\Phi_o(T_o)$$

$$I_t + I_o = qC\frac{\alpha}{\pi} \Phi_o(T_S)$$

(16)

Figure 4 shows the ideal efficiencies as functions of the bandgap $E_g$ under one-sun illumination, under maximum concentration of sunlight, and what Shockley and Queisser called the ‘ultimate efficiency’—a result obtained earlier by Trivich and Flinn who approximated the open-circuit voltage by the voltage $E_g/q$ corresponding to the bandgap of the semiconductor.

A key element of the Shockley–Queisser result was to show that efficiency limit for solar cell operation is described completely by the characteristics of the incident and emitted light beams. Equations (14) and (15) describe the well-known current voltage characteristic of an ideal solar cell which has enjoyed much success since the early days of photovoltaics. From a more fundamental point of view, however, a correction is required to put the emitted photon flux on a more rigorous footing. This correction became apparent from the photoluminescence studies which indicated that the photon fluxes emitted as fluorescence or phosphorescence are described well by the Bose–Einstein distribution with a non-zero chemical potential. The emitted photon flux $\Phi_{out}$ then takes the form of a ‘generalized Planck’s law,’ where the occupation probability (3) is replaced by a value which follows from the full Bose–Einstein statistics

$$\rho_c(T, \mu) = \frac{1}{e^{(h\nu - \mu)/k_B T} - 1}$$

(17)

The chemical potential $\mu$ in (17) is set equal to the electrostatic energy $qV$ corresponding to the voltage produced by the solar cell. Numerically, the difference between the original and ‘corrected’ I-V characteristics has little significance except under a very high concentration of incident sunlight. The basic structure, however, completes the foundation of photovoltaics, and could be later built on to describe solar cell operation in terms of an ‘engine’ operating between two equilibrium reservoirs of the photon gas.

Although the open-circuit voltage cannot be calculated analytically, a useful approximation exists for weak to moderate illumination intensities:

$$qV_{oc} = \left(1 - \frac{T_o}{T_S}\right)E_g + k_B T_o \ln \left(\frac{T_S}{T_o}\right) - k_B T_o \ln \left(\frac{E_{out}}{\mathcal{E}_{in}}\right)$$

(18)

Additional corrections can be applied to improve the accuracy of this formula to bring it to a useful form for practical applications. Equation (18) will form the starting point for the discussion of solar cell voltage in thermodynamic terms in the section Thermodynamics of Photovoltaic Conversion, where we will identify the origin of each term in this equation.

**Photochemical Energy Conversion in Photosynthesis**

An early application of thermodynamics to quantum solar energy conversion was to describe one of the most ancient energy conversion processes on Earth: photosynthesis. Photosynthesis usually evokes the picture of a complex set of chemical reactions where sunlight converts water and carbon dioxide into carbohydrates and oxygen. The energy producing part of the photosynthetic reaction, however, bears a remarkable similarity to solid state photovoltaics. The key feature that underlines this similarity is that the primary reaction consists of a sequence of oxidation–reduction reactions: in other words, electron transfer. Energy is collected in a light-harvesting unit and transferred to the photochemical reaction center (trap) by exciton transport (Figure 5). The complex of energy conversion reactions (sometimes called storage) then follows, initiated by charge
Research into the primary steps in photosynthesis has contributed much to the understanding of thermodynamic concepts by linking energy production with luminescence.

A discussion of the photosynthetic primary energy conversion in thermodynamic terms was initiated by Duysens who proposed, on an intuitive basis, that the efficiency of the conversion process could be described by the Carnot efficiency \( \eta \). Similarly to the discussion in the section Light, Heat, and Work, the dilution of solar radiation was allowed by using an effective temperature \( T_{\text{eff}} \) instead of the true black-body temperature of solar radiation \( T_S \). This effective temperature was determined by equating the observed photoexcitation rate to the rate of photon absorption from a black-body radiation at temperature \( T_{\text{eff}} \). A more detailed description on molecular basis was provided by Ross and Calvin (see also Ross, Bolton, and Lavergne and Joliot) who introduced the chemical potential of the reaction products, linked to the concentration \( P^* \) of the excited state of the primary electron donor \( P^* \):

\[
\Delta \mu = k_B T_o \ln \left( \frac{P^*}{P^*_o} \right)
\]

where \( P^* \) is the concentration of \( P^* \) in thermal equilibrium in the dark at ambient temperature \( T_o \).

The field was reviewed, in a particularly clear form, by Knox who showed that

\[
\Delta \mu = \left( 1 - \frac{T_o}{T_{\text{eff}}} \right) \Delta E + k_B T_o \ln(\phi_f) + k_B T_s \ln(\phi_{\text{chem}})
\]

Equation (20) generalizes Duysen’s result which is represented by the first term on the right-hand side.

Since \( T_{\text{eff}} \leq T_S \), this term expresses both the second law of thermodynamics and the reduction in efficiency due to ‘dilution’ of solar radiation on Earth. The second term represents a correction for nonradiative transitions when the fluorescence yield \( \phi_f \) is less than unity. The last term which includes the probability of chemical reaction (the ‘chemical yield’ \( \phi_{\text{chem}} \)) links the energy production per electron (as expressed by \( \Delta \mu \)) to the ‘power’ production discussed already in the Light, Heat, and Work section, and indicates that if energy is to be produced at a finite rate, \( \Delta \mu \) must decrease from its maximum value at ‘open circuit’ (or ‘static head’ where the overall rate of chemical reaction is zero).

**THERMODYNAMICS OF PHOTOVOLTAIC CONVERSION. SOLAR CELL AS A HEAT ENGINE**

An alternative view to the detailed balance method discussed in The Shockley—Queisser Model can be obtained by combining the energy aspects of the conversion process with the quantum nature of sunlight and of the energy produced. The key parameter is then the useful work per photon—in thermodynamics terms, the free energy, or chemical potential:

\[
\mu = u - T_s
\]

where \( u \) and \( s \) are the energy and entropy per photon. The thermodynamic approach with focus on energy parameters bears the promise of shedding a new light on the fundamental losses in the conversion process, and providing a theoretical basis for novel devices and structures aiming to exceed the Shockley–Queisser limit or constructing a thermodynamic cycle for a solar cell.
Since a solar cell emits light as well as produces power in the external circuit, the analysis may be simplified by considering the solar cell simply as a light-emitting device (Figure 2(f)). Since, under optimum operation, the emitted photons are in equilibrium with the electron-hole system which performs work, the energy produced by the solar cell can be determined by equating the work to the chemical potential of the emitted beam.\(^\text{19}\) We can then follow a similar philosophy as in Light, Heat, and Work section to write down the required energy-entropy balance, but this time per incident photon:

\[
\frac{\mu_{\text{in}}}{s_{\text{in}}} = \frac{\mu_{\text{out}} + Q}{s_{\text{out}} + Q/T_o} - \sigma_i
\]

where the subscripts in and out refer to incident and emitted beams with étendues \(E_{\text{in}}\) and \(E_{\text{out}}\) at temperature \(T_S\) and \(T_o\), respectively, \(Q\) is the heat rejected into a low-temperature reservoir at temperature \(T_o\) and \(\sigma_i\) is the irreversible entropy generated in the conversion process. A simple transformation of Eq (22) now yields:

\[
qV = \mu_{\text{out}} \left(1 - \frac{T_o}{T_S}\right) \mu_{\text{in}} - T_o \sigma_i
\]

giving the energy efficiency of conversion in the form (see Table 1)

\[
\eta_e = \frac{qV}{u_{\text{in}}} = \frac{\eta_C - T_o \sigma_i}{u_{\text{in}}}
\]

Equations (23) and (24) express the work produced by a quantum of solar radiation in terms which are familiar from classical thermodynamics. Sometimes referred to as the Guy–Stodola theorem,\(^\text{74,75}\) the work that can be carried out by a thermal source is equal to the input energy (in this instance, radiation originating from a black-body source with \(\mu_{\text{in}} = 0\)) converted with the Carnot efficiency, less losses due to irreversible entropy generation \(\sigma_i\). Since the entropy-generation term \(\sigma_i\) depends on the current produced by the solar cell, Eq. (24) demonstrate a close link between the energy efficiency of a solar cell and its current–voltage characteristic, expressed in the form of voltage as a function of current.

To be of practical use, Eq. (23) has to be supplemented by a formula for the entropy balance

\[
T_o \sigma_i = \Delta u - T_o \Delta s
\]

where the \(\Delta\) denotes a difference between quantities pertaining to the incident and emitted beam. Equation (25) provides a recipe for how the irreversible losses can be determined using, for example, standard results from the statistical mechanics of radiation.\(^\text{13,22}\) In keeping with an earlier remark concerning Eq. (21), we note that the expression on the right-hand side of (25) resembles the availability/exergy of one photon, without the pressure correction—in other words, describing a process at constant volume. We shall return to this point in the section The Maximum Efficiency of Solar Energy Conversion.

The use of Eqs. (23) and (25) will now be illustrated on the examples of two specific conversion devices: a monochromatic, or two-level, converter and a single-junction solar cell, providing a parallel to the Shockley–Queisser treatment in the section Quantum Solar Energy Conversion.

### Monochromatic Photon Gas

The analysis of a two-level converter which converts photons in a monochromatic beam (more precisely, quasi-monochromatic radiation with frequencies \(\nu \rightarrow \nu + \delta\nu\)) into useful work or electricity has been of interest as a prototype model for a solar cell since the early days of photovoltaics. It provides a clear link to thermodynamics and the Carnot efficiency, by effectively generalizing the Einstein’s balance between absorption and emission by introducing photon generation.

### TABLE 1 | Different Photovoltaic Efficiencies, Which Are Used in This Review

| Efficiency | Definition | Remarks |
|------------|------------|---------|
| \(\eta_e\) | \(\eta_e = qV/u_{\text{in}}\) | Energy (voltage) efficiency |
| \(\eta_p\) | \(\eta_p = \frac{1}{\Phi_{\text{in}}} \eta_e = \eta_e\) | Power efficiency, within the spectral range of the converter |
| \(\eta\) | \(\eta = scf \eta_p = scf \eta_e\) | Usual solar cell conversion efficiency |

\(u_{\text{in}}\) is the average incident photon energy and \(\Phi_{\text{in}}\) is the incident photon flux, both within the absorption range of the converter / solar cell. The spectral coverage factor is given by \(scf = \int_{\lambda_{\text{b}}}^{\lambda_{\text{c}}} \frac{U_{\text{inc}}(\lambda) d\lambda}{U_{\text{inc}}}\), where the energy fluxes in the numerator and denominator refer to the spectral range absorbed by the semiconductor and the full spectrum, respectively.

---

\(^\text{19}\) guy and stodola theorem

\(^\text{74,75}\) standard results from the statistical mechanics of radiation
fluctuations at different temperatures\(^\text{76,77}\) (see also Ref 78). The key relation which underpins the thermodynamic analysis is the expression for the monochromatic photon entropy:\(^\text{13}\)

\[
s_e = k_B \ln \left( 1 + \frac{G_c}{\Phi_v} \right)
\]  \hspace{1cm} (26)

where \(G_c = 2\nu^2d\nu/v^2\) and \(\Phi_v\) is the photon flux in a small frequency range \(d\nu\) at frequency \(\nu\). We note that entropy per photon increases with increasing étendue \(\Phi \) and decreases with increasing photon flux.

For monochromatic radiation \(u_in = u_out = h\nu\).

The conversion process therefore proceeds with no photon energy losses between absorption and emission, the first term on the right-hand side of (25) vanishes and the irreversible entropy generation \(\sigma_i\) is determined solely by the entropy balance between the incident and emitted photons of monochromatic light at frequency \(\nu\).

We shall consider first the conversion process under maximum concentration of sunlight. The Landsberg–Tonge dilution factor \(e\) (12) is then equal to unity and the open-circuit voltage corresponds to the photon energy converted with the Carnot efficiency:

\[
qV_{oc} = \left( 1 - \frac{T_o}{T_s} \right) h\nu
\]  \hspace{1cm} (27)

Comparison with (23) shows that entropy generation \(\sigma_i\) vanishes at open circuit indicating a reversible energy transformation as implied, of course, by the thermodynamic nature of the Carnot engine.

As finite current is extracted from the converter, the irreversible entropy generation \(\sigma_i\) becomes non-zero—in fact, as a consequence of the second law of thermodynamics, \(\sigma_i\) can only be positive. This also follows from the application of the detailed balance (13) to the monochromatic converter. Use of the generalized Planck law (15) then shows that, for \(I > 0\), the chemical potential \(\mu\) must be smaller than at open circuit. Since the energy \(h\nu\) is constant, (21) implies an increase of entropy on account of irreversible nature of the conversion process. The voltage produced by the two-level converter \(qV = qV_{oc} - T_o\sigma_i\) must therefore decrease from the open-circuit value as current is extracted from the converter. We can draw a parallel between entropy generation resulting from non-zero current (to be denoted by \(\sigma_{kin}\)) and the losses in photothermal and endoreversible engines due to a finite rate of turnover of the heat engine. For the two-level converter, the entropy generation can be written down in a closed form by using Eq. (26)

\[
\sigma_i = s_{out} - s_{in} = k_B \ln \left( \frac{1 - ie^{-x_S}}{1 - i} \right)
\]  \hspace{1cm} (28)

where \(i = I/(q\Phi_{in})\), with \(\Phi_{in}\) the incident black-body photon flux in the frequency range \(d\nu\), denotes the normalized current produced by the converter, and \(x_S = h\nu/k_B T_S\).

The energy efficiency \(\eta_e\) is a useful characteristic of a heat engine but, as in the analysis of thermodynamic engines in the section Light, Heat, and Work, the key parameter of solar cells is the power efficiency \(\eta_P\) (see Table 1) which takes into account the kinetic nature of the conversion process. As defined here, the power efficiency \(\eta_P\) refers only to the monochromatic radiation which is absorbed by the solar cell. In comparison with the energy efficiency \(\eta_e\), the power efficiency \(\eta_P\) contains an additional loss \((1 - \eta_e)\eta_e\) due to the (free) energy carried away by

**FIGURE 6** | The \(i-V\) characteristic of a two-level converter as energy efficiency. (a) The energy efficiency (blue line) showing the Carnot energy not available for conversion (shaded by blue) and the loss on account of irreversible entropy generation on account of current extraction. The power efficiency (red line) includes additionally the power loss by photon emission \((1 - \eta_P)\). The inset in (b) shows losses at the maximum power point.
photons emitted by the solar cell. It highlights the fact that, while the principal loss channel for power at short circuit is the irreversible entropy generation \( \sigma_i \) contained in \( \eta_{\text{oc}} \), losses near the open circuit are dominated by photon emission (Figure 6).

The interplay between the thermodynamic and kinetic losses is usually summarized by the fill factor: ratio of the maximum power divided by the product of open-circuit voltage and short-circuit current. The fill factor provides a ‘conversion factor’ between the power efficiency and the energy efficiency at short circuit, including losses by both kinetic entropy generation and photon re-emission:

\[
\eta_p = ff \eta_{\text{oc}} \quad (29)
\]

For the ideal monochromatic converter under maximum concentration \( \eta_{\text{oc}} \) is equal to the Carnot efficiency. We note that (29) can be written in a form familiar from standards solar cell theory:

\[
P_v = ff I_v V_{oc} \quad (30)
\]

where \( P_v \) is the power produced by the monochromatic converter at the maximum power point.

We are now in position to analyze the conversion process under one-sun illumination. The Landsberg–Tonge dilution factor then becomes \( \varepsilon = \pi/\omega_S < 1 \). The concomitant étendue expansion results in entropy generation (to be denoted by \( \sigma_{\text{exp}} \)), in a process analogous to the expansion of gas into vacuum, resulting in an additional further voltage loss \( T_o \sigma_{\text{exp}}/q \). This has a further consequence that a monochromatic converter can only meaningfully convert a part of the solar spectrum under one-sun illumination as low energy photons cannot produce a positive chemical potential, or voltage. At frequencies above this threshold, the entropy generation can be written as

\[
\sigma_i = \sigma_{\text{exp}} + \sigma_{\text{kin}} \quad (31)
\]

where \( \sigma_{\text{kin}} \) is the entropy (28) and

\[
\sigma_{\text{exp}} = k_B \ln \left( e^{-x_S} - \frac{\pi}{\omega_S} (1 - e^{-x_S}) \right) \approx k_B \ln \left( \frac{\pi}{\omega_S} \right) \quad (32)
\]

where the approximate expression holds at sufficiently high-photon frequencies.

**The Single-junction Solar Cell**

No discussion of the thermodynamics of photovoltaic conversion would be complete without at least a brief look at the ideal single-junction solar cell. As already indicated, this analysis parallels the Shockley–Queisser treatment but focuses on voltage rather than current as the principal variable. In the present terminology, we consider a converter that absorbs all radiation with photon energy above a certain threshold defined by the semiconductor bandgap \( E_g \), and converts an incident beam with photon flux \( \Phi_{in} \) étendue \( \Omega_{in} \) at temperature \( T_S \), into a beam with parameters \( \Phi_{out}, \Omega_{out} \), and \( T_o \), while producing useful work \( w = \mu_{out} \approx qV \) per photon.

The voltage of such a converter can again be obtained from Eq. (23). In comparison with the monochromatic converter, the conversion of broadband solar radiation results in an additional loss through entropy generation and heat rejection into the low-temperature reservoir. The new entropy-generation term \( \sigma_{\text{cool}} \) describes ‘photon cooling’ due to the thermalization of photogenerated electron-hole pairs (and thus also of the emitted photons with which they are in equilibrium) by the interaction with lattice vibrations. \( \sigma_{\text{cool}} \) can be determined from Eq. (25), allowing for the fact that photons emitted at the ambient temperature \( T_o \) now have a lower energy than the incident photons at temperature \( T_S \). The analysis is particularly simple in the limit of weak to moderate illumination when the photon statistics resembles an ideal two-dimensional gas:

\[
\sigma_{\text{cool}} = k_B \left\{ \frac{T_S}{T_o} - 1 \right\} - \ln \left( \frac{T_S}{T_o} \right) \quad (33)
\]

Although present in all current-generation solar cells, the thermalization loss expressed by \( \sigma_{\text{cool}} \) is not, in principle, unavoidable. A hypothetical device where this loss is avoided—a hot-carrier solar cell—is discussed further in the section *The Model of Ross and Nozik*.

Combining all three irreversible losses gives the total entropy generation \( \sigma_i = \sigma_{\text{exp}} + \sigma_{\text{kin}} + \sigma_{\text{cool}} \) and evaluating the resulting expression for voltage (23) confirms the result (18), obtained by the Shockley–Queisser detailed balance. The present treatment, however, distinguishes the different contributions to the fundamental losses, as shown by the different processes that make up the energy efficiency (24) in Figure 7(a).

We can now approach the key attribute of solar cell operation: power conversion. The power efficiency \( \eta_p \) (29) was defined for monochromatic radiation. In a similar fashion, we can consider the power efficiency for a broadband converter for radiation which is actually absorbed by an ideal solar cell—in
other words, by considering only the spectral region with photon energy in excess of the semiconductor bandgap $E_g$. Similarly to the two-level converter, $\eta_P$ is obtained from the energy (or voltage) efficiency by including an additional loss due to photon re-emission, giving rise to the fill factor as discussed in the section The Single-Junction Solar Cell (see Figure 7(a)).

The power efficiency $\eta_P$ is not the usual conversion efficiency used in the textbooks on photovoltaics. This efficiency—which we shall simply denote by $\eta$—includes, as a loss, photons with energies below the bandgap $E_g$ which cannot be absorbed by the cell. From the thermodynamic viewpoint, this loss is clearly of a different nature than losses considered so far and should be considered on a different footing. We shall include this loss in terms of a spectral coverage factor $scf$ which describes the fraction of below-bandgap light in the black-body spectrum (see Table 1).

The expression for solar cell efficiency as a product of the spectral coverage factor, the normalized rate of energy extraction $i$, and the energy efficiency summarizes the thermodynamic view of fundamental losses in solar cells. The solar cell efficiency $\eta$ as a function of the bandgap $E_g$ is plotted in Figure 7(b) which extends, corrects and refines a similar plot of Ref 79 to include a full classification of losses in thermodynamic terms.

**FUTURE DIRECTIONS: BEYOND THE SHOCKLEY–QUEISSER LIMIT**

Thermodynamics is particularly useful in mapping out the potential of new conversion devices and schemes. It has also proved to be a valuable tool in identifying ideas which violate the fundamental physics—usually the second law of thermodynamics (see, e.g., the suggestion and the arguments which demonstrated the internal inconsistency of the proposed device).

The number of ideas and proposed structures that employ a reasoning based at least in part on thermodynamics is now too large to cover in a review of this size. We shall focus here on two well-known areas of photovoltaics research where thermodynamics plays an indispensable role.

**The Maximum Efficiency of Solar Energy Conversion**

Arguably, the quest to determine the maximum attainable efficiency for any solar energy converter has provided one of the grand challenges to
theoricians since the early days of research in this field. Two limits that have been prominent in this discussion include the Landsberg efficiency and the efficiency of the so-called infinite tandem,81 identical to a combination of an infinite set of monochromatic converters discussed in the section Monochromatic Photon Gas and to be discussed below, which would cover the full solar spectrum. Below, we review a recent unified framework85 which elucidates the link between these two limits and proposes a new limit that combines the two.

To this end, we note that the argument used to obtain the Landsberg efficiency was based on the maximum work determined in terms of availability. An identical result can be obtained from the maximum work \( w_v \) per photon at a frequency \( \nu \), and the results weighted by the number of photons and integrated over the full spectrum:

\[
W_{\text{max}} = \int_0^{\infty} w_v \nu n_v(T_S) d\nu = \eta_u U(T_S) \tag{34}
\]

where \( w_v = h\nu(1 - T_o/T_S) - \delta_p \), and \( \delta_p \) is the pressure correction per photon. When integrated, (34) gives the total pressure correction \( \Delta_p \) in (9)—in other words, \( w_v/q \) and the open-circuit voltage (27) for the monochromatic converter are linked in an analogous manner as the Landsberg and Carnot efficiencies (10) and (6) for the full spectrum of solar radiation.

To complete the parallel with a solar cell, we use the Planck relation (4) between photon density and hemispherical flux which corresponds to the photogenerated current \( (q/c_4) n_v \rightarrow f_\nu \). Finally, we set \((c/4) W_{\text{max}} \rightarrow P_L\), where \( P_L \) is the power produced by a converter obtained by combining all the spectral contributions to obtain

\[
P_L = \int_0^{\infty} V^{\text{oc}} f_\nu^p d\nu = \eta_u U(T_S) \tag{35}
\]

A comparison of Eq. (35) and the result based on standard solar cell theory (30) now reveals the difference between work obtained the energy and power efficiencies obtained using the availability argument: the power \( P_L \) (35) obtained using the availability argument does not contain the fill factor—in other words, it does not include losses described by the kinetic entropy generation \( \sigma_{\text{kin}} \). We have argued in this review that this loss is unavoidable by virtue of the second law of thermodynamics: as the entropy is a decreasing function of the number of photons in the beam and the number of emitted photons is less than the number of incident and absorbed photons, the extraction of current from each elemental solar must necessarily leads to entropy generation (see also Monochromatic Photon Gas section). This argument shows that the suggestion in Ref 31 that \( \sigma_{\text{kin}} \) can be made to vanish with the use of nonreciprocal structures would violate the second law of thermodynamics.

We can now progress to obtain the maximum conversion efficiency allowed by thermodynamics. The elementary work \( w_v \), and hence \( V^{\text{oc}}_\nu \), can be determined without difficulty by methods of statistical mechanics, giving also \( \sigma_{\text{kin}} \) and the fill factor.85 Inserting the fill factor into (35), we obtain the maximum efficiency \( \eta_{\text{max}} \) attainable by any solar energy converter, which makes allowance for pressure correction as expressed in the Landsberg efficiency:

\[
P_{\text{max}} = \int_0^{\infty} V^{\text{oc}} f_\nu^p f_\ell^\ell d\nu = \eta_{\text{max}} U(T_S) \tag{36}
\]

The efficiency \( \eta_{\text{max}} \) as a function of the ratio \( T_o/T_S \) is shown in Figure 8; for \( T_S = 6000 \) K, \( \eta_{\text{max}} = 85.0\% \).
A previous widely used result for the maximum overall efficiency was obtained by deVos81,82 by a detailed balance argument for the efficiency of an infinite stack of tandem solar cells which, for $T_S = 6000$ K, comes out as 86.8%. A thermodynamic argument later showed that the resulting efficiency is equivalent to the method of Monochromatic Photon Gas—in other words, setting the open circuit voltage of each elemental converter equal to the energy $h\nu$ converted with the Carnot efficiency $(1-T_e/T_S)$ but neglecting the pressure correction of the Landsberg efficiency. The deVos efficiency is plotted as a function of the ratio $T_e/T_S$ in Figure 8. Interestingly, this graph is very close to the graph of the photothermal efficiency, as noted already in Ref 31 (see also Ref 88). The relationship between different efficiencies that have been suggested as representing the maximum achievable efficiency of solar energy conversion discussed in this review are shown in Figure 9.

**FIGURE 9** | The efficiencies discussed under the maximum concentration of sunlight in this paper for $T_e = 6000$ K and $T_o = 300$ K. PT, Photothermal; ER, Endoreversible (both discussed in the Light Heat and Work section); IT, Infinite tandem; IT-PC, Infinite tandem with pressure correction; HC, Hot-carrier (the last three discussed in the Future Directions section). The four efficiencies in the Carnot—Landsberg scheme are linked by dashed gray arrows to indicate the insertion of the fill factor/kinetic entropy generation and by full arrows to show the pressure correction.

**Hot-Carrier Solar Cell. The Model of Ross and Nozik**

In an attempt to increase the solar cell efficiency above the Shockley–Queisser limit, Ross and Nozik89 proposed a model which aims to eliminate the thermalization loss due to entropy generation (33) on photon cooling. In such a hot-carrier solar cell, photogenerated electron-hole pairs created by light come to a mutual thermal equilibrium by electron–electron interaction alone, without interaction with lattice vibrations, and do not therefore incur the associated energy loss. In their model, the interaction of carriers in the absorber/hot reservoir with carriers at contacts at ambient temperature occurs via ‘selective energy contacts’: only and holes in a very narrow energy range are extracted in the charge separation process (Figure 10). The optimum energy $\Delta E_{\text{loss}}$ which was transferred between the two reservoirs was to be determined by an optimization of the overall conversion process. Ross and Nozik assumed that this limited interaction between the two reservoirs does not disrupt the thermal equilibrium, and that work in the form of electrochemical potential is thus carried reversibly, without any entropy generation.

On further analysis, Würfel et al.86 concluded that the Ross and Nozik model contained serious inconsistencies. The extraction of electron-hole pairs at a single energy other than the average energy would make it impossible for the system to achieve steady-state operation upon illumination. A further objection can be raised with respect to the elective energy contacts which remove carriers within a very narrow energy range from the hot reservoir and inject a monoenergetic jet of hot carriers into the ambient temperature reservoir. It is far from obvious, on the grounds of equilibrium thermodynamics, how this mechanism provides a thermodynamically reversible pathway for the exchange of electron-hole pairs between two reservoirs at different temperatures while carrying out the maximum amount of work.

Notwithstanding, a consistent model of hot-carrier converter can be reconstructed based on elements of the Ross and Nozik scheme, in search of the maximum efficiency which can be attained by eliminating the entropy generation by photon cooling. To this end, we assume, in keeping with Ross and Nozik, that electron-hole pairs reach an equilibrium without energy loss to phonons. The hot carriers are then cooled to ambient temperature and perform work in a Carnot engine, details of which we leave unspecified.

The model to be consider here, summarized in Figure 11, considers incident photons in a beam with
étiendue $\mathcal{E}$ that are absorbed in an absorber. Photons which are not converted into electrical current are emitted, in a beam with étiendue $\mathcal{E}_{\text{out}}$, in such a way that the energy per photon is conserved. The entropy of photons in the emitted beam will be higher than in the incident beam since $\mathcal{E}_{\text{out}} > \mathcal{E}_{\text{in}}$. The chemical potential of photons in the emitted beam (denoted by $\mu_H$) will therefore be lower than in the incident beam of black-body radiation, and must be therefore negative. In general, the étendue expansion will also result in a lower absorber temperature (to be denoted by $T_{\text{H}}$) since the full-spectrum black-body radiation is not an ideal gas, unlike the moderate-intensity radiation with an energy threshold considered in Quantum Solar Energy Conversion section. The emitted photons are in equilibrium with the hot electron-hole pairs, at temperature $T_{\text{H}}$ and chemical potential $\mu_H$ which are now cooled to the ambient temperature whilst carrying out reversible work (Figure 11).

The model can be readily analyzed for an ideal hot-carrier converter operating under one-sun illumination. The analysis is similar to the single-junction solar cell although differences arise in detail as an optimum hot-carrier solar cell absorbs the full solar spectrum which implies that, unlike in conventional solar cells, the ideal bandgap is close to zero. The first steps in the conversion process—photon absorption and subsequent equilibration of the hot-carrier reservoir at temperature $T_{\text{H}}$ and chemical potential $\mu_H$ are conveniently considered together. Under one-sun operation, the étendue expansion results in a chemical potential which is negative and large in magnitude. The analysis can be carried out analytically with the results, at open circuit,

$$T_{\text{H}} = \frac{\pi^4}{90\zeta(3)} T_S = 5402 \text{ K}$$

$$\mu_H = k_B T_{\text{H}} \ln \left( \frac{\zeta(3) \omega_S}{\pi} \left( \frac{T_S}{T_{\text{H}}} \right)^3 \right) = -4.76 \text{ eV}$$

where $\zeta(3) = 1.202$ is the Riemann zeta function. A similar model was considered by Parrott as a representation of solar radiation by black-body spectrum. When finite current is extracted from the cell and fewer photons are emitted by the cell, the temperature $T_{\text{H}}$ remains constant along the current–voltage characteristic but chemical potential $\mu_H$ decreases (Figure 12(a) and (b)).

The work carried out by the hot electron-hole pairs is now set equal to the chemical potential at $T = T_{\text{H}}$, and can be found from the energy/entropy balance equations (22) by setting $u_{\text{in}} \rightarrow u_{\text{H}}$, $s_{\text{in}} \rightarrow s_{\text{H}} = (u_{\text{H}} - \mu_H)/T_{\text{H}}$ and $u_{\text{out}} \rightarrow u_{\text{out}} - T_{\text{H}} s_{\text{out}}$, giving

$$\mu = u_{\text{H}} - T_{\text{H}} s_{\text{H}} = \left( 1 - \frac{T_{\text{H}}}{T_0} \right) u_{\text{H}} + \frac{T_0}{T_{\text{H}}} \mu_H$$

analogous to the Ross and Nozik result with the replacement $\Delta E_{\text{use}} - u_{\text{H}} = u_S$. The final output from
the hot-carrier solar cell can be described by a conventional current—voltage characteristic of an ideal single-junction solar cell with $V_{oc} = 1.055\text{ V}$, $J_{s} = 1147\text{ A/m}^2$ and a fill factor of 0.887 (Figure 12 (c)). The resulting conversion efficiency of 67.0% can be compared with the Ross and Nozik result 65.7% (obtained, however, under a different spectrum) and the efficiency 68.2% for an infinite tandem under one-sun illumination.

The operation of a hot-carrier solar cell under maximum concentration is similar in principle. At open circuit, the temperature of emitted photons and excited electron-hole pairs is equal to the temperature of the solar radiation $T_{s} = 6000\text{ K}$, and the chemical potential is zero. The open-circuit voltage corresponds to the average photon energy $u_{s}$ in the full solar spectrum equal to 1.397 eV, converted with the Carnot efficiency: $qV_{oc} = u_{s}K_{B}T_{H}/(1-T_{o}/T_{s}) = 1.327\text{ eV}$. As finite current is extracted from the cell, the temperature $T_{H}$ and chemical potential $\mu_{H}$ both decrease (Figure 12(a) and (b)). At short circuit, the photogenerated current corresponds to the full photon flux of $52.6 \times 10^6\text{ A/m}^2$.

**LIGHT TRAPPING**

Not all energy aspects of radiation with relevance to photovoltaics involve temperature or heat, or are directly concerned with energy conversion. One such area is the capture of solar radiation and the phenomenon of light trapping.

The fundamental nature of this concept can be understood by considering the balance of energy and photon flow near the interface between two media with different refractive indices (Figure 13(a) and (b)). As the photon density per unit volume in a

**FIGURE 12** | The thermodynamic parameters of the hot-carrier solar cell. Red lines correspond to maximum concentration; blue lines to one-sun illumination. (a) The ratio $\mu_{H}/K_{B}T_{H}$ of the chemical to thermal energy for the absorber. (b) The temperature $T_{H}$ of the hot absorber. (c) The current–voltage and power characteristics (full and dashed lines, respectively).

**FIGURE 13** | The energy densities (a) and photon fluxes (b) at the interface between two media with different refractive indices. (c) The radiation and trapped modes in a medium with a higher refractive index, separated by the ‘escape cone’ with critical angle $\theta_{c}$ defined by the Snell’s law.
dielectric with a refractive index \( n \) is \( n^3 \) times higher than in vacuum, Planck’s relation (4) predicts different photon fluxes directed from opposite sides toward an interface between two media of different optical density. The equilibrium balance of flows across the interface is established by virtue of geometry and Snell’s law: only photons within the ‘escape cone’ are allowed to escape, creating a directional barrier for photon flow from the optically denser medium (Figure 13(c)). This constraint makes it more difficult for photons to escape, trapping photons in the optically denser medium.

An range of ingenious ways have been proposed how this situation can be exploited to improve the capture of solar radiation (see Ref 92 for a recent comprehensive review of this field). In this chapter, we confine ourselves to statistical techniques that have proved most successful in practical applications.

The key feature of statistical light trapping is that the photon gas achieves completely random orientations. We may recall that such concept was already considered by Kirchhoff and Planck (see Black Body Radiation section). The randomness in orientations in black-body radiation occurs by virtue of strong absorption and re-emission. In contrast, light trapping is considered for weakly absorbing media where random orientations of photon directions are caused by scattering. The maximum permitted occupation of the trapped photon states is then reached under a full directional equilibrium, resulting in the highest enhancement of absorption.

Let us consider a volume \( V \) of such optically random medium with a refractive index \( n \), in equilibrium with a surrounding medium with a refractive index of unity (Figure 14). The requirement that the absorption and emission of external radiation be balanced by photon creation and annihilation in the bulk then gives the fundamental condition for statistical light trapping. This is expressed in mathematical terms by linking the Kirchhoff’s law for emission from the surface of the medium with the total emission rate within the volume described by Planck’s law:

\[
e_v \varepsilon_v = (1 - r_v) e_v' V
\]  

(39)

where \( e_v \) and \( e_v' \) are the Kirchhoff’s surface emissivity and Planck’s volume emission coefficient (see Balance between Absorption and Emission of Radiation section). For full generality, we have assumed that photon emission or absorption from the volume is constrained to a beam with any étendue \( \varepsilon \). By virtue of equilibrium, we could assume the photon density per unit volume in the medium to be constant both with respect to position and orientation.

Equation (39) expresses the fact that all photons emitted inside a volume will be emitted to the exterior unless reabsorbed. It introduces a new quantity \( r_v \): \(93,94\), the average probability that a photon, created in the interior of the medium, is reabsorbed before being emitted from the volume. From an alternative viewpoint, \( r_v \) complements Kirchhoff’s absorptivity \( a_v \) for photons arriving from the interior of the medium.

Equation (39) can be transformed into an absorption balance with the use of the relevant Kirchhoff’s and Planck’s laws, relating, at the same time, photon fluxes inside and outside the medium with the use of the brightness theorem (Balance between Absorption and Emission of Radiation section):

\[
a_v \varepsilon_v = 4\pi (1 - r_v) a_v n^2 V
\]  

(40)

Equation (40) can easily be solved for strongly scattering media where the stochastic mature of photon paths ensures that the probability of photon absorption is the same, regardless whether photons originate inside or outside the medium. This makes it possible to set \( a_v = r_v \), giving:

\[
r_v = \frac{\ell_{opt} a_v}{1 + \ell_{opt} a_v}
\]  

(41)

where

\[
\ell_{opt} = \frac{4\pi n^2 V}{\varepsilon}
\]  

(42)

denotes the mean path length that photons traverse before escape. Result (42) can also be obtained directly based on the stochastic nature of radiation by using an argument analogous to the escape of gas through a hole\(^94\) if augmented by a factor due to the directional barrier to photon escape.
Equation (42) can be written in a number of modified but similar forms, and has been used to discuss light trapping in a wide variety of solar cell structures—such as thin layers where scattering is generated by plasmon modes at metallic nanoparticles deposited on the surface. The trapped modes then form a discrete set, and a full understanding is needed of the relationship between the optical path length (42) and the density of trapped modes in the thin layer or waveguide (see, e.g., Refs 102 and 103). The gains through increased absorption in specific spectral regions may be offset against dissipative losses in the metal particles and a reduced entropic advantage of fewer trapped modes. The use of molecular dipoles for a similar purpose has also been suggested. Whatever the final outcome, ideas based on thermodynamics are already being used to advantage. An example of recent developments can serve the recent clarification based on the reciprocity between absorption and emission, that the increase in short-circuit current due to light trapping is mitigated by an increase in the dark saturation current, lowering the open-circuit voltage. Whatever the enhancement, light trapping by itself cannot therefore be used to surpass the Shockley–Quisser limit, as has recently been suggested.107

Other suggestion to enhance light trapping is based on expanding the thermodynamic analysis into the frequency domain. This is easily achieved by the management of photon directions as well as frequency using photon absorption and re-emission as fluorescence (Figure 16). In thermodynamic terms, the fluorescent medium then effectively exchanges energy with the photon field which no longer represents as an isolated system. This energy loss can then be traded for an extension of the path length through solar cell beyond the monochromatic limit (42), or for an étendue reduction in a device that emits light. These two applications are briefly discussed below.

A device which transforms the entropy change on photon cooling into an étendue reduction is called a fluorescent concentrator/collector. It usually represents a fluorescent plate that absorbs light from the large face and emits the fluorescent light through the edge, making it possible to employ significantly smaller solar cells. Studied since the late 1970s, the

![Figure 15](https://example.com/figure15.png)

**FIGURE 15** | Examples of light trapping schemes in several current types of solar cells. (a) Light trapping in the form of small pyramids etched in the top surface as implemented in, for example, the COMSAT ‘black’ solar cell. (b) A more sophisticated form of surface texturing in the form of inverted pyramids on the UNSW PERL cell. (c) Structure of the dye-sensitized (Grätzel) cell with light trapping by scattering from titanium oxide nanoparticles.
interest in fluorescent collectors has recently been revived due to the availability of a wider range of dyes and the developments in photonics. There is much optimism for a substantial increase over the current overall efficiencies (solar cell plus collector) of 7–8%. Particularly, fruitful direction appears to be the application of photonic structures to trap the narrow-band fluorescent light while allowing most of the incident broadband solar flux to be absorbed by the collector (Figure 16(c)). Such structures can limit photon losses to less than about 10% of the incident light, leading to overall efficiencies of 18–20% with a good crystalline silicon solar cell.

This ‘thermodynamic squeezing’ of light which lies in the heart of operation of the fluorescent collectors can also be used to advantage to improve the capture of weakly absorbed light. The use of a photonic filter in combination with frequency management extends the photon path length by a factor equal to an inverse of the Boltzmann factor appropriate to the frequency bandwidth of the trapped light:

$$\ell_{opt} \approx 4n^2 d e^{h\Delta\nu/k_BT}$$

(44)

If the width of the frequency band stop $\Delta\nu$ is large, the photonic structure would block a large part of the spectrum but for an optimum value which transmits a sufficient part of the solar spectrum while ensuring a substantial enhancement in light trapping, as illustrated on the example of a predicted quantum efficiency that can be reached by a solar cell (Figure 17).
The predicted power conversion efficiencies are shown in Table 2. Remarkably, the cell efficiency of a cell with thickness merely 1 μm is now comparable with (and even slightly exceeds!) the efficiency of the 500 μm cell.

### CONCLUSION AND OUTLOOK

Solar radiation can be represented as high-temperature heat and its conversion into useful work or electricity is described well by the laws of thermodynamics. It is therefore not surprising that thermodynamics now forms a routine part of the modeling toolset for both the current and future generations of solar cells, and our thinking should not be about if but how thermodynamics can guide us to make better solar cells.

The theoretical framework of thermodynamic applications to solar energy conversion has witnessed steady development but a number of theoretical questions and problem areas remain. How can thermodynamics be used to increase the solar cell efficiency? Several ideas have been discussed (for example, hot-carrier solar cells, reviewed in the Model of Ross and Nozik section) but the theory still requires development to reach a satisfactory level of understanding. Questions remain about the relationship between the application of classical thermodynamics to kinetic processes and the issues of reciprocity or microscopic reversibility. Can nonreciprocal structures lead to higher efficiencies than those that were discussed in this review?

What clues can thermodynamics provide as to new mechanisms and materials? With increasing use of nanotechnology and a drive toward ever thinner devices, effective capture of sunlight is key to the efficient new solar cells. A classical approach to light trapping was reviewed in the Light Trapping section, but there is a need to extend the theory to ultrathin solar cells in the form of wave guides or photonic structures that trap or concentrate sunlight. Quantum heat engines have been proposed based on the thermodynamic description of masers and lasers involving coherent transitions between quantum levels coupled to heat baths. These engines can operate as quantum amplifiers or refrigerators—a similar approach (possibly based on rectifying antennas) be exploited to benefit solar energy conversion?

These are just a few, almost random thoughts. Few persons alive during the age of the steam engine would have predicted the success of thermodynamics in the design of modern aircraft, rockets, automobiles, and energy equipment that we enjoy today. It is likely that the ‘thermodynamics of light’ will see many years of further development, with application to new devices that are yet to be discovered. Its true moment of success may well be ahead of us.

### NOTES

- The possibility to excite photons with energy higher than the corresponding applied voltage. See Ref 1.
- A comprehensive review of efficiencies that have been considered for solar energy conversion can be found in Ref 4.
- Although the name appears to be fairly recent, similar concepts have been associated much earlier with such distinguished names as Poincaré, Lagrange, and Helmholtz.
- A clear exposition of the optical ideas behind the concept of éndue can be found in Ref 6.
- The first paper that appears to have drawn attention to the link between éndue and a volume on the phase space appears to be in Ref 7.
- A particularly clear discussion of this point can be found in Ref 11.
- In photon terminology that will be used throughout this paper, the balance between absorption and emission was formulated for semiconductors (but can be easily generalized).
- This subject is reviewed in a particularly clear form in Ref 32.
- See, for example, Section 20 in Ref 13 or Chapter 7 in Ref 14.
- More rigorously, the internal energy \( \mu \), entropy \( s \) as well as the chemical potential \( \mu \) refer to adding or removing a photon at constant volume rather than at constant pressure, as in the usual analysis of chemical reactions. We shall return to this assumption later in Thermodynamics of Photovoltaic Conversion section.
- A full treatment in terms of rate of photon emission and work (as depicted in Figure 2(c)) is described in Ref 67, leading to identical results.
- In our analysis, the fill factor contains the current corresponding to the full photon flux \( \Phi_n \) rather than the more usual photogenerated current \( I_n \). In practical applications, the difference between the two—equal to the dark saturation current \( I_n \)—is very small and can be safely neglected.
- In practical terms, this implies a concentration ratio of less than about a hundred for a silicon solar cell.
This value was obtained by a more accurate numerical procedure than in Ref 85, and is slightly lower than the result 85.2% reported there.

Detailed discussions of reabsorption (also called photon recycling) with application to solar cells can be found in Refs 83, 84 and 93.

ACKNOWLEDGMENTS

The author’s initial stimulus to embark into research in this field came from many frequent conversations and debates with the late Peter Landsberg without whom this article would not have seen the light of day. Over many years, many topics in this review have been enriched by stimulating discussions with Gottfried Bauer, Philip Davies, Jeffrey Gordon, Martin Green, Marius Peters, Dieter Meissner, and Peter Würfel, as well as with my colleagues and students at Southampton Solar Energy Laboratory. Although the full agreement about many aspects is still to be reached, I hope that these debates have helped to convey the rich tapestry of science being woven into a picture which may, one day, reflect a satisfactory and thorough understanding.

REFERENCES

1. Rose A. Photovoltaic effect derived from the Carnot cycle. J Appl Phys 1960, 31:1640.
2. Carnot S. Réflexions sur la puissance motrice du feu et sur les machines propres a développer cette puissance. Paris: Bachelier; 1824.
3. Becquerel AE. Recherches sur les effets de la radiation chimique de la lumière solaire, au moyen de courants électriques. Comptes Rendus 1839, 9:561–567.
4. Landsberg PT, Badescu V. Solar energy conversion: list of efficiencies and some theoretical considerations. Prog Quant Electron 1990, 22:211–231.
5. Welford WT, Winston R. The Optics of Non-Imaging Concentrators. New York: Academic Press; 1978.
6. Miñano JC. Optical confinement in photovoltaics. In: Luque A, Araujo GL, eds. Physical Limitations to Photovoltaic Energy Conversion. Bristol: Adam Hilger; 1990, 50.
7. Joyce WB. Classical-particle description of photons and phonons. Physical Review D 1979, 3:3234–3256.
8. Markvart T. The thermodynamics of optical étendue. J Opt A: Pure Appl Opt 2008, 10:015008.
9. Kragh H. Max Planck: the reluctant revolutionary. Phys World 2000:31–35.
10. Boltzmann L. Ableitung der Stefan’schen Gesetzes, betreffend der Abhängigkeit der Wärmerstrahlung von der Temperatur aus der elektromagnetischen Lichttheorie. Ann d Phys 1884, 22:291–294.
11. Kuhn TS. Black-Body Theory and the Quantum Discontinuity. Oxford: Oxford University Press; 1978, 5.
12. Born M, Wolf E. Principles of Optics. Cambridge: Cambridge University Press; 1999.
13. Landau LD, Lifshitz EM. Statistical Physics. Oxford: Pergamon Press; 1958.
14. Pippard AB. The Elements of Classical Thermodynamics. Cambridge: Cambridge University Press; 1964.
15. De Vos A. Endoreversible Thermodynamics of Solar Energy Conversion. Oxford: Oxford University Press; 1992.
16. Landsberg PT, Tonge G. Thermodynamics of the conversion of diluted radiation. J Phys A 1979, 12:551–562.
17. Weinstein MA. Thermodynamic limitation on the conversion of heat into light. J Opt Soc Am 1960, 50:597–602.
18. Chukova YP. Thermodynamic limit of the luminescence efficiency. Zh Eksp Teor Fiz Pisma Red 1969, 10:458–460.
19. Markvart T. Solar cell as a heat engine: energy-entropy analysis of photovoltaic conversion. Phys Status Solidi (a) 2008, 205:2752–2756.
20. Kangro H. Early History of Planck’s Radiation Law. London: Taylor and Francis; 1976.
21. Kirchhoff G. On the relation between the radiating and absorbing powers of different bodies for light and heat (translation of a German original). Phil Mag Ser 4 1860, 20:1.
22. Planck M. The Theory of Heat Radiation. New York: Dover; 1991.
23. van Roosbroeck W, Shockley W. Photon-radiative recombination of electrons and holes in germanium. Phys Rev 1954, 94:1558.
24. Einstein A. On the quantum theory of radiation. Phys Z 1917, 18:121. English translation in van der Waerden BL. Sources of Quantum Mechanics, Dover, New York, 63.
25. Kennard EH. On the thermodynamics of fluorescence. Phys Rev 1918, 11:29.
26. Kennard EH. On the interaction of radiation with matter and on fluorescent exciting power. Phys Rev 1926, 28:672.
27. Stepanov BL. A universal relation between the absorption and luminescence spectra of complex molecules. Sov Phys Dokl 1957, 112:81.
28. Stepanov BL. Correlation between the luminescence and absorption spectra of complex molecules Izv. Akad. Nauk SSSR 1958, 22:1337.

29. Würfel P. Generation of entropy by the emission of light. J Phys Chem Solids 1988, 49:721.

30. DeVos A, Pauwels H. Comment on a thermodynamical paradox presented by P. Würfel. J Phys C: Solid State Phys 1983, 16:6897-6909.

31. Green MA. Third Generation Photovoltaiacs: Advanced Solar Energy Conversion. Berlin: Springer; 2003.

32. Gordon JM. Maximum power point characteristics of heat engines as a general thermodynamic problem. Am J Phys 1989, 57:1136.

33. Castañs M. Bases físicas del aprovechamiento de la energía solar. Revista Geofísika 1976, 35:227.

34. Castañs M, Soler A, Soriano F. Theoretical maximal efficiency of diffuse radiation. Sol Energy 1987, 38:267.

35. Jeter S. Maximum conversion efficiency for the utilization of direct solar radiation. Sol Energy 1981, 26:231.

36. Novikov II. The efficiency of nuclear power stations. J Nucl Energy 1958, 7:125.

37. Chambadal P. Les Centrales Nucleaires. Paris: Armand Colin; 1957.

38. Curzon F, Ahlborn B. Efficiency of a Carnot engine at maximum power output. Am J Phys 1975, 43:22.

39. Luneburg RK. Mathematical Theory of Optics. Berkeley & Los Angeles: University of California Press; 1964.

40. Leff H. Teaching the photon gas in introductory physics. Am J Phys 2002, 70:792–797.

41. Petela R. Exergy of heat radiation. Trans ASME Heat Transfer 1964, 36:187.

42. Press WH. Theoretical maximum for energy from direct and diffuse sunlight. Nature 1976, 264:735.

43. Landsberg PT, Mallinson JR. Thermodynamic constraints, effective temperatures and solar cells. In: Coloquelle International sur l’Electricité Solaire, CNES, Toulouse, 1976, 16.

44. Landsberg PT, Badascu V. Carnot factor in solar cell efficiencies J. Phys D 2000, 33:3004.

45. Parrott JE. Thermodynamic limits to photovoltaic energy conversion. In: Luque A, Araujo GL, eds. Physical Limitations to Photovoltaic Energy Conversion. Bristol: Adam Hilger; 1990.

46. Landsberg PT, Markvart T. Ideal efficiencies. In: Markvart T, Castaner L, eds. Practical Handbook of Photovoltaics: Fundamentals and Applications. Oxford: Elsevier; 2003, 123.

47. Landsberg PT, Tonge G. Thermodynamic energy conversion efficiencies. J Appl Phys 1980, 51:R1.

48. Landau LD. On the thermodynamics of photoluminescence. J Phys 1946, 10:503–506.

49. Lehovec K, Accardo CA, Jamochian E. Light emission produced by current injected into a green silicon-carbide crystal. Phys Rev 1953, 89:20.

50. Mungan CE. Radiation thermodynamics with applications to lasing and fluorescent cooling. Am J Phys 2003, 73:315.

51. Shockley W, Queisser HJ. Detailed balance limit of efficiency of p-n junction solar cells. J Appl Phys 1961, 32:510–519.

52. Trivich D, Flinn P. Maximum efficiency of solar energy conversion by quantum processes. In: Daniels F, Duffie J, eds. Solar Energy Research. London: Thames and Hudson; 1955, 143.

53. Müser HA. Thermodynamische Behandlung von Elektronenprozessen in Halbleiter-Randschichten. Z Phys 1957, 148:380–390.

54. Chel’tzov VF. Interaction of two-band semiconductor with radiation field. Solid State Commun 1971, 9:1343.

55. Bebb HB, Williams EW. Photoluminescence I: Theory. In: Willardson RK, Beer AC, eds. Semiconductors and Semimetals, vol. 8. New York: Academic Press; 1972.

56. Würfel P. The chemical potential of radiation. J Phys C: Solid State Phys 1982, 15:3967.

57. Ruppel W, Würfel P. Upper limit for the conversion of solar energy. IEEE Trans Electron Devices 1980, 27:877.

58. Knox RS. Chapter 2: Photosynthetic efficiency and exciton transfer and trapping. In: Barber J, ed. Primary Processes in Photosynthesis. Amsterdam: Elsevier; 1977, 58–60.

59. Knox RS. Thermodynamics and the primary processes of photosynthesis. Biophys J. 1969, 9:1351–1362.

60. Duysens L. The path of light energy in photosynthesis Brookhaven. Symp Biol 1958, 11:10–25.

61. Ross RT, Calvin M. Thermodynamics of light emission and free-energy storage in photosynthesis. Biophys J 1967, 7:595–614.

62. Ross RT. Thermodynamic limitations on the conversion of radiant energy into work. J Chem Phys 1966, 45:1.

63. Ross RT. Some thermodynamics of photochemical systems. J Chem Phys 1966, 46:4590.

64. Bolton JR. Solar fuels. Science 1978, 202:705–711.

65. Lavery J, Joliot P. Thermodynamics of the excited states of photosynthesis. In: Cramer WA, ed. Energy Transduction in Membranes. Biophysical Society; 2000. http://www.biophysics.org/education/lavergne.pdf.
66. Kedem O, Kaplan SR. Degree of coupling and its relation to the efficiency of energy transduction. *Trans Farad Soc* 1965; 21:1897.

67. Markvart T. Thermodynamics of losses in photovoltaic conversion. *Appl Phys Lett* 2007; 91:064102.

68. Kolodinski S, Werner JH, Wittchen T, Queisser HJ. Quantum efficiencies exceeding unity due to impact ionization in silicon solar cells. *Appl Phys Lett* 1993; 63:2405.

69. Werner JH, Kolodinski S, Queisser HJ. Novel optimization principles and efficiency limits for semiconductor solar cells. *Phys Rev Lett* 1994, 72:3851.

70. Barnham KWJ, Duggan G. A new approach to high-efficiency multi-bandgap solar cells. *J Appl Phys* 1990, 67:3490.

71. Araujo GI, Martí A. Absolute limiting efficiency of multi-bandgap solar cells. *J Phys D Appl Phys* 1994, 33:213.

72. Luque A, Martí A. Entropy production in photovoltaic conversion. *J Phys D Appl Phys* 1994, 37:1347.

73. Baruch P, Parrott JE. A thermodynamic cycle for photovoltaic energy-conversion. *J Phys D Appl Phys* 1990, 23:739.

74. Gouy G. Sur l’énergie utilizable. *J de Phys* 1889, 8:501–518.

75. Stodola A. Die Kreisprozesse der Dampfmaschine. *Zeitschr. d. Vereines deutscher Ingeniure* 1898, 32:1086.

76. Baruch P, Picard C., Swanson R. Thermodynamic limits to photovoltaic solar energy conversion efficiency. In: *Proceedings of the 3rd European Photovoltaic Energy Conference*, Cannes, 1981, 922.

77. Baruch PA. Two-level system as a model for a photovoltaic solar cell. *J Appl Phys* 1985, 57:1347.

78. Landsberg PT, Markvart T. The Carnot Factor in solar cell theory. *Solid State Electron* 1998, 42:657–659.

79. Hirst LC, Ekins-Daukes NJ. Fundamental losses in solar cells. *Prog Photovolt Res Appl* 2011, 19:286.

80. Araujo GL, Martí A. Electroluminescence coupling in multiple quantum well diodes and solar cells. *Applied Physics Letters* 1995, 66:894.

81. DeVos A. Detailed balance limit of the efficiency of tandem solar cells. *J Phys D Appl Phys* 1980, 13:839.

82. DeVos A, Pauwels H. On the thermodynamic limit of photovoltaic energy conversion. *Applied Physics A* 1981, 25:119.

83. Martí A, Balenzategui JL, Reyna RF. Photon recycling and the Shockley diode equation. *J. Appl. Phys.* 1997, 82:4067.

84. Badescu V, Landsberg PT. Influence of photon recycling on solar cell efficiencies. *Semicond. Sci. Technol.* 1997, 12:1491.

85. Markvart T, Bauer G. What is the useful energy of a photon? *Appl Phys Lett* 2012, 101:193901.

86. Würfel P, Brown AS, Humphrey TE, Green MA. Particle conservation in the hot-carrier solar cell. *Prog Photovolt Res Appl* 2005, 13:277.

87. DeVos A. The current–voltage characteristic of the ideal two-terminal tandem solar cell. *Prog Photovolt Res Appl* 2003, 11:237.

88. Badescu V. Unified upper bound for photothermal and photovoltaic conversion efficiency. *J Appl Phys* 2008, 103:054903.

89. Ross RT, Nozik AJ. Efficiency of hot-carrier solar energy converters. *J Appl Phys* 1982, 53:3813.

90. Markvart T. To be published.

91. Parrott JE. Choice of an optimum black body solar temperature. *Sol Energy* 1993, 51:195.

92. Peters IM. Phase space considerations for light path lengths in planar, isotropic absorbers. *Opt Express* 2014, 22:A908.

93. Parrott JE. Radiative recombination and photon recycling. *Sol Energy Mater Sol Cells* 1993, 30:221.

94. Kittel C, Kroemer H. *Thermal Physics*. New York: W.H. Freeman and Co; 1980, Chapter 14.

95. Markvart T, Castañer L, eds. *Practical Handbook of Photovoltaics: Fundamentals and Applications*. Oxford: Elsevier; 2003, 253, Chapters IIb-3, IIb-5, IIc-2 and IIe-2.

96. McEvoy AJM. Photoelectrochemical solar cells. In: Markvart T, Castañer L, eds. *Practical Handbook of Photovoltaics: Fundamentals and Applications*. Oxford: Elsevier; 2003, 459.

97. Haynos J., Allison J., Arndt R., Meulenberg A. The COMSAT non-reflective silicon solar cell: a second generation improved cell. In: *Proceedings of the International Conference on Photovoltaic Power Generation*, Hamburg, 1974, 487.

98. Wang A, Zhao J, Green MA. 24% efficient silicon solar cells. *Appl Phys Lett* 1990, 57:602.

99. Yablonovitch E, Cody GC. Intensity enhancement in textured optical sheets for solar cells. *IEEE Trans Electron Dev* 1982, 29:300.

100. Yablonovitch E. Statistical ray optics. *J. Opt. Soc. Am.* 1982, 72:899.

101. Yablonovitch E. *Plasmonics: Fundamentals and Applications*. New York: Springer-Verlag; 2007.

102. Stuart HR, Hall DG. Thermodynamic limit to light trapping in thin planar structures. *J Opt Soc Am A* 1997, 14:3001.

103. Schiff EA. Thermodynamic limit to photonic-plasmonic light-trapping in thin films on metals. *J. Appl. Phys.* 2011, 110:104501.

104. Yu Z, Raman A, Fan S. Fundamental limit of nanophotonic light trapping in solar cells. *Proc Natl Acad Sci USA* 2010, 107:17491.
105. Alderman N., Danos L., Fang L., Parel T., Markvart T. Enhancing light capture by silicon—with the help of molecules. In: Proceedings of the 40th IEEE Photovoltaic Specialists Conference, Denver, Co., 2014, 17.

106. Rau U, Kirchartz T. On the thermodynamics of light trapping in solar cells. Nat Mater 2014, 13:103–104.

107. Polman A, Atwater HA. Photonic design principles for ultrahigh-efficiency photovoltaics. Nat Mater 2012, 11:174.

108. Markvart T. Beyond the Yablonovitch limit: trapping light by frequency shift. Appl Phys Lett 2011, 98:071107.

109. Weber WH, Lambe J. Luminescent greenhouse collector for solar radiation. Appl Opt 1976, 15:2299.

110. Goetzberger A, Greubel W. Solar energy conversion with fluorescent collectors. Appl. Phys. 1977, 14:123.

111. Batchelder JS, Zewail AH, Cole T. Luminescent solar concentrators. 1: Theory of operation and techniques for performance evaluation. Appl Opt 1979, 18:3090.

112. Batchelder JS, Zewail AH, Cole T. Luminescent solar concentrators. 2: Experimental and theoretical analysis of their possible efficiencies. Appl Opt 1981, 20:3733.

113. Goldschmidt JC, Peters M, Bösch A, Helmers H, Dimroth F, Glunz SW, Willeke G. Increasing the efficiency of fluorescent concentrator systems. Sol Energy Mater Sol Cells 2009, 93:176.

114. van Sark WGJHM, Barnham KWJ, Slooff LH, Chatten AJ, Büchtemann A, Meyer A, McCormack SJ, Koole R, Farrell DJ, et al. Luminescent solar concentrators—a review of recent results. Opt Express 2008, 16:21773.

115. Markvart T. Detailed balance method for ideal single-stage fluorescent collectors. J Appl Phys 2006, 99:026101.

116. Markvart T, Danos L, Fang L, Parel T, Soleimani N. Photon frequency management for trapping & concentration of sunlight. RSC Adv 2012, 2:3173.

117. Scovil HED, Schulz-Dubois EO. Three-level masers as heat engines. Phys Rev Lett 1959, 2:262–263.

118. Geusic JE, Schulz-DuBois EO, Scovil HED. Quantum equivalent of the Carnot cycle. Phys. Rev. 1967, 156:343–351.

119. Kosloff R, Levy A. Quantum heat engines and refrigerators: continuous devices. Annu Rev Phys Chem 2014, 65:365–393.

120. Mashaal H, Gordon JM. Fundamental bounds for antenna harvesting of sunlight. Opt Express 2011, 36:900.

121. Mashaal H, Gordon JM. Efficiency limits for the rectification of solar radiation. J. Appl. Phys 2013, 113:193509.