Economic Potential for Thermophotovoltaic Electric Power Generation in the Steel Industry

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***ABSTRACT* - A steel mill extrudes steel billets at temperatures above 1400 °C continuously 24 hours a day. The steel billets then go to cooling beds where they slowly cool down to below 1100 °C. JX Crystals Inc makes Gallium Antimonide (GaSb) thermophotovoltaic (TPV) cells that can generate over 1 W/cm² when exposed to infrared radiant energy from glowing steel at temperatures above 1100 °C. There is a great opportunity to integrate GaSb TPV receivers into steel mill operations to generate electricity economically utilizing this now wasted radiant energy.**

In a recent visit to a steel mill in China producing 10 million Metric-Tons (MT) of steel a year, the operators of the mill told us that they have 2000 m² of glowing steel in process continuously. At 1 W per cm², this equates to the potential to produce 20 MW of electricity for that steel mill. In 2012, the world steel production was 1,548 million MT. So, the world wide potential for TPV electricity production could be 3.1 GW.

At what cost will TPV be affordable? This application has two advantages over solar PV. The first is the high power density, a factor of 100 over solar PV modules, translating to a potential cost advantage. The second distinct advantage over solar PV is the 24 hours of operation since the sun is only available on average for 8 hours per day. One can estimate the potential value of a TPV plant from the potential annual revenues. Assuming electricity at 8 cents per kWh, 1 kW of TPV electric power capacity will produce 8765x0.08 = $700 dollars per year. This implies a 3 year payback at $2.1 per W. Cost is a function of volume but should come down to below $1.5 per W at volumes above 1 MW.

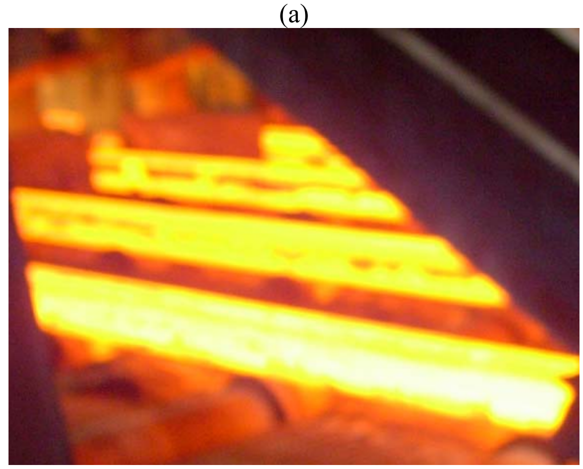
***Index Terms* — Co-generation, GaSb, Photovoltaic Cell, Steel-Mill, Thermophotovoltaics, TPV.**

I. INTRODUCTION

The melting temperature of steel depends on the type of steel. Carbon steel has a melting point of 1425 degrees C to 1540 degrees C while stainless steel has a melting point of 1510 degrees C. A black body at 1400 K (1127 C) emits 3.4 W/cm² of infrared (IR) radiant energy at wavelengths equal or less than 1.8 microns and the JX Crystals Inc GaSb infrared sensitive thermophotovoltaic cells [1, 2] can convert 30% of this radiant energy into electric power. This means that at least 1 W/cm² of electric power could be generated from the now wasted radiant energy in a steel mill. In a recent visit to a steel mill in Xuan Gong China, we were told that they have 2000 m² of glowing steel at temperatures above 1127 C in process 24 hours per day and 7 days a week. See figure 1. At 1 W/cm², this means that it is potentially possible to generate 20 MW of electricity with TPV at this steel mill alone.

A recent visit to a steel mill in China provided an interesting perspective. That steel mill produces 10 million Metric-Tons (MT) of steel a year. A typical billet has a square cross section of 16 cm x 16 cm and a length of 5.6 m and weighs 1 MT. This equates to 1,250 billets in process every hour. If TPV converter circuit arrays are placed along the two 15 cm x 5.6 m faces adjacent to each of these billets, the area of these TPV arrays would be 1,250 x 0.15 x 2 x 5.6 = 2100 m². This calculation is consistent with the input from the operator of the mill.

(a)



(b)

Fig. 1: (a) and (b) show photos of steel billets just after continuous casting.

One can now extrapolate to world wide TPV electric power production potential from the steel industry. In 2012, the world steel production was 1,548 million MT [3]. So, the world wide potential for electricity production could be 3.1 GW. In theory, one could double this number by utilizing all four facets from the billet. Furthermore, if one notes that each billet of steel gets heated to melting twice during production, once for casting and a second time for shaping, the potential TPV electric power production could then approach 10 GW.

Next, one might ask, at what cost will TPV be affordable? The fact that this potential TPV electric power facility would operate for 24 hours per day is a distinct advantage over solar PV where the sun is only available on average for 8 hours per day. One can estimate the potential value of a TPV plant from the potential annual revenues. Assuming the value of electricity to be 8 cents per kWh and noting that there are 365cx24 = 8760 hours per year, 1 kW of TPV electric power capacity will produce 8765x0.08 = $700 dollars per year. If one asks for a 3 year payback, the TPV power plant might be worth $2100/kW or $2.1 per W. Figure 2 shows an estimate of the cost of GaSb TPV circuits [4]. As is shown, the costs are a function of volume but will come down to affordable levels at volumes above 1 MW.

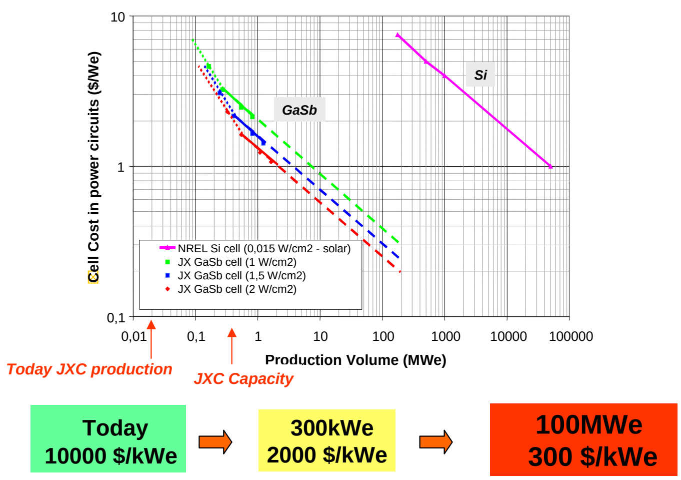


Figure 2: Achievable GaSb Cell costs vs cumulative production volume.

II. TPV Converter Concept

The challenge then is to design a TPV converter compatible with the steel making process. It should operate with steel at temperatures above about 1000 C. Thermal management for cooling the TPV cells will be important and spectral management to achieve respectable conversion efficiencies will be important. Durability will also be important and it will be necessary to design to avoid contamination of the TPV cells and optical elements from deposits of iron oxide and other volatile elements.

To meet these design criteria, a planar TPV module is described here [5]. The design is shown in figs 3 & 4. The module sits above or adjacent to the hot surface of a hot steel plate or billet. This TPV module consist of a SiC ceramic plate heated by radiation from the hot steel to about 1100 C or higher. This SiC plate serves as an IR emitter and it also serves to protect the TPV converter assembly from iron oxide deposits. On the side opposite to the hot steel, parallel with this SiC plate, a fused silica multi-pane window is placed as both a convection and radiation shield. Adjacent to this window in parallel and again on the opposite side from the hot steel and facing the SiC IR emitter, a TPV cell and circuit assembly is placed to receive IR radiation from the SiC emitter and convert a fraction of that radiant energy to electricity. The TPV cells in this circuit assembly are wired in series and mounted on an electrically insulating voltage stand off plate. A glass plate is bonded to the radiation side of this cell assembly and a multilayer alternating high and low refractive index filter [6] is applied to the top surface of this glass plate. Air flows above this filter plate to cool this optical filter and this cell assembly is mounted on a water cooled plate to cool the cell circuit.

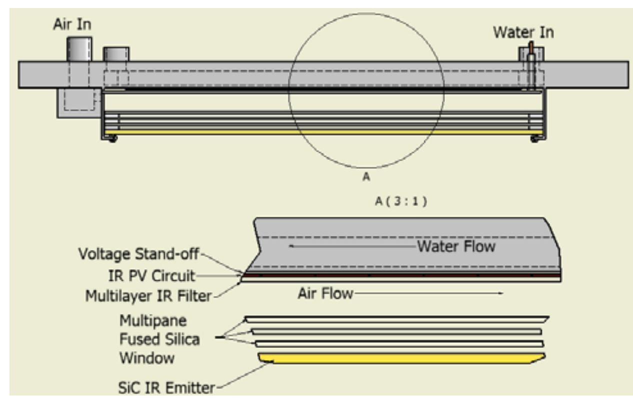


Fig 3. Cross section of TPV planar module.

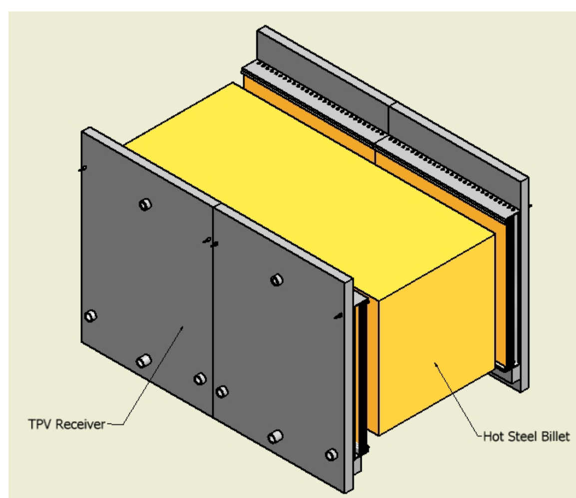


Fig 4. Four planar TPV modules arrayed on both sides of glowing steel billet.

III. Detailed Description of Specific Embodiment

From our visit to the Xuan Gong steel mill, we have designed the planar TPV module to fit with the 16 cm square billets shown in figure 1a & b. This design is merely exemplary. Specifically, the SiC and fused silica windows in figures 3 & 4 are 18 cm square. The TPV circuit is 16 cm square. The two important elements of this design are:

- The IR PV array design & fabrication &
- The spectral control.

A. IR PV array design and fabrication

The IR PV array should be a dense shingle circuit array as shown in figure 5. The TPV circuit is 16 cm square and contains 10x14 = 140 GaSb TPV cells. Each cell should generate a voltage at maximum power of approximately 0.33 V. Therefore, the maximum power voltage of this circuit should be approximately 46 V. The active area of each cell is approximately 1.8 cm^2. The current and power generated by this circuit will depend on the SiC IR emitter temperature as shown in table 1.

This dense shingle circuit array can be routinely fabricated as shown in figure 6. This fabrication method depends on using a Ni/Fe alloy substrate with coefficient of thermal expansion matched to the GaSb cells as described in a JX Crystals Inc US patent [7].

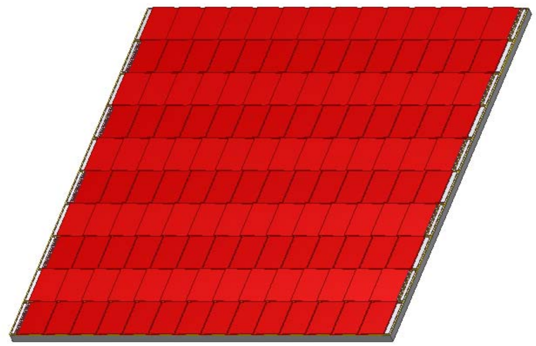


Figure 5: 16 cm x 16 cm TPV shingle circuit produces Approximately 350 W (depending on IR emitter temperature)

Table 1: Projected TPV planar module performance.

Temperatur (oK)	Wavelength Band (µm)	Blackbody Energy (W/cm^2)	Filtered Energy (W/cm^2)	Cell Electric Power (W/cm^2)
1500	4-12	6.8	1.7	
	1.8-4	15.4	1.5	
	0.4-1.8	5.9		1.8 (20% Effic)
1400	4-12	5.9	1.5	
	1.8-4	11.5	1.2	
	0.4-1.8	3.4		1.1 (18% Effic)

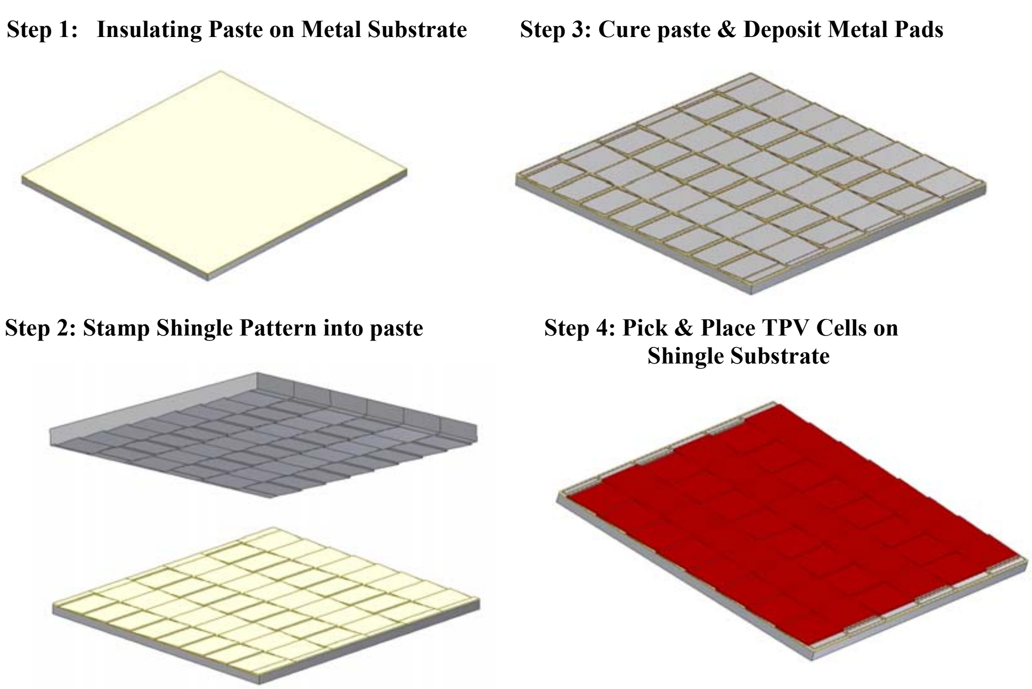
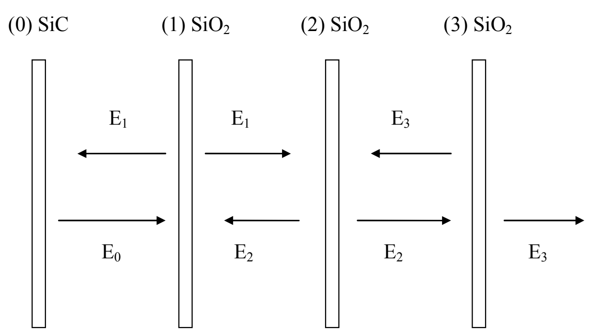


Fig. 6: TPV Shingle Circuit Fabrication

B. Spectral Control

The spectral control in this design is also very important and summarized in table 1. It is important to suppress the non-useful IR radiation at wavelengths longer than the IR PV cell band gap wavelength, λg. This is important both for conversion efficiency as well as for managing the cell cooling heat load. In the present embodiment, the IR PV cells are GaSb cells and the bandgap energy is 0.72 eV and corresponding bandgap wavelength, λg, is approximately 1.8 microns. However, it is possible to use alternative TPV cells which would also fall within this concept. Alternate cells might include InGaAs/InP, InGaAsSb, or Ge cells. Any cell with a bandgap between 0.75 eV and 0.55 eV can potentially be used with λg ranging between 1.5 microns and 2.5 microns. Table 1 presents efficiency and heat load calculations for the GaSb cell case and for exemplary IR emitter temperatures of 1127 C and 1227 C corresponding to 1400 K and 1500 K respectively.

Note that the multi-pane fused silica window with N fused silica sheets will suppress the IR emitted radiation in the wavelength band beyond 4 microns by E = E(SiC)/(N+1)as shown in figure 7.



Energy balance: $2E_1 = E_0 + E_2$; $2E_2 = E_1 + E_3$; $E_2 = 2E_3$
Therefore $E_1 = 3E_3$ & $E_0 = 4E_3$
Therefore $E_3 = E_0/4$

Figure 7: A multipane fused silica window will surpress the long wavelength radiant energy arriving at the IR PV array. Specifically, 3 window panes drops radiant energy to on quarter.

If N=3, then the radiant energy from the SiC IR emitter will fall to one-quarter of its initial value. For example, at 1400 K from table 1, the thermal energy heat load beyond 4 microns drops from 5.9 to 1.5 W/cm^2.

The high/low index filter [6] efficiency shown in figure 8 is assumed to drop the radiant energy heat load in the 1.8 to 4 micron band at 1400 K down from 11.5 to 1.2 W/cm^2.

The cell efficiency for the 0.4 to 1.8 conversion band is assumed to be 30%. So the electric power produced at 1400 K will be 1.1 W/cm^2 and the worst case heat load will be 1.5+1.2+3.4 = 6.1 W/cm^2. The worst case TPV conversion efficiency at 1400 K would then be 1.1/6.1 = 18%. At 1500 K, the electric power density, worst case heat load, and efficiency numbers all increase to 1.8 W/cm^2, 9.1 W/cm^2, and 20% respectively. Referring to the two TPV modules in figure 4, the power output for each should be between 215 W and 350 W depending on the SiC emitter temperature.

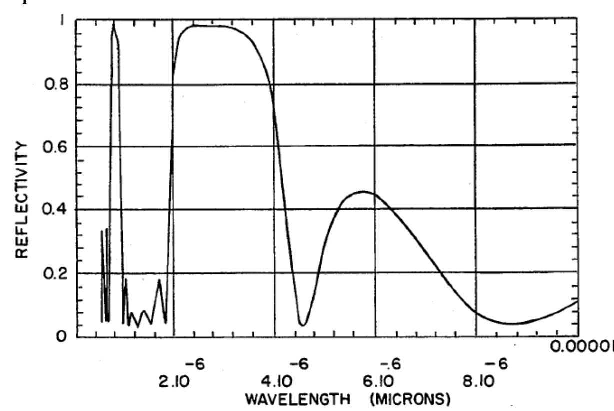


Figure 8: The high/low index dielectric filter reflects radiant energy in the 1.8 to 4 micron band back to the IR emitter.

Another important requirement for good spectral control is a good view factor between the IR emitter and the IR PV array. For this, it is fortunate that this steel application uses a relatively large IR emitter and IR PV array.

The calculations just described in Table 1 assume high radiation energy view factors, F_{12}, between the multilayer dielectric filter and the IR emitter. Figure 9 shows the calculation of this view factor as a function of the ratio of the emitter width, W and the spacing, H between the dielectric filter 60 and the IR emitter [8]. From figure 9, if W/H is larger than 8, the view factor will be ≥ 80%. A high view factor is important for high spectral efficiency. In the design discussed here, W = 16 and H=2. This ratio is important to minimize edge losses.

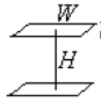
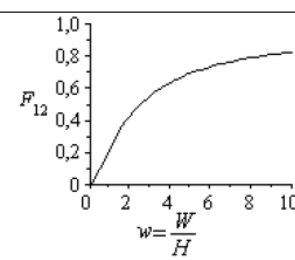
Between two identical parallel square plates of side L and separation H, with $w=W/H$. 	$F_{12} = \frac{1}{\pi w^2}\left(\ln\frac{x^4}{1+2w^2} + 4wy\right)$ with $x \equiv \sqrt{1+w^2}$ and $y \equiv x \arctan\frac{w}{x} - \arctan w$ (e.g. for $W=H$, F_{12}=0.1998)	

Figure 9: A high view factor is also an attractive feature for the TPV steel application.

IV. Single Cell Demonstration

Figure 10 shows test results for a water cooled single GaSb cell adjacent to a glowing radiant tube burner operating at a temperature of 1275 ºC [2]. The cell produces 1.5 W/cm^2.

GaSb cell power	1.5 W/cm^2
Emitter temp	1275 ºC
Spectral effic	74%
Cell effic	29%
TPV effic	21.5%

Fig 10: Single cell test

V. Conclusions

Applying TPV for waste heat conversion into electricity in the steel industry is an exciting opportunity. Furthermore, since half of the world's steel is now made in China with coal as the heat source, TPV could reduce the amount of coal burned and reduce pollution while simultaneously cogenerating electricity.

The economic potential for this application is particularly promising. This application has two advantages over solar PV. The first is the high power density, a factor of 100 over solar PV modules and the second is the 24 hours of operation instead of just an average of 8 hours per day for the sun, another factor of 3. These advantages translate to 300 times more kWh per unit area for TPV power circuits. It is also noteworthy that the GaSb cell fabrication process uses diffusions just like for silicon solar cells. It avoids the use of the toxic gases usually used for the fabrication via epitaxy of typical III-V based solar cells.

However, investment in development is still required for a full demonstration and then investment will be required for manufacturing scale up as was the case for the silicon solar cell and module industry.

References

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