Combined solar power and TPV

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Abstract: In this paper design for a combined TPV and solar power system for local heat and power production is discussed. PV cells are producing electricity when there is light, while TPV cells are used when it is dark. Biomass is combusted and the heat is generating photons for the TPV system. Higher combustion temperature will give higher electric output, but also faster deterioration of the materials in the combustor, where the temperature of the emitter is 1050-1250 °C. By combining PV-cells generating electric power summer time with TPV-cells generating electric power winter time, we can achieve a flexible local heat and power system all year round. As both systems generate DC-power, we also can see a potential to use the same DC components for e.g for charging batteries for electrical vehicles, DC-pumps, LED-lamps etc. Design criteria for the systems are discussed in this paper for a house that is principally self sufficient on energy. Both theoretical and practical obstacles are discussed, as there are a number of issues to solve before the technique can be used in ”real life”. The TPV system is not yet commercially available, but is tested in pilot scale.

Keywords: *Solar power, TPV, combination, heat, electricity*

1. Introduction

There will be a shortage of fossil fuels in the future and thus renewable energy like solar power and biomass will be interesting alternatives. One type of solar power is PV-cells, although there are other alternatives like Stirling engines, organic ranking cycles and even steam turbines when the sunshine is concentrated to heat an organic solvent or water/steam to high temperatures.

In this paper we are concentrating on the combination of PV-cells and TPV-cells, where the principles are to convert photons into electric power directly. In the PV-cells the photons are in the range 0.4- 0.8 um mostly, while in TPV cells we extend the wave lengths up t o approximately 1.9 um. The advantage with a combination of PV and TPV cells is that we will consume no fuel during spring to autumn periods, but still can produce both heat and power when there is no or little light. At the same time we can use the same infrastructure with respect to DC-current and lower voltage than the normal 220 V in Europe. In this way we can be both self-producing all electric power needed without having to store electricity in batteries. The cost to store biomass is radically lower than the cost for storage in the batteries, and thus makes sense.

2. Conversion of biomass to heat and electric power using TPV

The combustion unit can be a conventional boiler extended with a TPV-unit where heat and electricity are produced simultaneously. The principles for a TPV unit developed by Malardalen University together with Dalarna university college in Borlange is principally making use of photons produced by combustion flames heating a steel plate, the emitter [1],[2],[3] and [4]. The photons produced are then filtered in an energy glass, and thereby only the energy rich ones hit a PV-cell, but with a slightly lower band gap than normal PV-cells. The cut off wave length and correspondingly band gap are seen in table 1 f or different materials. Silica (Si) with a cut off at 1.1 um is good for visible light but not for longer wave length. GaSb and InGaAs are better giving cut offs suitable for TPV cells.

Table 1. Cut off and threshold energy for different materials

	Cut off wave length	Band gap
Si:	1.1µm	1.12eV
GaSb:	1.7µm	0.72eV
InGaAs	2.3µm	0.55eV
InGaAsSb	2.4µm	0.53eV

The cut-off here means that photons with a wave length higher than the cut-off are filtered off, while those with short wave lengths are passing through the glass to the PV-cell. The data are from [5]. By this the same amount of electricity can be produced with a surface area 100 times smaller than for conventional PV-cells. This means that the power output could be around 10 kW per m^2, compared to some 0,1 kW/m^2 for typical solar PV cells. As the TPV system can operate whenever you have a need, it can be used even when it is dark and in that way be acting as a back-up system for ”normal” PV cells.

Biomass can have many different origins. It can be biogas produced from household waste or crop waste like straw. The gas then will be mainly methane, which is the same fuel as if we use fossil “natural gas”. The biomass could also be produced from different algae specie, where the production will depend on the actual sun intensity, nutrients and temperature. Of course the technology can also be used for fossil fuels like oil, but that is from our perspective not interesting long term. Typical values of solar intensity at different places in Europe are seen in figure 1 below.

As can be seen the irradiation is approximately 8 kWh/m^2,day summertime at all sites, while only less than 1 kWh/m^2,day during December- January. We can assume that the growth rate for biomass is in the range 0.5 % to at best 5 % of the incoming sun light, which means 0.04-0.4 kWh/m^2,day summer time and 0.005 – 0.05 kWh/m^2,day winter time. The heat demand winter time would be some 0.5 – 240 kWh_{th}/d in single houses depending on the house type, and to this we can add an electricity demand for the house hold use of approximately 5 kWh_{el}/d for low consumers up to 40-50 kWh_{el}/d for high consumers. [6]. The lower heat demand is for modern “passive” houses while the higher values are for houses older than some 40 years and not retrofitted to modern standard.

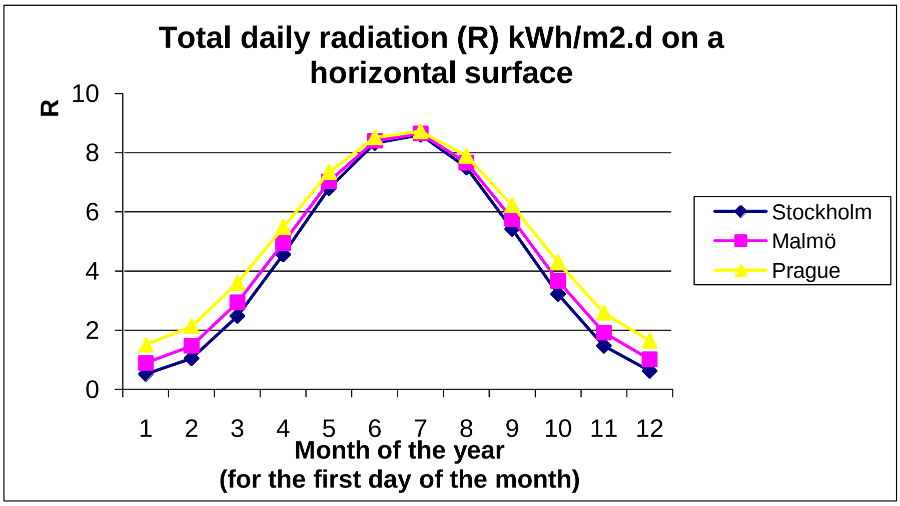

Figure 1 The total daily radiation by the sun on a horizontal surface in Stockholm, Malmo and Prague

The cells in the small pilot plant we have developed consist of 21 cells in three lines with 7 cells in each. The total surface area is 40 cm^2. The cells are from JX Crystals. The cells are mounted on a surface with water cooling, to keep the cell temperature below 50 ^oC. Different emitter materials were tested, but normal black iron actually turned out to be as efficient as more advanced materials. The reflectors were made of vacuum formed aluminium that was electro polished to get good reflectance properties. We had different type of edge filters. There was one specially designed glass surface, but it turned out that a normal energy glass was good enough. This simple pilot module thus was used in the tests performed and described below.

The heat source was an electrical furnace from Kanthal. This was a stable heat source which was easy to control. The experiments were made as seen in figure 2 below.

At the bottom we have the electric furnace, above the emitter and the reflecting cones. The glass edge filter was mounted between the two Aluminium cones as seen in figure 2. At the top are the cooled TPV-cells. The actual experimental set up is seen at the photo to the right, where also two of the authors (Eva Lindberg and Erik Dahlquist) are seen aside of Svante Nordlander.

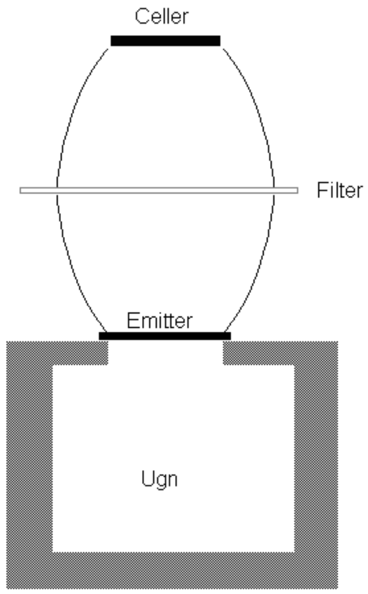

Figure 2. The experiment set up with the pilot TPV unit.

The efficiency calculations were made using the following formulas:

For the first experiment the efficiency was calculated according to equation (1)

$$\eta_1 = (P_c / A_c) / G \quad (1)$$

P_c = Electric power of the TPV cells [W]
A_c =Cell area [m^2]
G =Irradiation intensity at the plane of the cells [W/m^2]

For the second experiment equation (2) was used for the efficiency calculation:

$$\eta_2 = (P_c / Ac) / E_u \quad (2)$$

E_u [W/m^2] is the irradiation power per area unit from the emitter and is calculated from equation (3).

$$E_u = \varepsilon \, \sigma \, T_e^4 \qquad (3)$$

ε =emissivity [-]
σ =Stefan-Boltzmanns constant = 5,66697 10^{-8} [W/(m^{2}K^4)]
T_e =Emitter temperature [K]

Equation (3) also was used for the efficiency calculation in experiment 3. In figure 3 we see the results from experiment 1, where the effect of water cooling of the TPV cells was studied. As seen the water cooling of the cells gives a very strong impact on the cell performance. The efficiency calculations according to equation (1) was 4,8 % at 1950 W/m^2 and 8,7 % at 3000 W/m^2.

$$\eta_3 = (P_c / Ac) / (\gamma \, E_u)$$

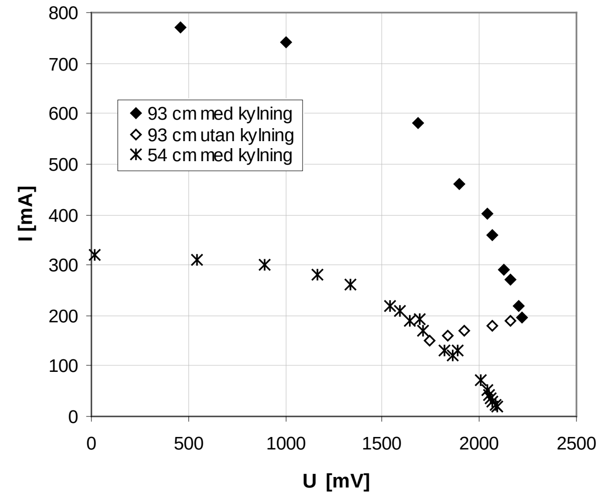

Figure 3. Results from experiment 1. Current – voltage curve for water cooled GaSb-cells irradiated with a halogen lamp at 1950 W/m^2 (93 cm) and ca 3000 W/m^2 (54 cm). The black prisms are with water cooling at 93 cm distance, the uncoloured prisms the same without cooling and the crosses at 54 cm distance with cooling.

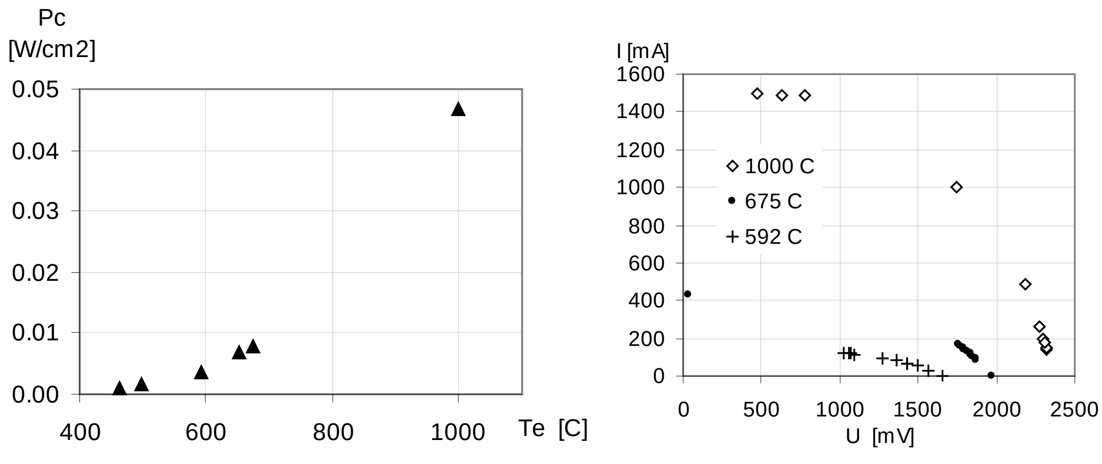

Figure 4. Power output as a function of the emitter temperature and current – voltage plot for different emitter temperatures.

In figure 4 we see the power output as a function of the emitter temperature. The average fill factor for the experiments was 0.6 calculated by the formula Fill factor = MPP/(I_{SC} x U_{OC}). Still, the spreading was relatively high as it was a bit difficult to measure the short cut current I_{SC} and the voltage at open circuit U_{OC} as well as the maximum power point MPP.

In figure 5 we see the current- voltage plots for emitter temperatures up to 1200 ^{o}C.

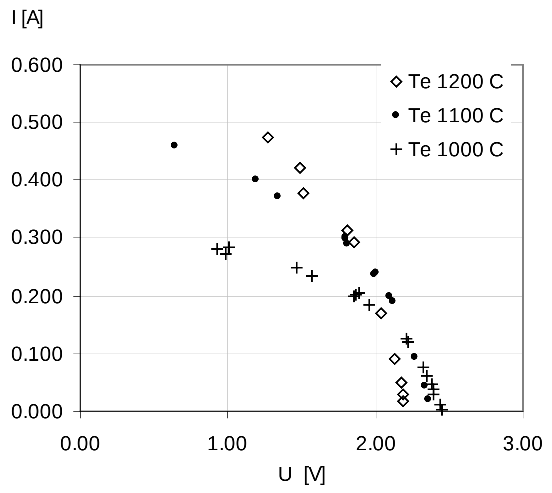

Figure 5. Current – emitter plot for higher emitter temperatures.

These higher emitter temperatures were tested in a special high temperature electric furnace from Kanthal which could be kept at constant temperatures up to 1700 ^{o}C. Still, it was not that easy to perform the actual measurements at the very high temperatures, so in practice we stopped at 1200 ^{o}C. These were the experiment 3 tests. In this last experiment we also tested the impact of the cones and the energy glass. The outcome can be seen in figure 6 below.

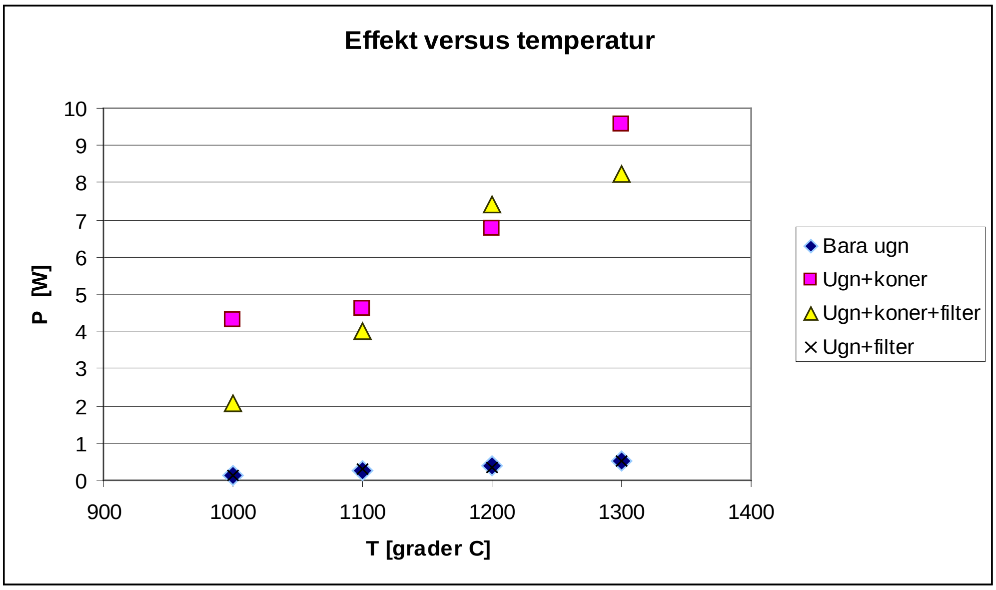

Figure 6. The power output from the TPV cells. At bottom (dark prisma) with radiation from furnace directly towards the TPV cell, (pink squares) furnace + reflecting cones and (yellow triangles) furnace, reflecting cones and edge filter using a standard energy glass.

At the bottom in figure 6 we see the power output when we only had the irradiation directly towards the cells placed at a distance corresponding to one cone. The squares are for furnace plus one reflector cone, but with no edge filter. Finally the triangles are for the two reflector cones with an energy glass in-between as seen in figure 2. The electric efficiency from fuel heating value to electricity production is going from around 0.5 % to 4- 5 % in the <1 $kW_{thermal}$ pilot plant tested. As we can see the reflector cones give a strong impact, and the two cones + an edge filter glass does not give significantly lower power output than with only one cone. Still, with two cones plus the glass we can have a long term good performance, which would not be possible without the energy glass, as the TPV cell would become too hot and deteriorate. The temperature drop in the combustion gases due to the TPV was negligible. By having a larger emitter and TPV area the electric output in relation to the heating value of the fuel can be increased. By this the efficiency as electricity divided by fuel heating value could be up towards 20%. Still, this also mean an increased cost for the TPV module. It should also be noticed that the remaining heat can be used to both heating water or drive an absorption cooling machine.

3. System aspects considering the demand and production capability of energy in detached houses.

The lowest heating demand is in so called passive houses that only utilize the heat from appliances and human bodies (approximately 100 W per person). If we should produce all electricity by TPV cells (5% efficiency) this means a fuel demand around (5 kWh/d) /(0,05) = 100 kWh fuel/day. For a four times larger TPV area the demand would be 25 kWh fuel per day. We assume that the electricity demand is only during 3 of 12 months, while the production is during 12 month, with an average of 5 kWh/m^2,day.

This means a demand of 100 kW h/d * 90 da ys = 9 000 kWh/year and assuming a net efficiency from the sun of 1% the biomass production will be 5 kWh/m^2,day*0.01 * 360 days = 18 kWh/m^2, year with respect to biomass. This means a need for 9 000/18= 500 m^2, if all the fuel should be produced in this way and all electricity come from the TPV-cells. For the four time larger TPV area the demand would be 25 kWh/d and the area for growing biomass would be 125 m^2 instead. With an efficiency from incoming sun to biomass of 5% would mean 100 m^2 instead of 500 m^2 , which might be economically feasible, but still on the high side. If we reduce the electricity consumption significantly by using low energy lamps, low energy refrigeration, using hot water instead of electricity in the washing machine and stay with low consuming TV and computers, it might be possible to reach perhaps even 50 m^2 solar heating surface area, and then also we could have PV-cells covering the rest of the need for the summer, autumn and spring time. With 5 kWh/ m^{2,} d, sunshine and 10-15 % net solar power efficiency, an average electric power output of 0.5 – 0.75 kWh/m^2,day could be achieved. We then would need some 5 m^2 for the house hold electricity for a single house. During summer there can be a net production that could be passed on to the power grid, while there might be a deficiency in October-November and February – March. A small battery would be good to have to give power also in the evening when it is dark, if there is enough PV-area to charge it during the day. Typical hot water and electricity demand for households have been presented in [6] and [7].

Summer time hot water production can be produced by solar heating panels. With a design with a tank above the solar heaters a self circulation can be achieved, but the technical installation and the need to insulate the tank may make it less cost effective than using a circulation pump and a tank in the building..

4. Combination of PV cells and TPV cells

In figure 1 we can see that the sun can give a significant energy contribution from March to October. We already said earlier that TPV-cells can be used during the dark period November - February to produce both heat and electric power. Still, during the more sunny part of the year, we can utilize a combination of PV-cells and solar collectors described above. The good thing with a combination of PV and TPV cells is that all the electrical equipments for DC/AC conversion could be the same for TPV and PV-cells. The TPV system also is an alternative to investing in a large battery.

5. Energy utilization in a household in relation to local production

From a design perspective a single household would need some 0.4 kW base load electricity as an average over the year. The need for hot water production will be significant. If we assume that every person take a 4 minute shower three times a week, and the water used has an average temperature of 15 ^{o}C and is heated to 40^{o}C, the heat consumption per shower will be at 10 l/min: 0.17 kg/s *4.2 *(40-15) = 17.5 kW. During 4 minutes this means 1.17 kWh. For five persons taking three showers per week this will mean 1.17*5*3*52 = 910 kWh/year. Teen agers often take 10 minute showers and seven times a week, which would mean 2.9 kWh/shower*3*7 times/w*52 = 3 200 kWh/y + two grown-ups 1.17*2*3*52= 365 kWh/y with a total amount 3 565 kWh/y.

To this we should add hot water for washing cloths and porcelain, which will add up another 500 kWh/y at least. A total of some 4 000 kWh hot water then is needed. If we distribute this per day, it means some 11 kWh/day.

With the assumption that the incoming sun light is 3-4 kWh/m2,day in April a solar panel will produce some 35 liter per m^2, day in April at the longitude of Vasteras/Stockholm with a temperature lift of 35 ^{o}C. This corresponds to 35*4.2*35/3600= 1.43 kWh/m^2,day. 11 kWh/day then mean 7.7 m2 solar panel. In March we only will get 15 liter/m^2,day, which would mean a need for 18 m^2 to cover all.

6. Use of DC in households

As both PV and TPV systems generate DC-power, we also can see a potential to use DC components generally, e.g for charging batteries for electrical vehicles, DC-pumps, LED-lamps etc. The advantage with this would be that normally lower voltages could be used for many applications. This is important as the voltage normally is quite low in PV-systems, typically 12, 24 or 48 Volt. The draw-back is that it is causing more losses to transport energy as low voltage, and thus the distance has to be optimized between the production units and the appliances. It is not clear where the economic limits are for using DC on a larger scale in the buildings, but worth to investigate more in the future. Normal distances within a single house of average size will be no problem.

7. Discussion

To sum up: We assume a house-hold electricity demand of 3600- 5400 kWh/year = 10-15 kWh/day. To this a hot water demand of the same amount 10 kWh/d is assumed. The heat demand will vary over the year with a demand around 70-120 kWh/day in November-February, some 30- 50 during March-April and in September- October. The rest of the year there will be no demand for heating. With a TPV system giving 10 kWh/d electricity we would produce also 50- 200 kWh/ heat and hot water, which would be enough to cover the demand during November – February. During the rest of the year a 18 m2 solar panel + 20 m2 PV cells would be enough to cover all energy demands.

Adding some 5-10 m^2 PV-cells will give a house producing more energy than it consumes (emitting < 20 W/ m^2 building area when the outdoor temperature is – 15 ^oC - the definition used in Sweden for so called “low energy houses”). If the roof area is some 170 m^2 the solar panel units will cover less than 50% of the roof area, which is quite feasible.

For the case with the TPV system and production of biomass as such it would be primarily the TPV that is an issue, as the unit only exists as a pilot plant today, and not a full commercial product. Still, the prize tag is estimated to be relatively low (1000 – 3000 €/kW_{el}).

8. Conclusions

The conclusions are that the alternatives discussed can be motivated economically if we can achieve high efficiencies for all technologies and steps. It is difficult to judge which technology is the economically best comparing different systems that are not yet commercial. Still, the alternative with biomass production followed by TPV for heat and power production locally has a relatively short distance to being realized commercially, and the potential to be economically competitive is reasonably high.

Acknowledgements

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