Hybrid solar converters for maximum exergy and inexpensive dispatchable electricity

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Abstract

Photovoltaic (PV) solar energy systems are being deployed at an accelerating rate to supply low-carbon electricity worldwide. However, PV is unlikely to economically supply much more than 10% of the world's electricity unless there is a dramatic reduction in the cost of electricity storage. There is an important scientific and technological opportunity to address the storage challenge by developing inexpensive hybrid solar converters that collect solar heat at temperatures between about 200 and 600°C and also incorporate PV. Since heat can be stored and converted to electricity at relatively low cost, collection of high exergy content (high temperature) solar heat can provide energy that is dispatchable on demand to meet loads that are not well matched to solar insolation. However, PV cells can collect and convert much of the solar spectrum to electricity more efficiently and inexpensively than solar thermal systems. Advances in spectrum-splitting optics, high-temperature PV cells, thermal management and system design are needed for transformational hybrid converters. We propose that maximizing the *exergy* output from the solar converters while minimizing the *cost of exergy* can help propel solar energy toward a higher contribution to carbon-free electricity in the long term than the prevailing paradigm of maximizing the *energy* output while minimizing the *cost of energy*.

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BROADER CONTEXT:

It remains a critical challenge to reconcile the world's consistent demand for inexpensive electricity with the imperative to combat anthropogenic climate change by reducing the release of carbon-dioxide to the atmosphere. Following decades of intensive R&D and rapid manufacturing scale-up, nearly carbon-free photovoltaic solar electricity generators can be deployed at or below prevailing grid electricity costs in certain electricity markets and this favorable geographic range will increase as the technology improves in the coming years. However, delivery of large quantities of photovoltaic power when sunlight is unavailable can only be accomplished at scale using electrical storage technologies. In the absence of appropriate sites for inexpensive pumped hydroelectric or compressed air storage, batteries become the storage system of choice. However, batteries remain too expensive for widespread deployment. Without an inexpensive means to store the solar electricity produced by photovoltaics, the value of future installations that produce only daytime power will fall and their fraction of the electricity supply will be limited. At present, the competing technology of concentrated solar power deploys plants that collect heat, stores it, and can dispatch electricity day and night, but the technology requires very large and expensive plants. This work describes the economics of the problem and proposes that *hybrid* solar converters combining elements of both photovoltaic and concentrated solar power systems can address the solar enegy storage problem that is coming soon in regions with high photovoltaic deployment. These hybrid converters could optimally exploit the solar spectrum to realize higher conversion efficiencies and low electricity costs while ensuring the availability of inexpensive dispatchable solar power.

1. Introduction: Limits to the impact of photovoltaics

During the daytime, PV provides low-carbon electricity at prices at or below parity with grid electricity in an increasing range of locations that have good solar insolation and high or moderate electricity prices.[1] Manufacturing scale and technological improvements drive continuing PV module price reduction, and efficient networks for PV distribution and installation are developing worldwide. Although the cost of PV will continue to fall[1, 2] and improvements to grid and demand response infrastructure can increase daytime solar penetration, PV's contribution to the electricity supply will ultimately be limited if the cost of energy storage remains high.

The experience of Germany provides a glimpse into the likely global future of PV at high penetration. A feed-in-tariff law has led to installed PV installations which provide ~6% of annual electrical energy production, and solar occasionally contributes more than 50% of the required grid power.[3] However, in 2013 the wholesale electricity price in Germany fell by about \$0.01/kWh for each 10% of additional solar and wind generation in the total hourly electricity mix.[4] When total renewables production during an hour exceeded about 40% and demand was modest or high, the wholesale price of electricity often became negative;[4] storage resources in Germany are insufficient.[5] To motivate continued investment in PV, an incentive program now offers up to 60 euro/kW subsidy to induce the use of electrical storage tied to PV.[6, 7]

In California, modeling shows that PV power will be curtailed at times of high solar availability once it supplies more than about 10% of total electricity;[8] another study suggests that without storage, the marginal economic value of PV will fall below the wholesale electricity price at approximately 6% PV penetration.[9] During 2014, utility-scale solar plants, including both Concentrating Solar Power (CSP) and PV, provided ~5% of California electricity[10] with most of that energy coming from PV. The reported annual PV installation rate in the state has increased 6-fold between 2011 and 2014,[11]driven by a Renewable Portfolio Standard (RPS) that requires 33% penetration of renewables into California electricity by 2020. PV is expected to contribute the largest share of all renewable power provided to California by 2020.[12] Sporadic daytime renewable generator curtailments have already begun in several parts of California; the California Independent System Operator (CAISO) reports that a small fraction of renewable electricity is curtailed due to a surplus over demand[13] and that high power ramp rates needed in the evening are becoming problematic.[14] Periods of negative electricity pricing, when neighboring jurisdictions are paid to accept overgenerating production, increased in California between 2013 and 2014 and are expected to become more frequent and widespread, reducing the value of installing new PV generating resources.[13, 15, 16] In the absence of inexpensive means of storing solar electricity for dispatch when needed, natural gas spinning reserves (online dispatchable capacity) will likely be used to compensate for variable PV generation, but spinning reserves are expensive and they emit CO_2 that lowers the carbon reduction benefit from PV.

Hours of energy storage will be needed to expand solar energy utilization beyond sunny daytime hours and into nighttime, and eventually days of storage will be needed for extended cloudy periods. This means that the cost must be low for both electrical energy ($\$/kWh_{el}$) and electrical power ($\$/kW_{el}$) delivered from storage. In this manuscript, we compare the high cost of electrical energy storage to the lower cost of thermal energy storage for electricity generation. We conclude that solar generating systems that produce *inexpensive* 200 to 600°C heat while hybridizing with high efficiency PV could provide the dispatchable electricity needed to balance PV and wind generation resources, allowing higher penetration of carbon-free renewable energy on the grid. In recent years, concentrating solar power (CSP) systems have been unable to provide solar heat at low enough cost for its electricity to match the price of photovoltaic electricity,[17] but hybrid solar converters may lower costs by combining PV and thermal collection with advanced optics and other technology innovations. While several hybrid converter designs have been proposed and analyzed,[18-22] the literature lacks experimental prototypes that could lead to efficient low-cost systems.

In Section 2 of this paper, we compare electrical and thermal energy storage costs. In Section 3, we discuss in broad terms the opportunity presented by hybrid solar converters. In Section 4, we analyze the technology pathways for hybrid converters in more detail. Finally, in Section 5, we propose new exergy-based metrics for evaluating the value of these emerging technology developments.

2. Comparing the costs of electrical and thermal storage

The levelized cost of electricity (LCOE) without subsidy for solar PV is as low as \$0.10/kWh in some regions of the U.S.[23] and is falling. With current methods, storing PV electricity for hours or days would double or triple its cost. Although electrical storage costs are decreasing, no storage systems available today can achieve low capital cost together with long calendar lifetimes and cycling durability. The lowest-cost options are pumped hydroelectric storage using natural reservoirs and compressed air energy storage (CAES) in underground caverns, with levelized costs of delivered electricity of \$0.16-0.22/kWh_{el} and approximately \$0.12/kWh_{el}, respectively.[24] Unfortunately, geologically and environmentally suitable sites are scarce and often far from the solar resource,[25] stimulating development and demonstration projects for more costly above-ground CAES systems. While more expensive electrochemical storage such as NaS, Li-ion and advanced flow batteries have become inexpensive enough to provide high-value short-duration ancillary services on the electrical grid, storing PV electricity economically for hours or days would require dramatic improvements in battery component costs and durability.[26]

Even if aggressive industry cost targets of \$200/kWh_{el} (pack level) for batteries are met,[27] they would add approximately \$0.10 /kWh_{el} to the cost of electricity, exceeding the marginal cost of adding thermal energy storage to a CSP system today (see below and the Supplementary Information, SI).

In contrast to PV, which converts sunlight directly to electricity, concentrating solar power (CSP) plants collect solar thermal energy by heating a fluid such as a silicone oil or molten salt to a temperature between about 300 and 600°C.[28] Downstream of the solar collector, this heat is sent to a heat engine and generator to produce electricity. The heat can be stored for later use as sensible heat in the collection fluid or another substance, as latent heat in a phase-change material, or through reversible thermochemical reactions.[29, 30] Review of installed CSP projects with storage is available elsewhere.[31]

The present marginal cost of adding thermal energy storage to a CSP plant is significantly lower than the cost of today's grid-scale electricity storage systems. Thermal storage will likely be applicable only with commercial, microgrid or utility-scale CSP and not in residential markets, due to present challenges in scaling down heat engines and safety concerns. The cost of dispatchable electricity from stored heat includes the lifecycle costs of the thermal storage medium, insulating containment structures, heat exchangers, heat engine and generator. The current cost of 580ºC molten salt thermal energy storage for a CSP plant (including its containment, pumps and heat exchangeres) is \$30/kWh_{th}.[32] Once converted to electricity in a 40%-efficient steam Rankine heat engine, this cost of storing thermal energy is equivalent to ~\$75/kWh_{el}. Assuming that the heat engine, generator and containment last for 30 years, we estimate that thermal storage of 580°C heat in molten salt, today, will add less than \$0.03/kWh_{el} to the levelized cost of electricity (see SI), far less than our aggressive \$0.10/kWh_e future estimate for batteries. Storage of heat at a lower temperature of 386°C raises the cost of thermal energy storage to \$80/kWh_{th} and reduces the generation efficiency to about 36%.[33] This roughly doubles the LCOE of the storage to ~\$0.06/kWh (see SI), still lower than battery storage. Since mechanical heat engines typically have field lifetimes longer than 30 years,[34, 35] the ~\$1000/kW_{el} cost of large heat engines and electrical generators used 10 hours daily contributes about \$0.01/kWh to \$0.02/kWh to the cost of energy. Thermal storage costs are likely to fall further as use of phase-change materials exploits the high latent heat of melting and system improvements are implemented.[31, 36]

However, the low efficiency of CSP systems means that solar energy collection costs dominate the costs of the thermal storage systems in determining the cost of dispatchable electricity from solar thermal energy today. The LCOE for CSP electricity is significantly higher than the LCOE of PV electricity.[17] Adding a component of PV collection in a hybrid solar converter can lower the effective cost of solar heat collection below that of CSP and make it possible to take advantage of low-cost thermal storage.

3. Comparison of concentrating solar technology options

In this Section, we roughly compare solar energy conversion options based upon photovoltaics and solar thermal collection. To make these comparisons, we must consider both sunlight collected as heat energy and sunlight converted to electrical energy. Because the thermodynamic Carnot efficiency limit applies to conversion of heat to useful work or electricity, solar-to-exergy efficiencies often provide a more practical measure to compare the different solar energy systems than solar-to-energy efficiencies. Exergy is defined as the thermodynamic limit $Q(1-T_c/T_h)$ to the amount of useful work that can be extracted from a quantity of heat, Q, at a temperature T_h. In this work, we assume that the cold temperature (T_c) of the Carnot cycle will be 37°C, as is typical for water-cooled steam turbines today. The energy and exergy content of electricity are identical, because there is no thermodynamic limit to the fraction of electricity that can be converted to useful work.

Figure 1 provides a crude comparison of three types of concentrating solar power systems. The concentrating PV (CPV) system (Fig. 1a) represents a high-concentration commercial system available today, based on III-V PV cells that convert concentrated sunlight to electricity at 37.5%-efficiency. This concentrating PV system, rather than the dominant silicon flat-plate PV module, serves pedagogically as a baseline for the two concentrating systems that collect heat. The CSP system (Fig. 1b) represents a parabolic trough system with storage operating at a sunlight-to-electricity conversion efficiency of about 20%. The hybrid solar converter (Fig. 1c) is meant to convey the near-term potential of technologies described in Section 4, below.

The leftmost "Energy" bar in each Figure 1 panel stacks up (from bottom to top) sections representing the percent of incident solar energy i) converted to PV electricity , ii) converted to heat, iii) lost as heat or thermal radiation, and iv) lost to system optical inefficiency. We assume each optical system is 80% efficient. The same fraction of heat energy incident on the receiver is assumed to be collected in the CSP and hybrid systems; the hybrid converter's heat collection is lower because energy collected as PV electricity is not available as heat.

The "Exergy" bars of each Figure 1 panel show the fraction of sunlight exergy collected. By definition, heat energy has an exergy fraction equal to the thermodynamic Carnot efficiency limit of its conversion to work. In Figure 1, heat exergy is significantly less than the heat energy because we assumed that it is collected at 386°C (typical of parabolic trough systems using silicone oil heat transfer fluid) and converted with a Carnot cycle having a 37°C cold temperature. In contrast, all the electrical energy from PV is exergy because there is no thermodynamic limit on the efficiency of its conversion to work.

In the "Electricity" bars of Figure 1, we assume that the heat engine used to generate electricity will approach the endoreversible efficiency limit, rather than the higher Carnot limit, because of entropy generation associated with transfer of heat in the operation of the engine.[37] A study of the heat-to-electricity efficiencies of mechanical heat engines operating at a wide range of CSP-relevant temperatures suggests that they achieve roughly two-thirds of the ideal Carnot efficiency,[17, 38] which approximates the endoreversible limit.

In the right-most bar ("Value") of each panel, we assign a 50% premium value to dispatchable electricity generated over PV electricity and graph the total value of the electricity produced. The economic basis for this premium is discussed in Section 5; we note here that this assumption makes the value of the electricity produced by the CPV, CSP or hybrid solar converter systems proportional to the exergy that each collects.

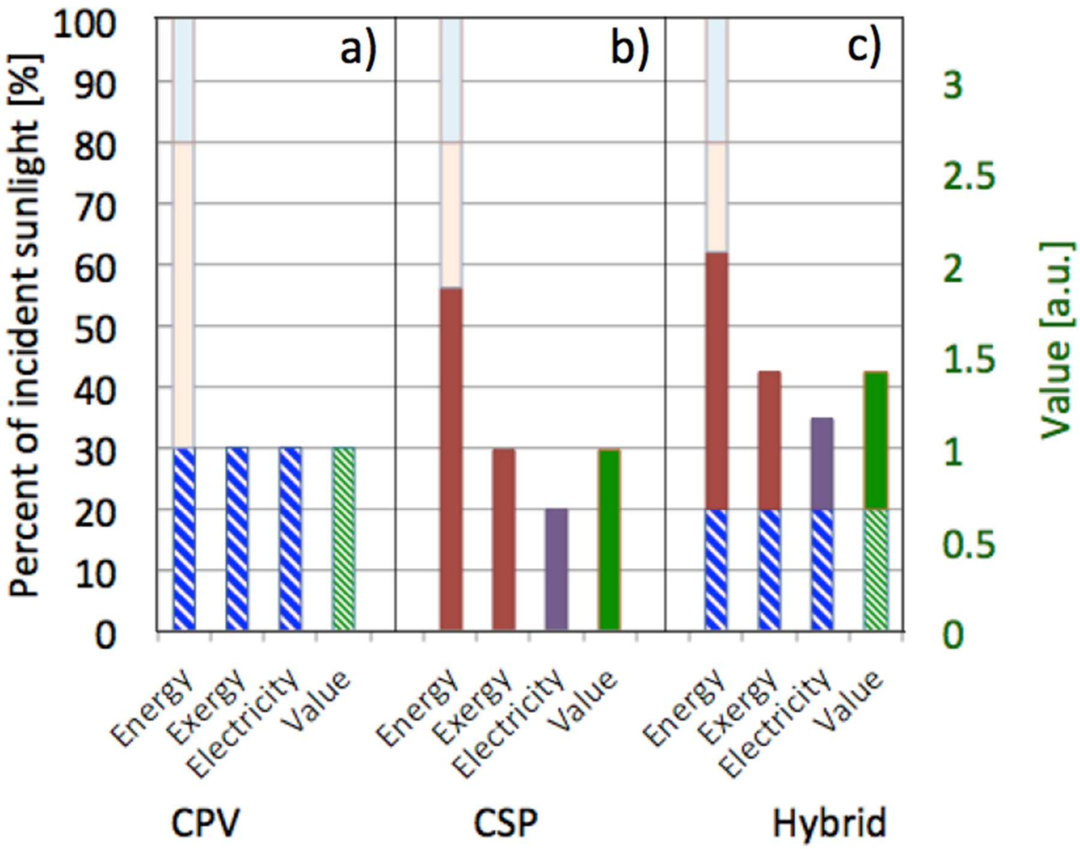

Figure 1. Schematic comparison of representative (a) CPV, (b) CSP and (c) hybrid solar converters. PV electricity production from the CPV and hybrid systems is shown by hatched blue bars. Heat energy and exergy collection are shown by red bars. Conversion of heat exergy to dispatchable electricity (purple bars) is assumed to approach the endoreversible limit. Green bars show the value of the electricity produced, assuming a 50% value premium for dispatchable electricity (solid) over non-dispatchable PV electricity (hatched). Topmost bars show optical inefficiency (light blue) and thermal energy and exergy losses (beige).

4. Hybrid solar converter technology opportunities

Recent solar cell improvements and cost reductions contribute to the emerging opportunity to hybridize photovoltaics with CSP systems to obtain inexpensive dispatchable solar energy. Sunlight must be concentrated to raise a thermal medium to high temperature; the use of concentrated sunlight means that the optimal solar cells are likely to be based on III-V materials used today in nearly all high-solar concentration PV systems. Technologies for lift-off of high-efficiency epitaxial solar cells from reusable wafer templates are commercialized and could soon dramatically lower the cost of III-V single and multijunction cells.[39, 40] Photon recycling enabled by liftoff cells has also led to a record 28.8%-efficient single junction GaAs cell.[41] Although concentrated photovoltaic (CPV) systems using III-V cells have not gained a significant market share because they compete in nearly the same niche as less expensive flat-plate silicon, Figure 1 suggests that hybrid solar converters attain higher efficiency than CPV systems and add value through low-cost electricity dispatchability.

A. Spectrum splitting hybrids

Spectrum splitting is an important strategy to realize the efficiencies presented in Figure 1. Photovoltaic cells and solar heat systems have complementary strengths in utilizing the solar spectrum: PV is energy efficient but solar thermal energy can be stored at low cost. Therefore, routing some or all of the above-gap sunlight to PV and sending the rest to a high-temperature thermal collector can capture the most value from each portion of the spectrum.[42, 43]

Solar photovoltaics efficiently convert photons in the visible and near-infrared to electricity, with cells most efficiently converting photons with energies slightly larger than the semiconductor bandgap, E_g. For example, efficiencies exceeding 50% have been demonstrated for Si[44] and GaAs[45, 46] single-junction solar cells using monochromatic light. The narrow range of wavelengths for which a 1-junction cell is optimized arises from two major PV loss mechanisms: 1) semiconductors cannot harness photons with energies lower than their E_g and 2) electron-hole pairs excited by photons larger than E_g quickly thermalize to the bandedge. This thermalization limits high efficiency conversion to photons no more than about 0.4 eV above the bandgap. Because high-quality III-V semiconductors with bandgaps suitable for solar conversion are available up to only about 2 eV, thermalization loss limits efficient photon conversion to below about 2.4 eV. Photons with energy approaching ~3 eV are especially challenging to convert because the violet and ultraviolet photons are absorbed very close to the front surface of the solar cell, usually in the low-lifetime emitter region where photogenerated carriers have a highprobability of recombining. Significantly, there is also a bandgap-independent 0.4 – 0.5 V shortfall in operating voltage relative to the bandgap due to radiative recombination;[47] therefore, as E_g drops below ~1 eV the efficiency of PV cells becomes poor at *every* wavelength. While record-setting triple and quadruple-junction PV cells use bottom cells with E_g as low as ~0.67 eV, the voltage shortfall results in diminishing returns from low bandgap cells and their contribution to the overall cell efficiency barely compensates for the spectral- and lattice-matching issues encountered. In summary, PV is best suited for converting photons between about 1 and 2.4 eV, while the solar spectrum spans from about 0.4 to 4 eV.

Typical III-V cells with bandgaps from about 1 eV to 2.4 eV can therefore convert many solar photons at 40 to 60% efficiency while leaving sufficient energy in the subgap spectrum to heat a thermal medium. In contrast, today's CSP systems capture the full solar spectrum as heat to provide electricity at system efficiencies that are generally below 20%. A major efficiency loss for CSP is the degradation of the exergy content of the collected solar energy. This energy is emitted from the sun in a roughly blackbody distribution corresponding to ~5500 ºC, but collected at far lower temperature (generally 380-580 °C), where the Carnot efficiency (with water- or air-cooling) is considerably lower. However, it can be advantageous to collect photons outside the optimal PV band as thermal energy that can be stored to provide dispatchable electricity.

Many approaches could be used to separate the solar photons into two or more streams for use in distinct PV and thermal conversion cycles. Dichroic interference mirrors can provide very sharp cutoffs in separating a reflected from a transmitted beam, suffer little absorption in their dielectric layers, and have been used to produce spectrum-split PV modules.[48, 49] There are also optical bandpass filter designs that will transmit only a desired wavelength band to the PV, while reflecting the extremes of the solar spectrum. However, there are challenges with the filter approach. The high costs of today's dielectric multilayer interference filters suggests they must be used under concentration: conservation of etendue in the concentrator means the filter must then separate light incident with a significant angular spread, and this inevitably reduces performance. System design must also account for this angular dependence of interference filter cutoff wavelengths, including both diurnal and seasonal angle-of-incidence variations.

To avoid band shifts associated with interference filters, the back surface metal of the PV cell itself could be used to reflect subgap wavelengths[50] to the thermal collector. Only wavelengths below the PV absorption edge are reflected, regardless of the incident angle or any changes in E_g due to variations of the PV cell temperature. A second angle-independent variant of this approach uses a semitransparent solar cell to transmit subgap photons to the thermal collector.[51] A third angle-independent spectrum splitting technique deploys a suite of plasmonic nanoparticles within a thermal fluid to absorb selected wavelengths so that only the optimum PV wavelengths are transmitted to the bandgap-matched solar cell.[20] However, it will be challenging to provide a stable dispersion of plasmonic nanoparticles in a high temperature fluid while still achieving a sharp absorption edge.

B. Hybrids with topping cycles

Topping is a second technique that can enable hybrid solar converters to realize the efficiencies shown in Fig. 1. Here, the system is a combined cycle in which PV operates at elevated temperature as the topping cycle and heat rejected from the PV (see Fig. 3 inset) drives an electricity generator that is the bottoming cycle.[18, 19] While the efficiency of any PV cell will be reduced when it is used at high temperature, hybrid converter systems using PV as the topping cycle can provide both more electricity and more dispatchability as the PV temperature is raised. The reduced solar cell efficiency at high temperature can be minimized by concentration of sunlight onto the cell. PV from GaAs and other semiconductors with bandgaps above about 1.4 eV suffer less efficiency loss than Si at elevated temperatures and will be the preferred topping cells.

Solar cells collect photoexcited carriers at a very high ’effective temperature’ before they thermalize (recombine) across the semiconductor bandgap. Assuming all losses in the topping PV cell are collected as storable heat without any temperature drop, the total exergy efficiency, η_x, of the ideal PV topping system[19, 52] is

$$\eta_X = \eta_{PV} + (1 - \eta_{PV})\left(1 - {T_c}/{T_h}\right), \qquad \text{Eqn. (1)}$$

(neglecting optical inefficiencies and re-radiated photons from the PV). This η_x is equal to the electrical efficiency that would be achieved with a Carnot engine converting the heat to electricity with its cold side at T_c, and its hot side at the temperature T_h of the hot PV. Here, η_{PV} is the PV cell efficiency at T_h; all the electrical output is exergy, as discussed in Section 3. We ignore the small losses associated with the usual conversion of DC output to AC electricity.

The black solid curve of Fig. 2 shows η_X from Eqn. (1), assuming that a modest 100 suns of AM1.5D illumination are concentrated onto the topping PV and T_c is 37 °C, typical of power plant cooling systems. The dotted PV curve shows $\eta_{PV}(T)$ for a single-junction PV that converts incident solar energy at the Shockley-Queisser thermodynamic limit.[53, 54] The $\eta_{PV}(T)$ curve of Fig. 2 is not representative of any one solar cell; rather, it is the optimum modeled efficiency at each temperature, calculated with operating bandgap as a free parameter.[54] As the temperature rises, higher E_g cells are needed to obtain maximum efficiency. For example, the cells at 100°C and 400°C have operating bandgaps (at temperature) of 1.38 eV and 1.63 eV, respectively.[54] The dashed black curve of Fig. 2 shows the exergy produced as storable heat. For comparison, the dashed green curve shows the larger heat exergy output of a CSP system computed with η_{PV} set to zero in Eqn. 1. The heat collection is lower in the hybrid converter than in CSP since a fraction of the solar energy is turned directly into electricity (exergy) by the PV cell. However, the total exergy from the hybrid converter is higher than that of the CSP system, as in Fig. 1. Below about 260°C, the exergy efficiency falls dramatically, but there is a large demand for heat from 140 – 260°C that might be met by topping solar systems in geographic areas with high direct insolation.[55] Higher PV operating temperatures raise the exergy efficiency of an ideal topping system in Fig. 2; higher concentrations make topping even more advantageous.

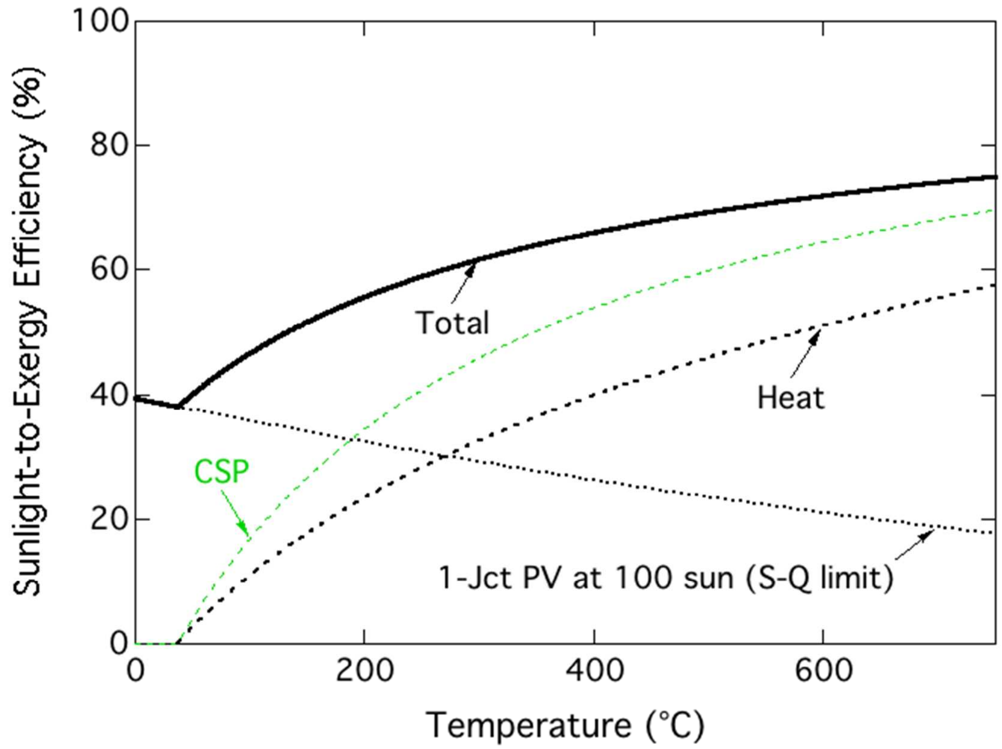

Fig. 2. Ideal exergy (black, solid) efficiency limit of a 1-junction PV topping hybrid solar converter at 100X concentration versus PV temperature, with T_c=37°C in Eqn. 1. There are no optical or thermal losses. PV efficiency (black, dotted) is the thermodynamic limit for 1-junction PV with E_g free to vary.[54] Dashed curves compare the heat exergy output without PV (green) and in the hybrid system (black). See Fig. 3 inset schematic for the hybrid converter configuration.

Practical systems would reach a lower level of performance, as illustrated by the electrical efficiencies shown in Fig. 3. This example assumes moderate 100X concentrating optics with an optical efficiency of η_{opt} = 0.8, typical of today's CSP and CPV systems. As a result, 80 suns of AM1.5D illumination reaches the PV cell. We assume that a practical generator provides 2/3 the ideal Carnot efficiency; this is close to the endoreversible limit as discussed in Section 3. The practical electrical efficiency of a topping converter without heat losses and temperature drops would then be:

$$\eta_{el} = \left[\eta_{PV} + \frac{2}{3}(1-\eta_{PV})\left(1 - {T_c}/{T_h}\right)\right] * \ \eta_{opt}\,, \qquad \text{Eqn. (2)}$$

where the second term summed inside the brackets represents the electricity generated from heat that can be stored. The solid black curve of Fig. 3 shows the total electricity generated according to Eqn. 2. The dotted black curve plots our crude estimate of $\eta_{PV}(T)$*0.8 for two-junction solar cells at elevated temperature and 100 suns, based on models with some non-radiative recombination.[54] The practical upper bound on PV temperature is likely about 450°C because of durability issues and the high concentrations that would be needed to maintain useful PV efficiencies. The dashed black curve of Fig. 3 shows the dispatchable electricity produced from the storable heat. For comparison, the dashed green curve shows the larger amount of electricity produced by a CSP system (η_{PV} set to zero in Eqn. 2). The dispatchable electricity production is lower in the hybrid converter than in CSP since the PV converts a fraction of the solar energy directly into non-dispatchable electricity. However, the hybrid converter produces more electricity in total than the CSP system, in agreement with Fig. 1. Above about 200 °C, raising the PV operating temperatures increases electrical output only slightly, but operating above 400°C raises the dispatchable fraction of electricity above 50%. Higher concentration will improve the advantage of the PV toppping system relative to CSP.

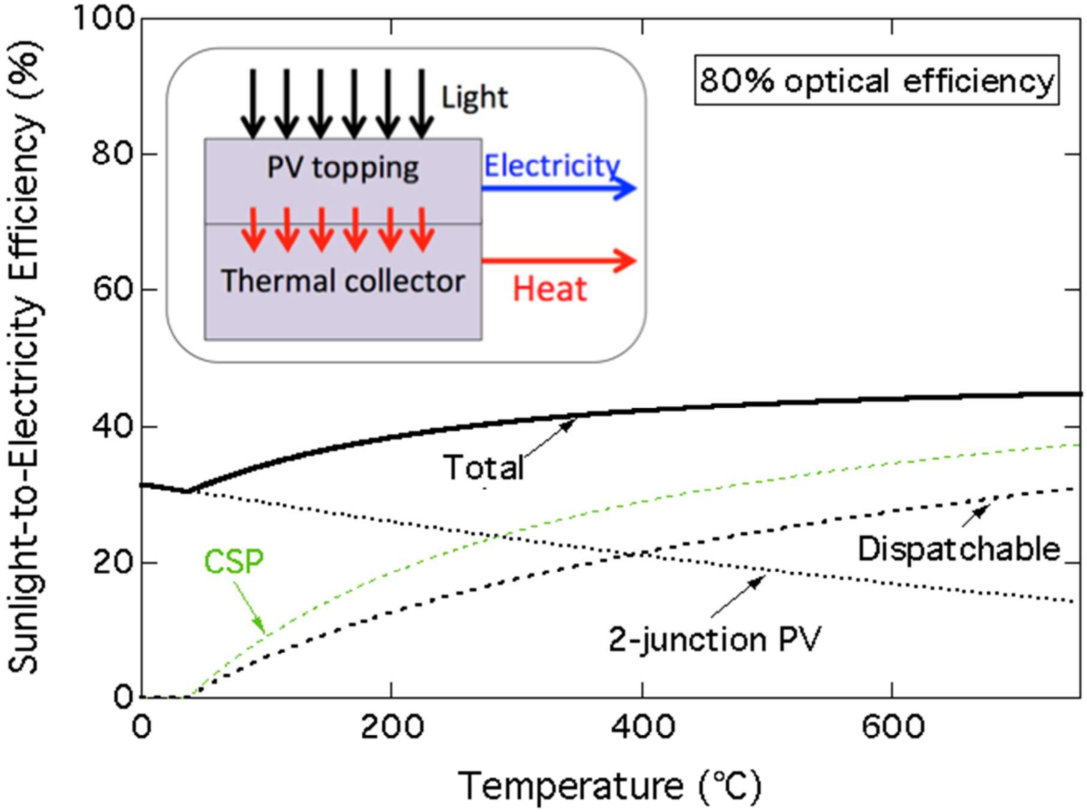

Fig. 3. Estimated practical electrical efficiency limit (black, solid) of a PV topping hybrid solar converter at 100X concentration, versus PV temperature, with T_c=37°C in Eqn. 2. Optical efficiency is 80%, there are no thermal losses and the generator is assumed to reach 2/3 of Carnot efficiency. PV efficiency (black, dotted) is 80% of that expected from 2-junction cells at 80 suns. Dashed curves compare the dispatchable electricity from heat without PV (green) and in the hybrid system (black). Inset schematic shows the hybrid converter configuration.

C. Limiting topping PV temperatures by spectrum splitting

While topping photovoltaic-thermal collectors (PV-T) have been under development since the 1970's,[52, 56, 57] nearly all have been used to heat water to 60 - 80°C. Silicon solar cells (E_g~1.1 eV) can be used at these low temperatures, but dark reverse currents caused by their low bandgap precludes efficient use as topping at much higher temperature. In preparation for missions to the inner planets, NASA has shown that III-V solar cells can function up to 350 °C for short periods,[58] but developing efficient solar cells and contacts that can survive for 20 to 30 years at 350°C to 450°C represents a significant technical challenge. New semiconductor materials may be advantageous at high temperature. Reducing reflection and radiation losses from topping PV cells while enabling efficient heat transfer to a thermal fluid also presents difficulties.

Efficient hybrid solar converter designs that limit the temperature of the topping solar cells to below about 200 °C would obviate the PV durability issues. To limit their temperature, PV cells could be as a topping cycle *below* the highest temperature that the thermal fluid reaches, by using a part of the solar spectrum *only* to heat the fluid.[20] One implementation is shown schematically in Fig. 4.[59] The thermal fluid is preheated by PV losses and then heated to its peak temperature by the near-infrared (NIR) illumination reflected from the PV. The second stage of NIR heating raises the exergy of the heat collected from all sources. Compared to a direct topping system (Fig. 3 inset) that reaches the same T_h, the PV is more efficient and the high temperature durability requirement is relaxed. Alternatively, heat can be collected from the points labeled A and B in the figure and stored at two different temperatures, as needed. The different heat streams could be used in different heat engines for dispatchable electricity, or one could be used as industrial process heat. Although Fig. 4 is based on a PV cell that reflects subgap IR, any of the spectrum splitting strategies discussed above could substitute. Finally, the incident illumination could be optically divided between the low-temperature PV and higher-temperature thermal zones without splitting the spectrum (*e.g.*, by dividing a heliostat field into two separately-focused zones).

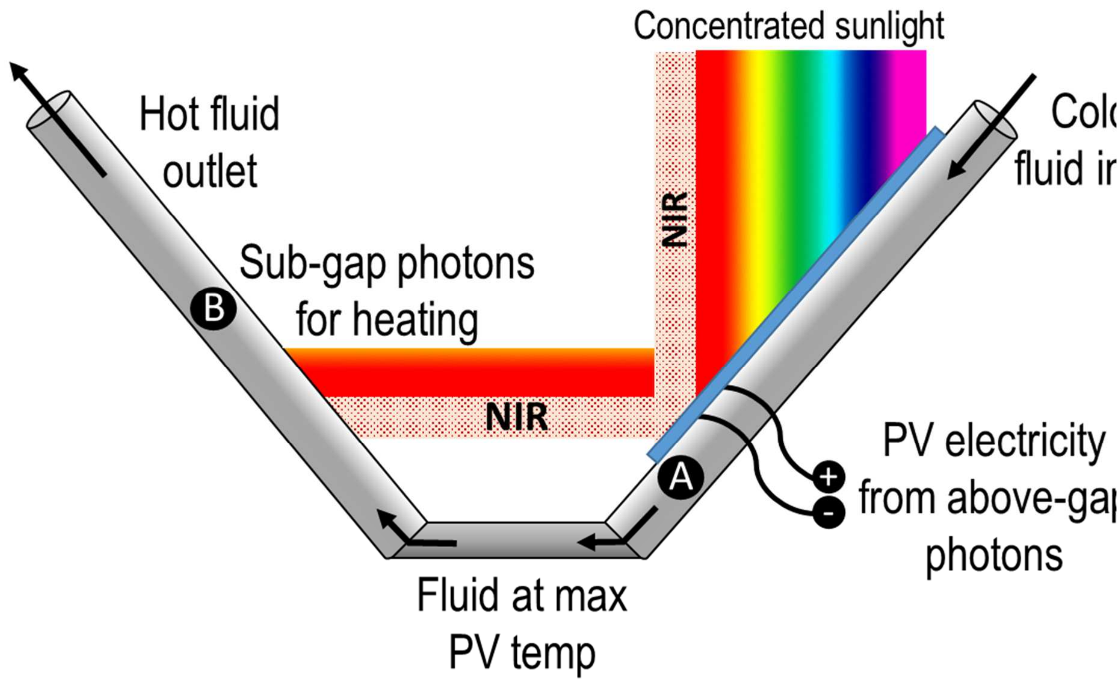

Figure 4. Conceptual schematic of a hybrid solar converter that combines IR-reflective PV with both spectrum splitting and topping. The PV losses heat the thermal fluid to the maximum PV operating temperature (A) while sub-gap photons are reflected to further heat the fluid (B). The maximum fluid temperature is higher than the PV temperature.

D. Technology challenges

Although prototype hybrid solar converters can be made today by small modifications to existing CSP and CPV components, scientific and technological advances are needed to create more efficient and less expensive systems. Useful advances could include new solar cells based on wide-bandgap materials that are durable for decades at temperatures between 300 and 450°C, inexpensive wide-angle spectrum splitting methods, advanced selective emitters optimized for incident infrared and/or ultraviolet photons, highly reflective PV cells, highly transmissive PV cells, low-cost dichroic filters for concentrated sunlight, plasmonic spectrum splitting and clever hybrid optical and thermal designs. Low-concentration optical designs will generally be more optically efficient, but high temperature optical designs are favored in systems with topping. Continued cost reductions in epitaxial growth, substrate reuse and Ge-on-Si substrates[60] can help provide the low-cost but efficient PV that is needed.

Eventually, there could also be value in nascent solar-driven topping cycles such as thermoelectric, thermionic- or photothermionic-emitter generators.[61, 62] However, the requirement of a high driving temperature difference for the topping cycle means that the hot-side temperature of the bottoming cycle would be reduced. Analysis similar to Eqn (2) (with η_{PV} replaced by η_{top}) shows that addition of a topping cycle is advantageous only if the topping cycle runs at a fraction of Carnot efficiency greater the bottom cycle, or if the hot-side temperature of the bottoming cycle is limited for some fundamental or cost reason.

5. Exergy metrics for hybrid solar converters

Photovoltaics are designed to provide electricity under sunlight, so their *energy* conversion efficiency under noon sun on a clear day has been the primary performance metric since efficient solar cells were first demonstrated.[63] The cost per unit power (in $/W) became another important metric for PV as the potential for economic viability of photovoltaics came into focus in the 1980s.[64, 65] By the 1990's, the levelized cost of PV energy (LCOE, $/kWh) over the plant lifetime was recognized as important.[66] These three energy-based metrics still drive innovations in PV cells, modules, manufacturing and installation. CSP research and development has also been driven by sunlight-to-electricity efficiency and cost per unit energy, though the CSP community has also highlighted the value of collecting and storing high temperature heat for electricity dispatchability for many years.[67, 68] However, evaluation of the practical and thermodynamic limits of hybrid solar converters has focused on energy efficiency, without considering any premium value for dispatchable energy from heat.[18-21]

When ARPA-E released its solicitation for advanced hybrid solar converter prototypes in 2013, sunlight-to-*exergy* efficiency and cost per unit *exergy* produced were chosen as the principal performance metrics.[69] If Carnot efficiency could be achieved by heat engines, these exergy-based metrics would equally value dispatchable electricity from heat and instantaneously available electricity from PV. However, practical heat engines in CSP systems operate at only about two-thirds of the Carnot limit (see Section 3 and Eqn. 2), so an exergy metric implicitly places a 50% premium for dispatchable electricity from heat over PV electricity, as illustrated in Fig. 1. Some premium value for electricity that can be dispatched at times of high demand is certainly justified by the growing need for grid storage. However, the precise amount of the dispatchability premium over PV electricity will depend strongly on the grid generation mix, patterns of demand and, critically, on the level of PV penetration.

Modeling helps establish the dispatchability premium that should be chosen. Jorgenson *et al*. simulated the value to the California ISO in 2020 of energy from a new PV field, compared to energy from a new CSP system that dispatches from 6 hours of storage capacity.[16] Their base scenario assumes that the 33% California RPS is met, nearly 11% of electrical energy is generated by PV and the RPS-mandated 1,175 MW of new grid storage is deployed. Their model estimates that the marginal operational (*e.g.*, avoided fuel, maintenance, and CO_2 emission penalty of $21.9/ton) and capacity (avoided fossil-fuel plant investment) value together will be $0.047 – $0.058 per kWh for PV, mainly in capacity value. In contrast, CSP with thermal storage provides a combined value of $0.095 to $0.107 per kWh to the system operator, again mainly in capacity. Thus, the marginal *value* of electricity from solar energy dispatched from stored heat will be 1.6 to 2.3 times the marginal value of electricity generated with the time-of-day profile of PV. In a 40% renewables penetration scenario, with PV penetration increased to 14% PV, the value of new CSP with storage rises to 2 to 3 times that of PV. While this study[16] represents an important base case, it may have underestimated the deployment of alternate strategies that can mitigate the high daytime production of PV, including: 1) electrical storage above the RPS minimum; 2) demand-side load management; and 3) PV solar tracking to extend the generating day.

An optimization of hybrid solar converters for *exergy* is therefore equivalent to adopting a conservative 50% premium for dispatchable electricity. This premium is considerably less than today's electricity cost increase from adding battery storage to a PV installation (see Section 2). Discussions with utility operators, solar developers and other knowledgeable parties have not revealed additional supported estimates of the 'dispatchability premium,' though it is likely that the future will bring different premiums in different electricity markets with diverse regulatory structures.

We propose that exergy efficiency and cost-of-exergy are good starting points for evaluation of hybrid solar converter technologies. In the future, hybrid systems will likely be optimized to a ratio of heat to electricity that maximizes revenue to stakeholders using forecasts of the future conditions on the local grid. Tradeoffs between electricity from heat and PV electricity can be made in topping systems simply by increasing the temperature of the PV cells (see Fig. 3). In systems using spectrum splitting, changing cutoff wavelengths provides a similar measure of control over the dispatchable fraction.

6. Conclusions

In high penetration locations, photovoltaic deployment has increased to the point where oversupply of daytime electricity reduces the marginal value of additional PV installations. Once PV production approaches 10% of total electricity on the grid, the marginal value of additional PV falls, with significant reductions in capacity value seen in models of 20% penetration scenarios. The higher cost of electricity storage compared to heat storage for electricity generation means that hybrid solar converters could augment PV with low-cost dispatchable solar energy. To use the full solar spectrum most effectively, hybrid system designs exploit: 1) a combined cycle, using heat rejected from PV operating at elevated temperature; 2) two separate cycles, where spectral splitting optics provide the optimal wavelengths to PV while directing infrared and/or ultraviolet light to a thermal receiver; and 3) combinations of spectral splitting and topping that achieve a PV temperature lower than the maximum thermal fluid temperature. Hybrid solar converters can best be evaluated by exergy metrics, instead of electrical energy metrics, to account approximately for the premium value of solar energy that can be dispatched when needed.

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