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C. M. Iftekhar Hussain cmih
Technological University Dublin, iftekhar.hussain@mydit.ie

Brian Norton
Technological University Dublin, brian.norton@tudublin.ie

Aidan Duffy
Technological University Dublin, aidan.duffy@tudublin.ie

See next page for additional authors

Authors

C. M. Iftekhar Hussain cmih, Brian Norton, Aidan Duffy, and Mohamed Oubaha

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C. M. Iftekhar Hussain, Brian Norton, Aidan Duffy, Mohamed Oubaha[2]

[1] Dublin Energy Lab, Dublin Institute of Technology, Grangegorman, Dublin 7, Ireland

[2] CREST, Focas Institute, Dublin Institute of Technology, Dublin 8, Ireland

iftekhar.hussain@mydit.ie, president@dit.ie

ABSTRACT

Three conceptual designs have been developed for hybrid solar-biomass/gas thermophotovoltaic (TPV) system for a non-intermittent power generation which can operate at relatively low TPV operating temperatures. TPV cells with lower band gap has been chosen for this conceptual hybrid device. The low band TPV cell generates electricity at longer photonic wavelength which corresponds a lower operating temperature. The development methodology is presented for a spectrally matched emitter which emits maximum photonic energy in the 600°C -1000°C temperature range with correspondingly lower photonic energy emission in the 0°C -600°C range. This approach for spectral control in TPV systems requires fewer system components.

***Key words*: Thermophotovoltaic, Spectral Control, Absorber/Emitter, Hybrid STPV**

INTRODUCTION

Standalone CSP plants are mostly located in location where solar Direct Normal Irradiance (DNI) is 1800 kWh/m^2 as shown in Figure 1. The use of secondary sources such as biomass/gas can extend standalone CSP operation regions to above 1600 kWh/m^2 as also shown in Figure 1. Termosolar Borges (TSB), for example, is a unique 25MW hybrid solar-biomass power plant dispatching electricity to the grid in Lleida, north eastern region of Spain. While the average direct normal irradiation (DNI) in the vicinity ranges from 1500-1700 kWh/m^2, the remainder of Spain's standalone CSP plants are located in regions where the DNI is between 1700-1900kWh/m^2. This research is motivated to investigate the potential extension of hybrid solar-biomass power plant with a modular scale deployment where the DNI is less than 1600 kWh/m^2 [1, 2].

A new concept of hybrid solar thermophotovoltaic (STPV) - biomass/gas system for power generation. STPV has a potential solar to electricity conversion efficiency of 85.4%. The novelty of a STPV technology is integrating a secondary thermal energy source at various forms (gas/biomass/thermal storage etc.). To date, very limited work has been done to hybridize STPV with duel fuel source with no attempts to operate it at temperatures under 1000°C [3-6].

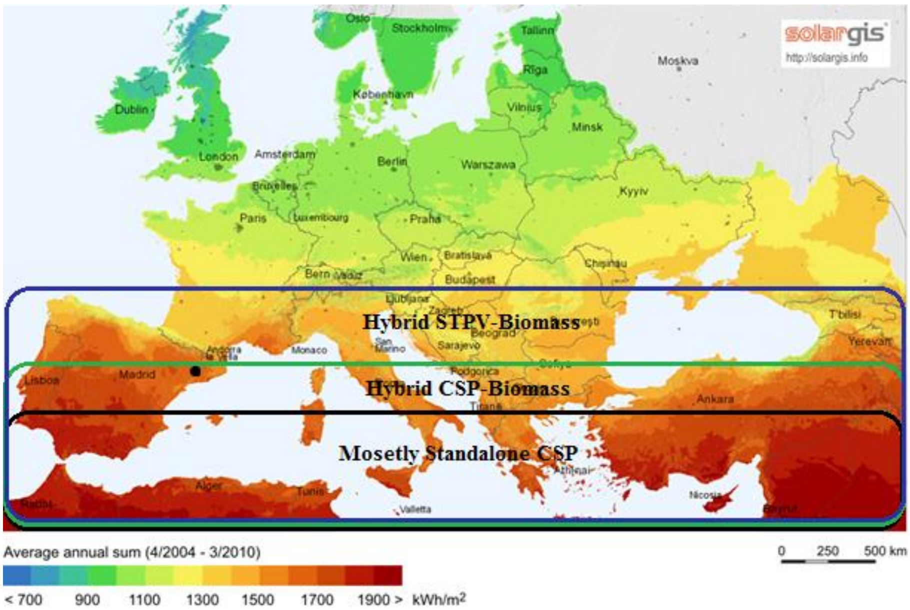

Figure 1: Direct Normal Irradiance in Europe [34]

Three designs of a small scale STPV systems which can be hybridized with additional energy sources (biomass/gas) are presented. Research on STPV has mainly focused the improvement of overall TPV cell efficiency via the use of different semiconductor materials and spectral control material for better utilization of energy photon. Only one hybrid STPV with secondary energy sources has been developed by EDTEK,Inc. in which STPV was integrated with gas for continuous power generation [7]. However, system performance data had not been reported.

STPV-BIOMASS/GAS SYSTEM DESCRIPTION

A thermophotovoltaic cell (TPV) is a device that can convert thermal radiation into electricity. When the thermal heat is produced by the solar energy and use a TPV cell to generated electricity, than the device is called solar thermophotovoltaic (STPV). STPV first converts the solar optical spectrum into thermal spectrum with an intermediate material which is a heat absorber [9,10]. The ideal absorber is an object which can absorb potentially all optical spectrum that falls at the earth surface. A material surface facing the thermophotovoltaic (TPV) cells, known as an emitter, then re-emits a narrower thermal spectrum. The photons emitted from the emitter falls onto the cell which then generates electricity. An intermediate spectral control material (filter) between the emitter and TPV cell can be integrated to redirect non-useful photons back to the emitter. This process further increases the system efficiency by recycling the photon captured from solar energy [11,12]. The presence of an intermediate high temperature heat absorber material of TPV allows it to integrate with various input such as solar, biomass or fuel/gas, thus allowing this technology as one of the promising candidate for hybridization with multiple energy sources. Figure 2 shows a schematic of a hybrid solar-biomass/gas system.

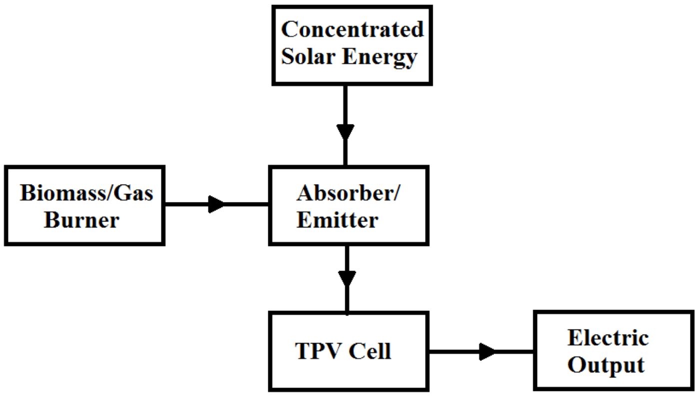

Figure 2: Hybrid STPV System Schematic

HYBRID SOLAR-BIOMASS/GAS TPV DESIGN & MODEL

Three unique design concepts of hybrid solar-biomass/gas TPV system are described in this section. All three systems are commonly having a parabolic dish solar collector and a cylindrical chamber where the absorber/emitter, TPV cell, fuel burner and auxiliary system components are integrated. Different arrangements of individual components are the only difference between each system. A methodology to select PTV cell and spectrally matched absorber/emitter material for fabricating low temperature STPV-biomass/gas system is also presented in the later part of this section.

Duel TPV Cell Arrangement

Figure 3 shows a duel TPV cell arrangement in a hybrid solar-biomass/gas TPV setup. The concentrated solar energy is collected from a parabolic dish concentrator which has been redirected to a metal based absorber chamber. The absorber chamber acts as a black body as all the collected solar energy in conserved within the body.

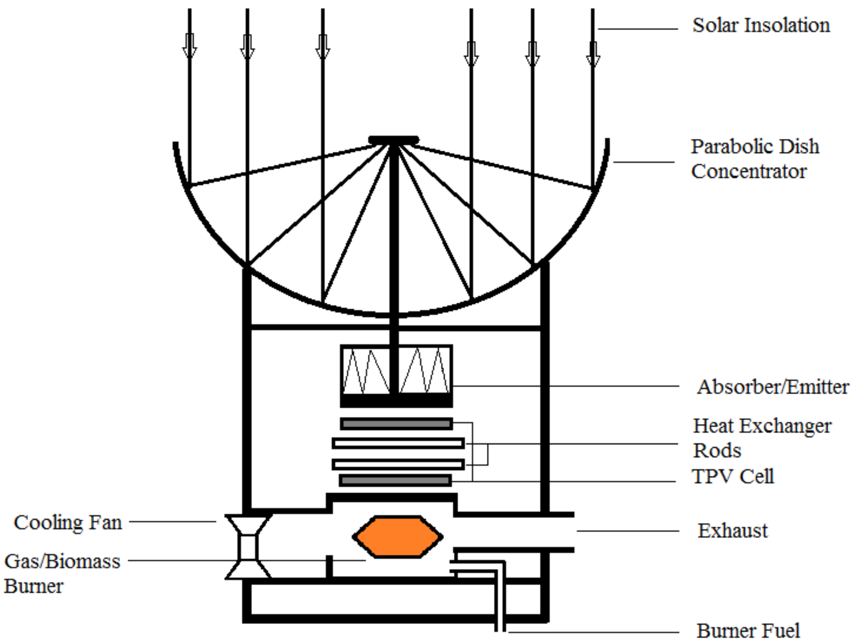

Figure 3: Solar-Biomass/Gas TPV Design with Duel TPV Cells

According to the blackbody radiation, the emitter (opposite side of absorber) then transfers all of the collected thermal heat to the TPV cell by which electricity is generated. A secondary fuel burner is placed underneath the solar absorber/emitter and the TPV cells. Two sets of TPV cells along with cooling rods are placed in-between the absorber/emitter and the fuel burner. Both TPV cells can be operated at any given time by this arrangement. An exhaust system is incorporated in such a way that it does not affect system's internal vacuum environment.

System	Advantage	Disadvantage
Duel PV cell		(1) Limiting system efficiency by 50% as one side of PV cell works at a time if operated in a single mode.
	(2) Heat transfer loss in minimum as it uses less heat transfer medium.	
		(3) Relatively high cost as duel TPV is required
	(4) System can run in dual mode simultaneously.	

Table 1: Performance Analysis of STPV-Biomass/Gas with Duel PV Cell

Sliding TPV Cell Arrangement

Figure 4 illustrates a cross section image of internal component of the sliding TPV cell system. The arrangement of solar concentrator is same as previous design. The absorber has an internal reflector which distributes the concentrated energy and heats up absorbing surface. A secondary fuel burner is also placed adjacent to the solar absorber.

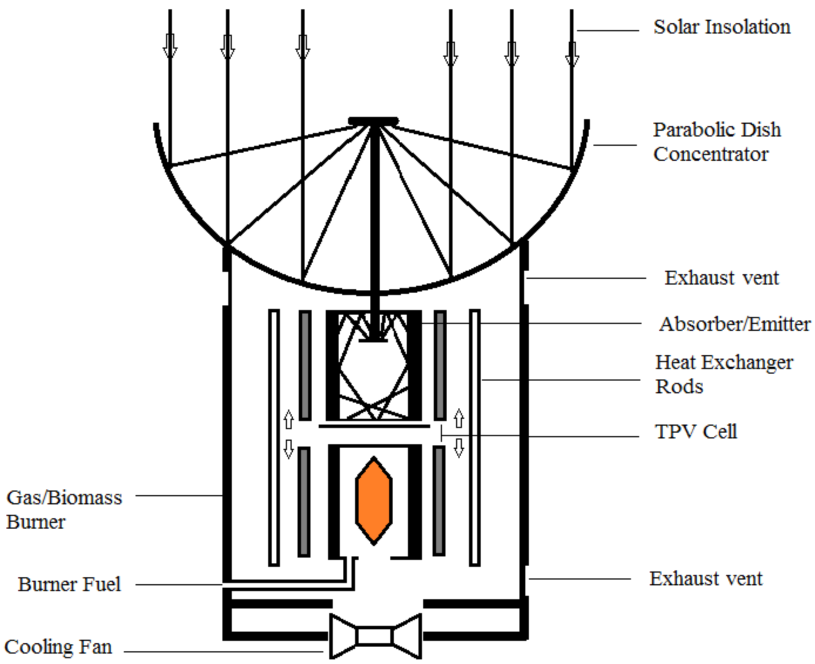

Figure: 4: Solar-Biomass/Gas TPV Design with Sliding TPV Cells

However, unlike the duel TPV cell arrangement a sliding TPV cell is placed around the emitter surface within a cylindrical chamber. The TVP cell can be operated externally to adjust either on solar or burner mode when necessary. It is presumed to be operated at solar mode during the availability of sufficient solar insolation and can be turned into a TPV burner operation during the solar intermittent time.

System	Advantage	Disadvantage
Sliding TPV Cell		(1) Vacuum environment is difficult to fabricate. Heat to electricity conversion efficiency may decrease significantly.
	(2) Minimum heat transfer loss as it has less heat transfer medium.	
	(3) Cost effective system as it uses single TPV cell.	
		(4) Single set of TPV cell allows to operate in one mode at a for both energy sources.

Table 2: Performance Analysis of STPV-Biomass/Gas with Sliding TPV Cell

Heat Injected Emitter

Figure 5 shows a hybrid solar-biomass/gas unit where heat from secondary sources is injected to a heat emitting surface rather than directly heating up an absorber/emitter. The absorber is heated in the same way as described in sliding TPV setup as described in Figure 4. The auxiliary fuel burner arrangement is same as it is described in duel TPV setup (Figure 3).

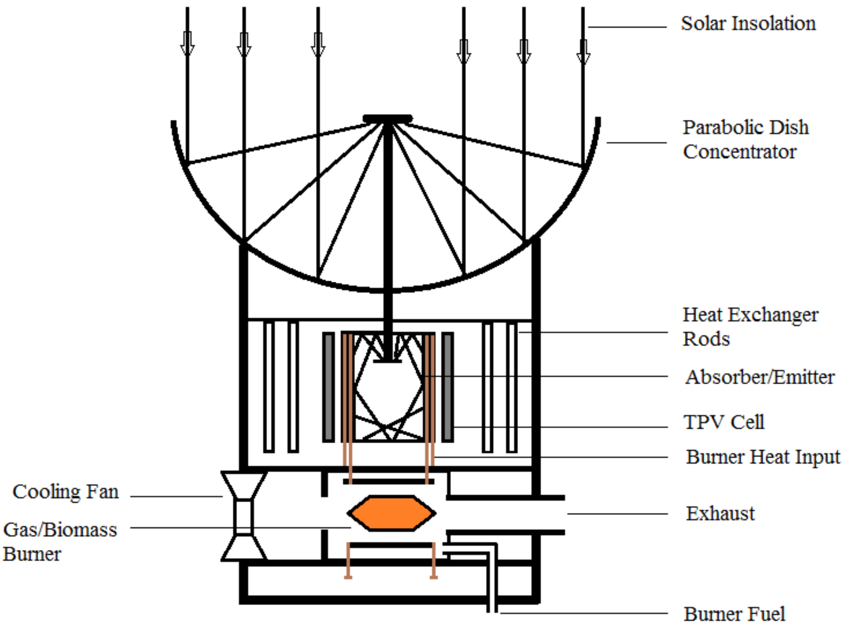

Figure: 5: Solar-Biomass/Gas TPV Design with Heat Injected Emitter

Unlike two previous arrangements, this hybrid solar-biomass/gas system uses two sets of heat injectors inserted to the emitter surface which act as the heat transfer medium. This heat injection can be made through thermal fluid transfer within an injector tube or using a heating coil attached to the emitter. The novelty of this concept is that it uses single absorber/emitter and TPV cell, allowing a cost effective hybrid STPV-biomass/gas system fabrication.

System	Advantage	Disadvantage
External Heat Injector	(1) Internal vacuum environment is easier to fabricate giving an efficient heat to electricity conversion	
		(2) A small heat loss may occur while transferring heat from secondary energy sources
	(3) Reduced cost as it only uses single TPV cell without any external adjustment mechanism	
	(4) Can be operated in both singe and dual mode.	

Table 3: Performance Analysis of STPV-Biomass/Gas with External Heat Injector

Solar Concentrator Selection:

In order to extend the operational region of hybrid solar-biomass system into the area with DNI less than 1600 kWh/m^2 it is essential to consider a solar technology which generates high thermal heat from lower solar DNI. Solar thermophotovoltaic (STPV) technology requires high operating temperature which can be provided by either solar parabolic dish or solar tower concentrator which are technically the most efficient solar collectors because of their high concertation ratio. Figure 6 shows that at higher temperature a parabolic dish gives higher efficiency.

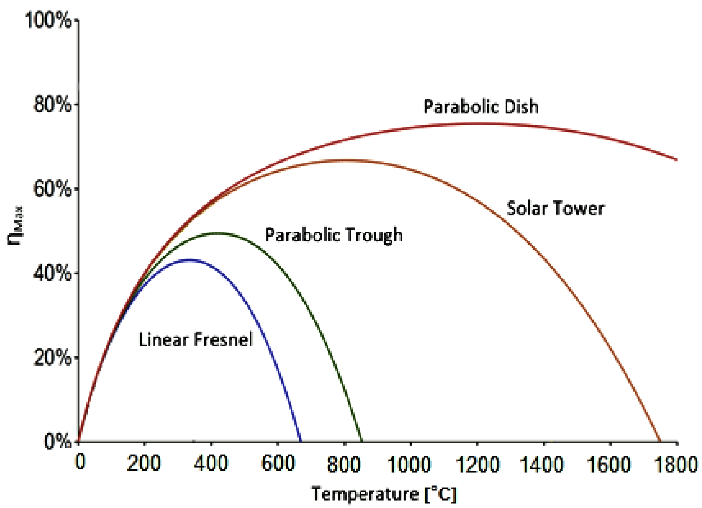

Figure 6: Temperature vs Efficiency Curve of Different CSP Technologies [13]

The broader operating range (800°C-1800°C) at higher temperature is the attraction of parabolic dish concentrator. Solar tower performs best between 600°C to 1100°C which gives a fare range of options for heat and power generation. In comparison to that the parabolic trough gives a smaller window for CHP generation with optimum efficiency. Maximum efficiency spectrum is in between 300°C to 600°C. Linear Fresnel has the least operating range and efficiency which are between 250°C -450°C. The obtainable maximum efficiency is better in parabolic dish where it offers around 80% followed by solar tower (65%) and parabolic trough (50%) [13,14].

TPV Cell Selection

To design a low temperature hybrid solar-biomass/gas TPV system, it is essential to select a low bandgap TPV cell. This secction presents the correlation between temperatures, wavelength and the cell bandgap as, all these three parameters are required to model a hybrid STPV-biomass/gas system. The wavelength is particularly important to identify specific emitter material which should emit specific wavelength of photons matching the TPV cell bandgap. The relation between the wavelength and temperature is given by the following equation.

$$\lambda = 2898/T \quad \text{……………………..…. (1)}$$

Where, λ is the wavelength in μm and T is the temperature in K. Once the wavelengths are determined by its corresponding temperatures, it can be used to find the bandgap of TPV cell by the equation 2.

$$E = 1.24/\lambda \quad \text{………………………. (2)}$$

Where, E is the energy/band gap in eV and λ is the wavelength in μm. A table can be obtained using above equations.

Temperature (°C)	**Wavelength (λ)**	**Bandgap (eV)**
2500	1.04	1.18
2200	1.17	1.06
2000	1.27	0.97
1800	1.39	0.88
1600	1.54	0.80
1400	1.73	0.71
1200	1.96	0.63
1000	2.27	0.54
800	2.70	0.46
600	3.32	0.37
400	4.30	0.28

Table 4: Correlation of Bandgap, Wavelengths and Temperature of TPV Cells

To design a STPV system under operating temperature of 1000°C would require to select a TPV cell with bandgap of 0.54 eV or less. InGaAsSb/InAsSbP has a bandgap of 0.5 eV where InAs has 0.36eV [15 - 18]. The peak photo response of InAs is found in between the temperature range at 555°C -886°C. Total operating spectrum of InGaAsSb/InAsSbP falls between 555°C -1659°C, however it operates most efficiently up to 1176°C.

Absorber/Emitter Material Selection

Most solar absorbance accurse at ultraviolet to near infrared spectrum where the photonic wavelength are very small. An ideal emitter for TPV cell is an object having a narrow emittance/transmission spectrum at particular temperature or wavelength which matches the bandgap of the TPV cell. In order to match the emission spectrum of an emitter for InAs TPV cell it is essential to select a material with a high emissivity in between the temperature range of 555°C -886°C [19]. The most effective emitter temperature range for InGaAsSb/InAsSbP is between 555°C - 1176°C.

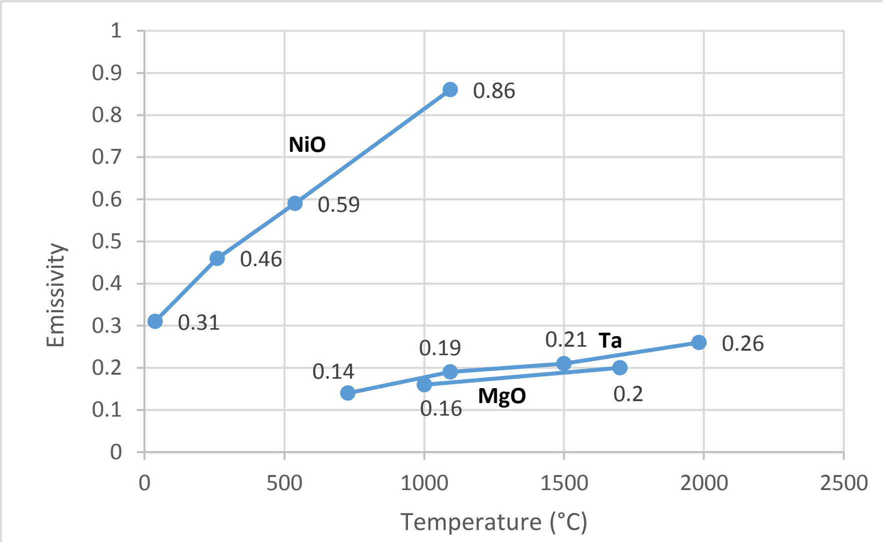

Figure 7: Emissivity of Various Metal Surface at Different Temperature [20]

Figure 7 presents few material's emissivity at different temperatures. Nickel Oxide (NiO) for example can be used as for an emitter as it has relatively low emissivity at lower temperature and the emissivity increases as the temperature increases. For the temperature window 800°C -1200°C, the NiO gives emissivity around 0.75-0.89. Therefore, theoretically this material can be used for all InGaAsSb/InAsSbP and InAs TPV cell [15, 21-23]. However, NiO is found to be thermodynamically unstable at temperature 600 °C or above. Therefore a pure NiO may not be a good candidate for spectrally selective absorber/emitter. It's worth mentioning that, eelectrochemical doping can significantly increase emissivity of an emitter surface. The ideal approach is to select a low emissive material at all possible operating temperatures and then dope with another metal oxide which has higher emissivity at particular temperature zone. For example Magnesium Oxide (MgO) or tantalum (Ta) has consistent low emissivity at all the temperature zone in the graph, and NiO has a linear increase of emissivity in relation to temperature [24, 25]. Therefore, there is a possibility to increase the emissivity of MgO or Ta surface by NiO doping at different % weight.

DISCUSSION & CONCLUSION

To date, the operating temperature of STPV systems are around 1400°C -1800°C. None of these STPV devices are reported to operate at lower temperature. This paper designed a hybrid STPV-biomass/gas system to operate under 1000°C. Different configuration of biomass/gas burner integrated hybrid STPV system is presented with potential operating performance analysis. These are the unique concepts which had not been attempted in any previous research. The low temperature STPV system can be used in various new applications for example; portable battery, micro-generation for households etc. The spectral control of STPV device is the most important component. If the emitter is not matched with the TPV cell band gap, maximum generated heat will be rejected and not utilized for electricity conversion. Moreover, the unused photons increases temperature at TPV surface which reduces cell efficiency significantly. This paper identified TPV cell which can generate electricity at lower temperature and proposed a method to develop TPV cell matched absorber/emitter for efficiency improvement.

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