Ecological And Economical Advantages Of Efficient Solar Systems

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Abstract. A strategy to optimize the positive climatic effect of solar energy requires a minimization of embodied energy and a maximization of efficiency to compensate for the upward temperature forcing effect of low albedo solar collector surfaces. Climatic effects of low albedo surfaces are related to those of carbon dioxide emissions. The resulting positive climate forcing effect (cooling) then depends directly on the embodied energy, the absorption, and the efficiency of the system. This analysis favors high efficiency CPV, and even more so dual-use HCPVT systems, over low-efficiency flat panel and thin film technologies. The effect is most prominent in large low latitude cities, where urban heat islands and the subsequent demand for cooling negate positive effects of low-efficiency solar installations.

Keywords: albedo, heat island, solar, photovoltaic, CPVT, payback time, life cycle analysis
PACS: 88.40, 88.40hj, 88.40me, 92.60.Ry, 92.70

INTRODUCTION

The last years entailed a remarkable reduction in solar panel cost, so that low-efficiency, low-cost thin film photovoltaics (PV) prevail over more complex higher efficiency technologies. Conversely, in the traditional energy sector, every percent of increased energy conversion efficiency is critically important to reduce the levelized cost of energy (LCOE) and make new installations economically viable.

Solar energy is considered one of the cornerstones in battling climate change. However, by installing PV systems, the absorption properties of the surface are changed and less sunlight from the Earth's surface is reflected back into space. A local heating effect due to human deployment of dark surfaces has been extensively studied for cities and is typically referred to as urban heat island effect. In this context the reflective power of a surface is characterized by the albedo. An albedo reduction from the global average of 0.3 to 0.2 in cities causes more heat to be absorbed which induces a 2-12ºC local temperature increase, as well as a 0.2-0.4ºC average global temperature increase.[1] A proposed measure to counteract global warming is to convert all low-albedo urban surfaces into white high-albedo surfaces. When the albedo levels of cities in sunny regions are higher than the 0.3 global average, a local and global cooling results, which induces an additional benefit through the reduced local demand for cooling energy.[1]

It is known that the gray energy in renewable energy systems determined by life-cycle analyses defines the energy payback time of an installation. In this paper we are extending the concept of payback time for PV installations by additionally including the effect of albedo change, which gives a much more accurate assessment of the system sustainability. Traditional silicon flat panel and CdTe thin film systems are compared to concentrated photovoltaic (CPV) and high-concentration photovoltaic thermal systems (HCPVT). For this analysis solar cell efficiency proves to be of prime importance in order to limit the overall payback time by minimizing the area of deployed solar absorbers. We also explain the mechanisms of the current economic development of low-efficiency solar technologies and anticipate changes.

HIGH-CONCENTRATION PHOTOVOLTAIC THERMAL SYSTEM

High concentration photovoltaic thermal (HCPVT) systems reach highest system-level efficiency by providing more than 27% electrical power and more than 50% heat recovery (Fig. 1).[2-4] The key component is an active cooled silicon microchannel multi-chip solar receiver. This allows much higher optical concentrations while enabling higher coolant temperatures and a minimized need of semiconductor PV materials. The heat provided by the HCPVT system is used to prepare desalinated water and provide cooling through (1) a multi-effect vacuum membrane distillation system and (2) an adsorption cooling system, which are optimized for the temperature level of the coolant outlet. The optimal collection and use of heat in an integrated system provides a maximal amount of electrical energy and desalinated water and/or cooling with a minimum area of solar-panel surface.[5,6]

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TABLE 1. Photovoltaic technologies assessed against each other.

Photovoltaic Technology	Electrical System Efficiency	Performance Ratio	Mean Annual Irradiation in Life-Cycle Analysis	Life-Cycle CO_2 Emissions
Multi-crystalline silicon[7]	13.2%	0.75	1700 kWh/m^2	37.6 g CO_2/kWh
Mono-crystalline silicon[7]	14.0%	0.75	1700 kWh/m^2	45.3 g CO_2/kWh
Cadmium telluride (CdTe)[7]	8%	0.75	1700 kWh/m^2	21.6 g CO_2/kWh
High concentration PV[8]	27%	0.90	2480 kWh/m^2	22 g CO_2/kWh

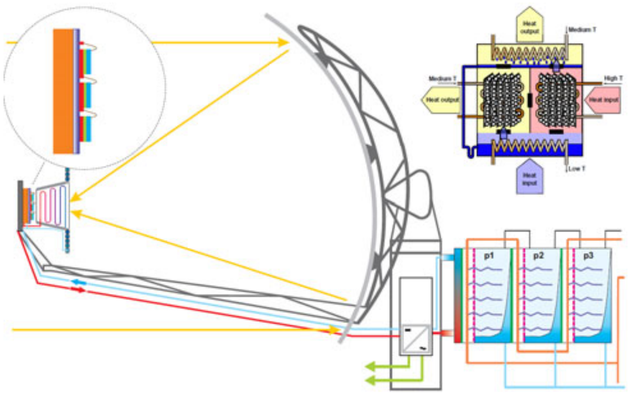

FIGURE 1. The solar HCPVT system is based on a microchannel cooled multichip receiver (left inset) which supplies hot water for thermal driven adsorption cooling (top right) and membrane distillation desalination (bottom right).

METHODOLOGY

In order to determine the overall PV installation payback time, both, contributions of gray energy and the effects of albedo change on the global climate must be considered. The gray energy is determined by life-cycle analyses which include material and energy flows of the module, frame and balance of system. The energy payback time for gray energy is the period required for a renewable energy system to generate the same amount of energy that was used to manufacture the system itself. Therefore system specific parameters such as efficiency, life time, performance ratio, and mean annual irradiation need to be fixed.[7]

The albedo change induced by PV systems changes the surface radiation absorption properties and creates a temperature increase. By simulating long-term effects of albedo changes using a spatially explicit global climate model, a relationship between albedo change and CO_2 emissions is established through global temperatures. For each m^2 an albedo decrease of 0.01 corresponds to 7 kg of CO_2 emissions.[1] These CO_2 emissions are then related to a fossil fuel source to determine the albedo change induced payback time.

Four competing PV technologies are assessed and compared against each other (Tab. 1).[7,8] A higher performance ratio, which gives a measure of the output power delivered as a proportion of the total power which the solar modules should be able to deliver, is assumed for HCPVT systems due to their tracking and improved electrical output matching capabilities.[3] A life time of 30 years is assumed for all systems.

Payback time is determined against the three most common fossil fuel sources and their world average CO_2 emissions generated in electricity production (Tab. 2).[9] Two albedo cases are evaluated against each other. The first considers a desert case where a typical albedo of 0.4 is reduced to 0.05 through the installation of a PV power plant. The second considers an ideal urban case where all buildings and roofs are painted white with an average albedo of 0.8, before it is reduced to 0.05 after the installation of rooftop PV systems. A mean annual irradiation on the PV installations to determine the electricity output is fixed at 2000 kWh/m^2 and all life cycle gray energy results are normalized against this value.

TABLE 2. Fossil fuel world average CO_2 emissions.[9]

Fossil Fuel	CO_2 emissions
Oil	796 g CO_2 / kWh
Coal/Peat	958 g CO_2 / kWh
Gas	451 g CO_2 / kWh

RESULTS

Gray energy payback time remains the same for both albedo cases. It does not matter where the PV installation is installed as long as the efficiency of the system and insolation remain identical. Depending on the fossil fuel source, gray energy payback time is typically in the range of 1.5-2.5 years for Si-based solar cells, which is a generally accepted value. Thin film CdTe systems have a reduced payback time, mainly due to their less energy intensive fabrication. For high-concentration PV systems, the gray energy is also reduced compared to Si-based systems, mostly because the high efficiency PV cells only make up a comparatively small area and the system structure consists of well established construction materials, which in particular limits material flows.

Albedo change payback time is location dependent. Particularly replacing highly reflective surfaces with PV installations has a strong adverse effect on albedo change payback time, often superior to the gray energy payback time (Fig. 2). The albedo change payback time is also directly dependent on the efficiency of the PV installation, as this determines the overall energy output. For efficient systems, less area coverage is required and the overall surface albedo change is limited in comparison to less efficient systems. This aspect is especially evident for thin-film CdTe which despite comparatively low gray energy payback time has a considerable albedo change payback time and highest overall payback time of all PV technologies compared. When extended to solar thermal systems, this analysis shows that the albedo induced payback time dominates over the material payback time.

A measure to mitigate urban heat islands is to paint building surfaces white to reflect incoming sunlight. In contrast, installing rooftop solar installations has the opposite heating effect. So therefore, even while these installations provide a good renewable energy source, their payback time is considerable, for some over a third of their lifetime (Fig. 3).

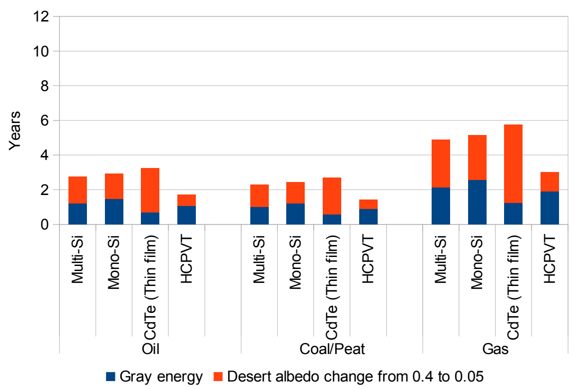

FIGURE 2. Albedo change induced payback time is larger than gray energy payback time. It is also directly dependent on the efficiency of the PV system as this determines the necessary area coverage for a given power output.

DISCUSSION AND CONCLUSIONS

It is crucial to consider both, gray energy and albedo change, in the overall payback time of PV and solar thermal installations. High-concentration PV systems provide substantial benefits in comparison to flat panel technologies. Gray energy is reduced by minimizing the necessary PV cell area and using common construction materials for the supporting structure. High efficiency solar cells reduce deployment area, thus minimizing the adverse effects of albedo change on global climate. Consequently high-concentration PV systems have less than half overall payback time than other competing systems. CPVT will have even shorter payback times because of the dual output and lower amount of heat released.

When installed on buildings, solar panels substantially aggravate the heat island effect of urban areas and cities. In colder climates like Germany this helps to reduce heating demand in winter. In warm and sunny climates, however, cooling demand increases. Studies have shown that a reduction of urban heat island effects using white roofs can reduce overall annual power consumption in cities up to latitudes of Chicago.[10] Inhabitants of hot countries have accumulated very well adapted skills to control temperatures in settlements through passive solar technologies, which include bright building surfaces and controlled shading without inhibiting wind driven ventilation. However, it is apparent that much of this knowledge has been ignored in fast growing urban areas in hot climates, which makes them suffer from strong heat island effects and increasing energy demand for cooling.

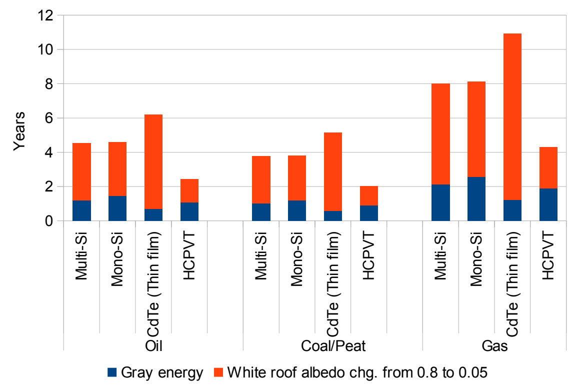

FIGURE 3. Replacing white roofs with rooftop solar installations has very long payback times, particularly for low-efficiency systems. It makes therefore more sense to install high-efficiency solar power plants outside cites.

Energy consumption of cities in hot climates is related to ambient temperature. Beyond a threshold temperature of 25ºC the energy demand increases by ~5%/ºC due to the increased demand for air conditioning and cooling.[11] The increased heat island effect from solar installations is thus related to an increased energy consumption. Therefore this quantity needs to be subtracted from the electrical output in order to determine the net renewable energy output. It could be that this net electrical output is negative, in particular for low-cost, low-efficiency solar thermal and photovoltaic installations in hot and sunny urban areas. In such areas painting buildings and roofs white may be an environmentally superior and more cost effective approach for solar cooling than solar rooftop installations. The best option is to construct solar power plants outside cities and to transport the electrical energy and cooling fluid to the city.

The reason for the current spread of low-efficiency solar devices is that they are simpler to develop and thus scale and spread quicker than more complex high efficiency systems. With limited scaling these systems face economic constraints. These economic constraints are, however, temporal and will be reversed once the development speed of the low-complexity technology drops below a certain threshold.

Current “uncorrected” economy favors cheaper, less efficient technologies until development of this technology stagnates. This leads to the installation of inferior technology and a delay of the scale-up of the superior technology. Knowing the negative effects on the climate and long-term economic effects, corrective actions (*e.g.,* subsidies) for the more efficient technologies are needed in order to support the most suitable technologies. These measures accelerate their cost reduction and allow a quicker transition towards the economically and ecologically optimal technology.

The economics of HCPVT systems is more complex but also more flexible due to the two separate products. For exploitation, a good understanding of the strengths and weaknesses of electrical grids, district heating/cooling systems, and of demand patterns is a prerequisite.[6] Initially, low-grade heat transport is more expensive than the transport of electrical energy but for large volumes it becomes more attractive due to its more favorable scaling, in particular when thermal storage is added. Further, there is a demand for different levels of exergy. While 60% of the requirement is composed of high exergy fuels (electricity, oil, coal), the remaining demand is for low exergy products (heating, cooling, desalination). Meeting this part of the demand with low-grade heat allows higher overall efficiency and lower cost, in particular when the effects of heat islands are included in the analysis.

SUMMARY AND OUTLOOK

In this paper, an improved and expanded life cycle analysis for solar systems is presented which takes into account the surface properties of the deployment location. This approach allows ecological comparisons between solar systems and passive solar technologies, such as white surfaces. Deployment of building integrated solar technologies in sunny regions increases the urban heat island effect and energy consumption.[11] This effect can fully negate the alleged benefit of solar thermal installations and PV panels when compared with white roofs. A main conclusion is that high-efficiency solar power stations have to be placed outside of large cities in the sunbelt and connected to district cooling networks.

More studies are required to link the urban heat island effects with power demand and consequently determine the location and efficiency requirements of solar installations. The reason why classical power stations favor high efficiencies are the cost associated with the fuel they need. Solar energy up to now was considered emission free. We show that harvesting solar energy comes with a price similar to fuel cost. The radiative forcing induced by the harvesting device is independent of the system efficiency, similar to the overall fuel consumption not being linked to the efficiency of the power station. For this reason solar technologies will be subject to a similar trend towards higher efficiencies.

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Contributions To Reproducible CPV Outdoor Power Ratings

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Abstract. Methodologies that aim to obtain a reproducible power rating are still under discussion at the WG7 of the IEC and there is a need for feedback from real field application in order to validate or improve these methods. These procedures are evaluated through the outdoor rating of seven modules from four different CPV technologies, which have been measured at the CEA outdoor monitoring bench at the Institut National de l'Energie Solaire (INES) site. The benefit of introducing other procedural considerations is analyzed, namely the inclusion of spectrally-corrected irradiance, the utilization of lens temperature as a new parameter for regressions and the optimization of dataset filtering.

Keywords: solar concentrator, multi-junction cells, power rating, operating conditions
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INTRODUCTION

The CPV industry and the scientific community are working on the development of standards for rating CPV module power [1]. The WG7 from TC 82 of the IEC is making advances on the future norm IEC 62670-3 for the power rating of CPV modules, but many procedures are still under discussion mainly due to the lack of feedback on their reproducibility from real field application [2]. The difficulty in defining such procedures lies in the sensitivity of CPV module performance to changing ambient conditions. These dependences are either less well-known or of larger impact than in flat-plate PV (e.g. light spectrum) [3].

This work contributes to the discussion by applying power rating procedures to four different CPV module technologies under measurement at the CEA Lab for Concentrator Photovoltaics. Not only the procedures currently defined in the norm draft are studied but also other new proposals based on parameters having a special influence on CPV performance. The analysis of results will focus on the dispersion and reproducibility of the ratings performed.

MEANS AND METHODS

Operation Parameters With An Effect On CPV Performance

The use of Fresnel lenses and triple-junction cells in commercial CPV modules has an important impact on efficiency variations with changing outdoor conditions. In addition to the classical parameters of irradiance and cell temperature, two operation parameters have a special influence in this type of technology:

- Spectrum: any change in spectrum will impact current limitation by one of the multi-junction subcells and will thus induce variations of the efficiency [3]
- Lens temperature: refractive index varies with temperature and the thermal expansion of lens material induces modifications in its geometry. Both effects change the optical efficiency of the lens (e.g. varying the focal length or the size of the concentrated spot) and therefore modify the generation of current by the cell [4]. However, this sensitivity depends greatly on the particular optical architecture and materials involved. E.g. silicone-on-glass primary lenses show a stronger dependence than those made of PMMA.

Current draft of the norm already attempts to reduce power rating uncertainty caused by daily and seasonal spectrum variations. It considers a simplified measurement of the spectrum through the effective direct normal irradiance (DNI) measured by a set of components cells (DNI_{TOP}, DNI_{MID} and DNI_{BOT}, corresponding to top, middle and bottom subcells of triple-junction cells). The spectral mismatch ratio (SMR) is then defined as follows [5]:

$$SMR_{MID}^{TOP} = \frac{DNI_{TOP}}{DNI_{MID}} \quad \text{and} \quad SMR_{BOT}^{TOP} = \frac{DNI_{TOP}}{DNI_{BOT}} \qquad (1)$$

SMR equals 1 for both ratios corresponds to a spectral composition equivalent to that of the reference spectrum AM1.5D. Filtering around this value is a mean of limiting spectral impact on ratings.

An alternative approach is to accept spectral variations and correct the IV curve for them. A

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