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PV POWER AND HEAT PRODUCTION: AN ADDED VALUE

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ABSTRACT: Combined solar power and heat systems are reviewed and analysed with respect to temperature behaviour, efficiency, system choice and cost. Included are conventional PV panels with added thermal extraction devices (termed PV/T) as well as organic dye sensitised cells with heat extraction.
Keywords: Combined power and heat systems - 1: Photovoltaic-thermal collectors - 2: Photo-electrochemical-thermal cells –3: Building-integrated solar collectors – 4.

1. INTRODUCTION

Considerable effort is being made to construct solar devices, that make use of some of the 70-95% of collected solar energy not converted into electricity by current solar cells of various types. A heat transfer fluid is passed over or under the building-integrated solar collector, and is connected to a heat store serving building energy needs such as space heating, hot water provision and low-temperature process heat.

The heat transfer fluid is typically air or water. Use of water entails a requirement for sealed paths and protection against corrosion, just as in thermal solar collectors. Although the use of air as a transfer fluid is easier, the low heat capacity of and energy transfer rates to and from air place limits on its applicability.

Thermal collection in front of the solar cell (but below a cover glass) may alter the collection efficiency in a negative way, whereas collection behind the solar cell may be inefficient by the often used reflective rear of a panel. Incoming solar radiation is either made useful for electricity production, is transformed into heat taken up by components of the collector, or leaves the cell through front or rear walls. A reflective rear layer causes the light to pass through the solar cell twice, with greater chance of capture, but leaves only capture in front of the cell as an option for thermal capture. Use of heat generated by transfer of energy from light to long-wavelength degrees of freedom, on the other hand, is possible from either side, and likely best from the rear, where the largest proportion of heat is likely to form.

A study of the relative merits of these many possibilities is underway in a study performed for the Danish Energy Agency (Katic et al., 2000). Here, some general estimates will be made in order to give an overall feeling for the options at hand.

2. TEMPERATURE BEHAVIOUR OF SOLAR CELLS

In Figure 1, data on the efficiency of different types of solar cells as a function of operating temperature is shown. Each curve is normalised to a typical absolute efficiency for current commercial or near-commercial versions of the type of device in question. Early theoretical calculations by Wysocki and Rappaport (1960) are largely confirmed by current measurements, and the mechanisms are thus well understood, at least for conventional photovoltaic devices. The temperature dependence is chiefly due to band-gap effects, which explains why the slope of the crystalline silicon (c-Si) and multi-crystalline silicon (m-Si) are identical (Yamamoto et al., 1999). In other words, the grain boundaries does not give rise to additional temperature effects. Cd-S cells have a lower but still significant temperature gradient, whereas the temperature effect for amorphous silicon cells and organic dye sensitised TiO_2 cells is very small.

The temperature effect is negative with increasing working temperature for all devices except two: The organic cells show a maximum near 40°C (Rijnberg et al., 1998) and the amorphous silicon-hydrogen cells (a-Si) a reversal of temperature trends after annealing (Dutta et al., 1992). This positive temperature coefficient only persists until the undegraded efficiency is reached, and it requires annealing as opposed to the light soaking treatment, which causes the development of a much stronger negative temperature coefficient.

The interest in operating temperature-dependence of the solar energy to electricity conversion efficiency is of course, that the cooling effect of extracting heat may improve the electric performance of the cell and thereby pay for some of the extra expense of the heat extraction equipment. Typical operating temperatures for uncooled cells are about 50°C. Figure 1 shows that improvement is indeed obtained for e.g. crystalline or multi-crystalline silicon PV cells, but not notably for dye sensitised cells or amorphous PV cells. On the other hand, in order to make use of the heat it should preferably be collected at higher temperatures, which would indicate that the best solutions are those with little operating temperature effect of the electricity yields. This trade-off is the subject of the discussion below.

3. LOAD TEMPERATURE CONSIDERATIONS

The conventional heating systems used before 1973 often had operating temperatures of 80°C, both for central heating systems and for district heating lines. Currently used distribution systems would typically employ temperatures of 60°C, with the exception of floor heating systems (30°C) and airflow heating systems rare in Northern

Europe. Also temperatures used for bathing, showers, cleaning, dishwashing and clothes' washing have dropped to rarely more than 40°C. This has helped solar heating systems to penetrate, and the aim for combined electricity and heat systems might be heat delivery at temperatures up to 40°C. However, solar heating systems require storage of heat, implying in most cases two heat exchange loops, as illustrated in Figure 2. The losses across heat exchangers are typically 10°C, although 5°C is possible. Simulation studies (Sørensen, 2000) show a difference in outlet and inlet temperatures for a water-based solar collector system of 10°C, as an average over a one year operation at Danish latitudes. For air flow systems the temperature differences are often higher, in the simulation studies up to 40°C. The estimates presented below assume a temperature drop of 20°C over the two heat exchange transfers. Optimal temperature steering requires variable flow velocities through the collector, e.g. computer controlled.

4. HEAT PUMP SYSTEMS

The need to extract heat at an elevated temperature is seen to imply a reduced efficiency for the power production of the most efficient solar cell types. It is therefore a natural thought to add a heat pump, allowing heat to be removed from the solar collector at a temperature of say around 20°C, and delivered to the heat distribution system at sufficiently high temperature, say 50°C. This entails partly the extra cost of a heat pump, but also an expenditure of electric power to drive the heat pump compressor. With a coefficient of performance, COP, of 3-4 valid for many current heat pump systems based upon environmental heat at the temperatures quoted, the power consumption will be COP^{-1} times the amount of heat treated. The cost of this is discussed below.

Heat pumps may also be part of heat delivery systems not using solar heat. Indeed, the comparison of a solar electricity system furnishing power to a heat pump (using environmental heat from the air or in Northern Europe more often from soil pipes, giving heat of temperatures around 8°C) to a solar thermal system is often favourable for the heat pump system. The solar thermal system has a primary collection efficiency of about 60%, but diminished to under half of this value by the need for storage, if considered for more than summer hot water supply. The solar cell plus heat pump offers an efficiency of say 15% times 350% (COP), minus storage losses which are typically much less than for heat systems (Sørensen, 2000b). Still, the efficiency advantage of heat pump systems may not be reflected as an economic advantage, due to the presence of more expensive components than in the thermal system.

5. SPECIAL SYSTEMS

The discussion in section 2 above indicates, that heat collection from a combined power and heat module could be enhanced by removing the reflective layer often present at the back-side of solar modules. This might suggest use of a system, where reflection is used at times when high power output is desirable, and not used when high heat output is desired. Such a system could be constructed using a "smart window" between the cell and a heat collection layer below it (Sørensen, 1999). Smart windows use techniques similar to dye-sensitised solar cell, with electric signals determining the transparency of the "window" layer (Granqvist et al., 1998). Possible integration with organic solar cells is an interesting possibility, but so far the cost of these techniques do not warrant the modest improvement in energy collection.

6. ECONOMIC COMPARISON

The economic evaluation of hybrid solar power and heat systems based on current prices would not be very meaningful. The price of solar cells per unit of installed capacity is much higher than that of solar thermal systems, so that the relative advantage of additional heat production will appear small. However, assuming that both systems some day become economically attractive, this means that the cost of solar electric systems and of solar thermal systems will roughly reflect the value of the energy quality delivered, i.e. that solar power could be at most 3-4 times more expensive than solar heat (due to second law efficiency). However, in reality the price difference is likely to be smaller, because indirect costs (such as environmental impacts of energy use) will be similar for the two systems, as they both has to have a required area given by solar radiation input needs (Kuemmel et al., 1997). Indeed, current energy prices in Europe, including taxes that to some extent may reflect externalities, are typically exhibiting a range of heat-to-power price ratios of 0.5-0.8.

The cost of two solar systems, one for power and another for heat, should be higher than that of any combined power and heat system, due to common components. This is even more true, if the cost of a suitable surface upon which to mount the building-integrated systems is included. In case a renewable energy future is planned for, the total extent of suitably oriented building surfaces may be too small for accommodating both thermal and electric panels capable of meeting future demands.

The cost comparison shown in Table 1 and Figure 3 makes the simple assumption of the same capital cost (per unit area covered) for all types of solar cell panels, a 30% increase if heat is also to be extracted, and a 10% surplus if a heat pump is required. The size of this latter cost reflects the fact that it does not scale with the area covered by solar panels, and thus represents some "typical" building-integrated system. The value of a unit of heat energy is taken as z=0.5 times the value of electric power, and the total cost then

$$\text{Cost} = (\text{cost per unit of electric power})/(x+yz),$$

where x is the yield of electric energy and y the yield of heat energy. Collected heat energy is taken as 50% of the radiation energy not contributing to power production.

It is seen that the dependence on extraction temperature is extremely weak for the combined systems (i.e. that the temperature decrease of solar yield is little important), and that the heat pump systems are always more expensive (due to their consumption of part of the generated electricity). However, all systems have a better economy than the corresponding system producing only power, meaning that the combination of heat and power production produces energy of more strongly increased value than the (assumed) capital cost increase. This effect is smallest for the CdS and GaAs cells but substantial for all others.

7. CONCLUSIONS

The simplified estimates presented here first of all gives strong support for the rationality of adding the value of heat extraction to solar cells, no matter what the type of cell. It further discourages solutions with use of heat pumps to increase the temperature of extracted heat, because the electric efficiency loss in raising the temperature without use of heat pumps is always modest. This also means that the temperature of extraction is not essential, as long as it can be kept above what is needed for heat exchange processes leading to final demand temperatures of 30-40°C. Whether water- or air-based systems are preferable requires further investigation. The cost differences between the lowest curves in Figure 3 are not decisive, as the Figure is constructed on the assumption that all solar cells reach the same price. In reality, there will of course be a price differential that will determine which type of cell will be used in the future.

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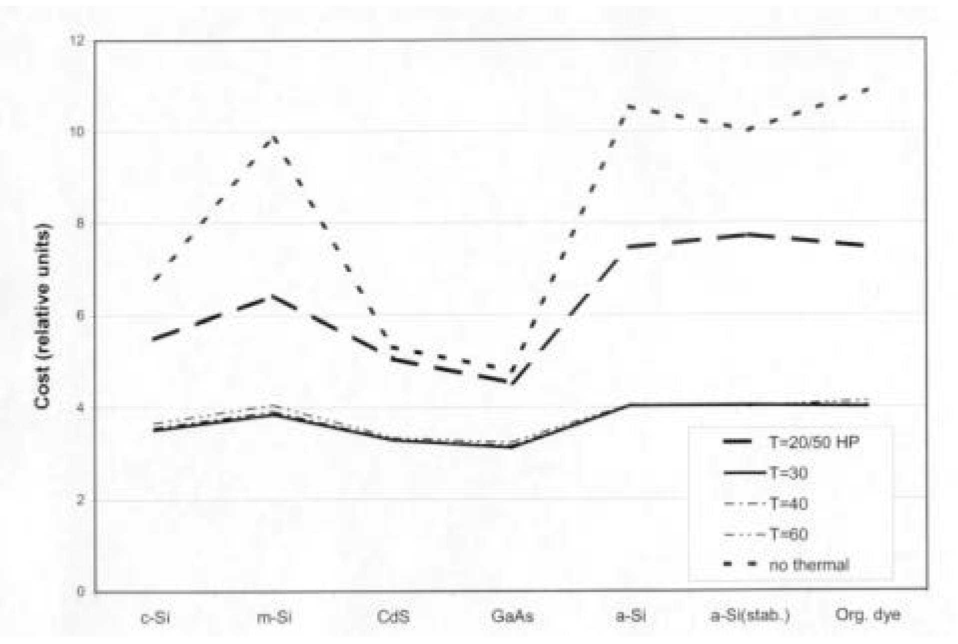

Figure 3. Relative cost of different combined solar power and heat systems, compared to cost of a corresponding pure electricity-producing system. The temperature T denotes load delivery temperature, and the heat pump solution (denoted “HP”) involves raising the temperature from 20 to 50°C.

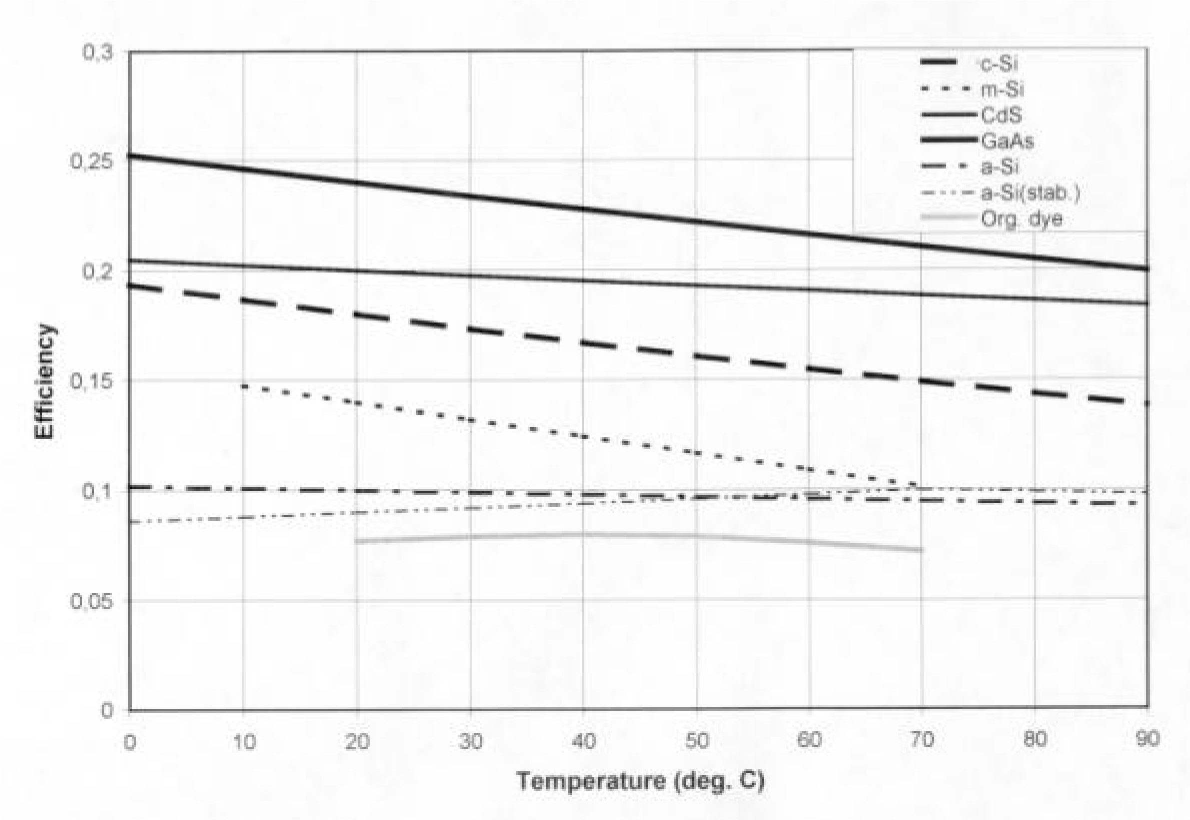

Figure 1. Solar cell efficiency as function of operating temperature, normalised to typical 25°C efficiency for each cell type. Based on Ricaud, 1999; Dutta et al., 1992; Sørensen, 2000; Wysocki and Rappaport, 1960; Yamamoto et al., 1999; Rijnberg et al., 1998.

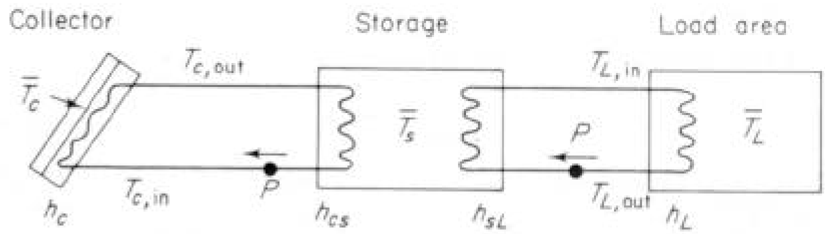

Figure 2. Heat transfer from solar collector to load, with nomenclature of temperatures employed (Sørensen, 2000).

cost (rel.units)	c-Si	m-Si	CdS	GaAs	a-Si	a-Si (stab.)	Org. dye
T=20/50 HP	5,50	6,43	5,06	4,53	7,46	7,72	7,46
T=30	3,51	3,85	3,29	3,13	4,03	4,04	4,01
T=40	3,56	3,92	3,31	3,16	4,04	4,02	4,04
T=60	3,66	4,06	3,34	3,23	4,06	4,01	4,13
no thermal	6,82	9,85	5,32	4,79	10,53	10,00	10,87

Table 1. Relative cost figures for different solar combined electricity and heat systems, compared with cost of pure electricity producing system. The solar cell systems for pure electricity production all have the same cost per square metre, but different cost per W delivered (column "no thermal"). The combination systems assume that adding a heat collection and transfer system entails a cost of 0.3 times that of the "no thermal" system. Likewise, the cost of adding a heat pump system is simply taken as 0.1 times that of a "no thermal" system. The line denoted "T=20/50 HP" assumes addition of a heat pump lifting the temperature from 20 to 50°C.