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Economic appraisal of hybrid solar–biomass thermophotovoltaic power generation

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The techno-economic parameters that influence the commercial deployment of hybrid thermophotovoltaic (TPV) solar power generation are determined using annual system simulations. It has been found that a TPV cell price of €5/cm^2 or less together with a TPV operating temperature under 800°C is required for a hybrid solar–biomass TPV power plant to be economically competitive with the state-of-the-art hybrid solar–biomass Rankine cycle power plants.

1. Introduction

A solar thermophotovoltaic (TPV) device comprises a solar heated surface from which heat is conducted to a surface that emits thermal radiation converted directly to electricity by a TPV cell as shown in Figure 1 (Daneshvar *et al.*, 2015; Ferrari *et al.*, 2014; Mustafa *et al.*, 2017).

By incorporating additional appropriate components, a TPV system can also harness energy from biomass/gas combustion, stored heat or waste heat to overcome the intermittency in the output associated with a stand-alone solar power plant (Datas, 2016; Hussain *et al.*, 2017). A conceptual diagram of a hybrid solar–biomass TPV system combining the direct use of solar energy with biomass combustion is shown in Figure 2.

The analysis presented here seeks to determine the key parameter values for a hybrid solar–biomass TPV power plant that are required to be achieved for competitiveness with a conventional solar–biomass power generation option. Levelised cost of electricity (LCOE) is chosen to compare the projected economic viability of different hybrid solar–biomass power generation systems. The LCOE is set by two variables: (*a*) TPV cell price/cm^2 and (*b*) annual biomass fuel expenditure. A threshold economically viable TPV cell price is determined by varying the TPV cell cost. LCOEs for TPV power plants operating at different TPV temperatures are evaluated by varying biomass fuel expenditure.

2. Background

Previous studies have presented economic analyses of concentrated solar power (CSP)–thermal energy storage (TES) power plants (Guédez, 2016; Locatelli *et al.*, 2015; Naranjo *et al.*, 2014; Wagner and Rubin, 2014). A hybrid solar–biomass Rankine cycle power plant has been compared with hybrid solar–biomass–TES Rankine cycle power plants to determine the most economically viable hybrid power plant configuration (Hussain, 2019). In that study, a stand-alone biomass system was simulated to obtain annual fuel expenditure; a hybrid CSP–biomass power plant and a hybrid CSP–biomass–TES Rankine cycle power plant were then simulated to compare fuel consumptions for the same electrical power output. It was found that a hybrid CSP–biomass Rankine cycle power plant was more economically viable than a hybrid CSP–biomass–TES power generation option. The baseline annual biomass fuel cost for a CSP–biomass power plant was found to be €132/kW at an operating temperature of 400°C (Hussain, 2019). The annual fuel price was obtained from a simulation that calculated cumulative fuel prices over 20 years of plant lifetime operating 357 d/year (with 8 d/year shut down for maintenance); equivalent to €0·015/kWh. A hybrid solar–biomass power plant fuel cost was combined with an initial capital expenditure, capacity factor, discount rate and fixed and variable costs to obtain the LCOE. In this study, a LCOE of €0·139/kWh was obtained from the annual biomass fuel consumption of €132/kW.

€50/cm^2 (€10 416/kW) is an indicative current cost of a high-band-gap TPV cell (Fraas *et al.*, 2014). This TPV cell price is high due to the limited volume of TPV cell production. Previous studies have shown that TPV cell production volume above 1 MW/year could bring the prices to commercially viable levels (Fraas, 2014). With the production volume increasing from 10 kW to 100 MW, TPV cell cost has been estimated to decrease significantly from approximately €9000/kW to €270/kW as illustrated in Figure 3 (Fraas *et al.*, 2014). Photovoltaic (PV) cells have experienced an almost similar price reduction trend with increased production volumes (Feldman *et al.*, 2012). Fraas *et al.* (2014) evaluated the cost-reduction trend of TPV cell using data sets presented in previous studies. As can be seen in Figure 3, a price of

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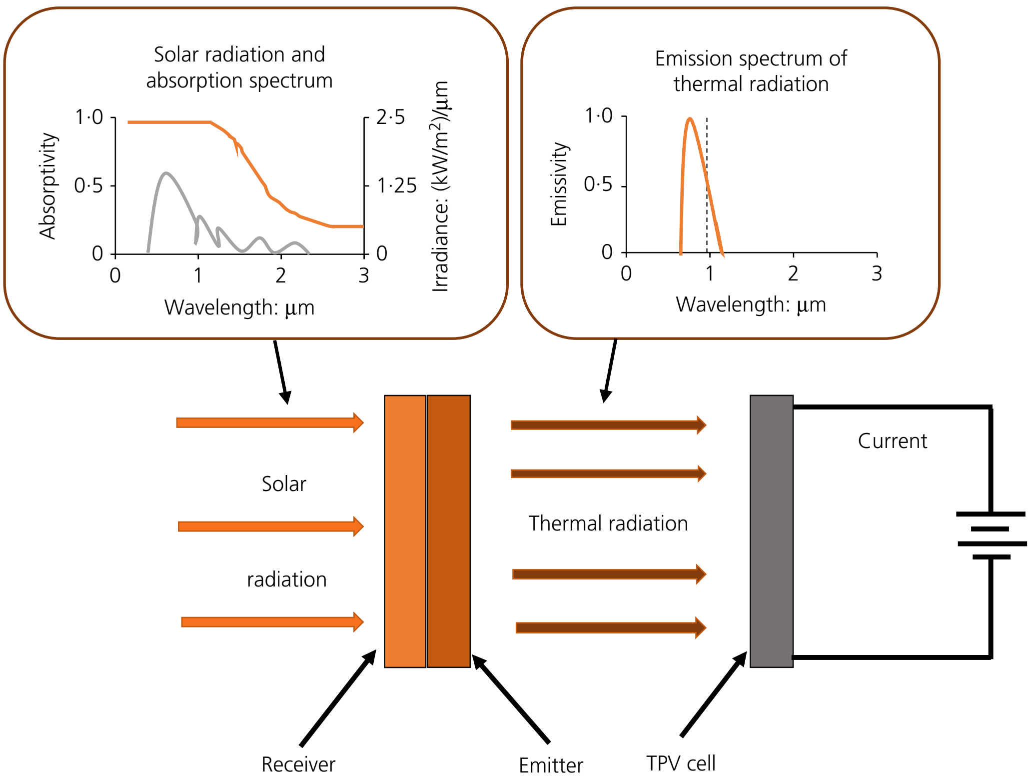

Figure 1. Solar TPV system

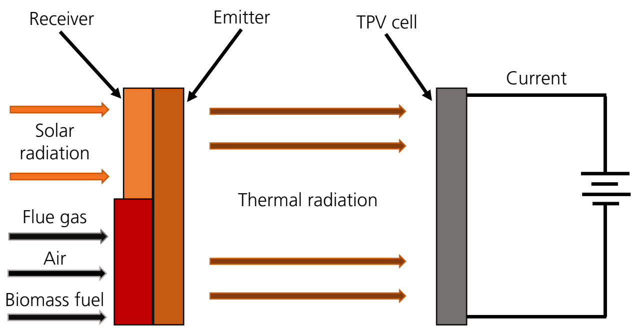

Figure 2. A hybrid solar–biomass TPV system concept

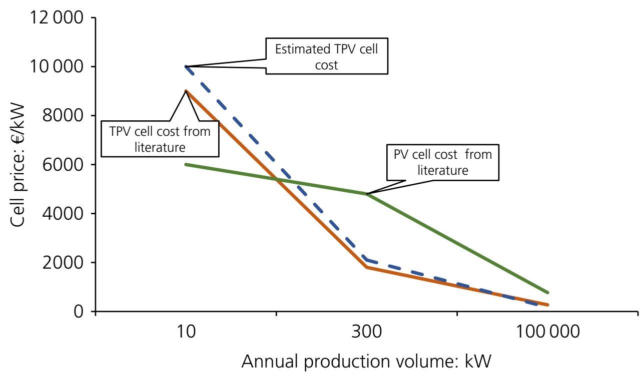

Figure 3. Potential cost reduction of TPV cells with increased production (source: Feldman *et al.* (2012), Fraas *et al.* (2014))

approximately €5000/kW represents a production volume of 300 kW/year which further reduces to approximately €500/kW when the production volume is increased to 10 MW/year.

3. Cost parameters

Assuming that the economies of scale in production, illustrated in Figure 3, do provide a substantial future cost reduction, the TPV cell prices of (*a*) €10/cm^2, (*b*) €5/cm^2 and (*c*) €1·25/cm^2 were assumed. A TPV cell price of €10/cm^2 was calculated to be equivalent to a €2083/kW installed cost. A €5/cm^2 TPV cell was equivalent to €1041 kW installed cost, and €1·25/cm^2 TPV was equivalent to the installed cost of €260/kW, illustrated in Figure 3 (calculated in Table 1).

A CSP–biomass Rankine cycle power plant model operating at 400°C was simulated using TRNSYS 17 software. This work used the fuel consumption profile from a relevant previous study (Hussain, 2019; Perilhon *et al.*, 2012) with fuel costs extrapolated

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Table 1. Economic parameters for hybrid TPV-based solar–biomass power plants

	TPV cost			
	€1·25/cm²	€5/cm²	€10/cm²	€50/cm²
Input cost				
Solar + biomass installed cost: €/kW	7000			
Solar + biomass installed total cost: €	8 400 000			
Other fixed costs: (€/kW)/year	200			
Operation and maintenance costs: (€/kW)/year	50			
Economic parameters				
Discount rate: %	9			
Capacity factor: %	85			
Plant capacity: kW	1200			
Plant lifetime: years	20			
Output system costs				
Total TPV cost: € for 250 000 cm² area	312 500	1 250 000	2 500 000	12 500 000
TPV cell cost: €/kW	***260***	***1041***	***2083***	***10 416***
Total investment cost: €	8 712 500	9 650 000	10 900 000	20 900 000
Overall energy cost: €/kW	7260	8041	9083	17 416

Bold/italic numbers indicate installed TPV cell cost obtained from validated results as presented in Figure 3

for higher-temperature TPV processes, as a solar–biomass TPV power plant operates at a higher temperature than a hybrid CSP–biomass Rankine cycle power plant. As current commercially available TPV cells have high band gaps that require high temperatures to operate optimally, this study considered higher system operating temperatures at 800 and 1200°C. The annual fuel costs for a TPV-based hybrid power plant were assumed to be (*a*) at €264/kW (or €0·031/kWh) for 800°C and (*b*) at €396/kW (or €0·046/kWh) for 1200°C. In a low-band-gap TPV cell, a higher power output can be obtained at a lower temperature (Chubb, 2007). This would approximately maintain a steady power output of a TPV-based power plant when considering power plant operation at different temperature ranges (Hussain, 2019). The maximum capacity of the TPV-based hybrid power plants studied in this work was assumed to be 1200 kW.

A solar tower concentrator power plant comprises tracking heliostats that concentrate solar radiation on a tower-located absorber. These, together with the cost of the required land and construction, give a capital expenditure estimated to be €3575/kW (Turchi, 2017). The installation cost of a biomass power plant was estimated to be €3500/kW (KAPSARC, 2014). Assuming savings of €75/kW arising from common shared equipment in a combined plant, this study calculated the overall capital expenditure would be €7000/kW for a hybrid solar CSP–biomass TPV power plant.

4. Economic analysis of a hybrid solar–biomass TPV power plant

4.1 Methodology

Power of 1200 kW was generated by a TPV cell area of 250 000 cm² as calculated using a TRNSYS 17 simulation model. At €1·25/cm², the total cost of the TPV cell was estimated to be €312 500, giving a TPV cell unit price of €260/kW. Therefore, the overall capital cost of a solar–biomass TPV power plant was estimated to be €7260/kW (i.e. capital expenditure of the solar–biomass power plant/kW + TPV cell price/kW = €7000/kW + €260/kW). Similarly the capital costs were estimated as (*a*) €8041/kW for TPV cell cost €5/cm², (*b*) €9083/kW for TPV cell cost €10/cm² and (*c*) €17 416/kW for TPV cell cost €50/cm². The system cost breakdown with different TPV cell prices is given in Table 1. The systems in Table 1 were each considered with annual fuel costs obtained from simulations of €132, €264 and €396/kW.

4.2 LCOE and sensitivity analysis of a hybrid solar–biomass TPV power plant

The LCOEs for the hybrid solar–biomass TPV power plant are ranked on the basis of (*a*) TPV cell price/cm² and (*b*) biomass annual fuel expenditure in Table 2.

The biomass fuel expenditure in Table 2 varied according to the amount of fuel consumed to maintain the required combustion temperature. High combustion temperature incurred higher biomass fuel expenditure, whereas lower-temperature operation required less fuel.

The LCOE of the hybrid power plant with a TPV cell price €50/cm² combined with any of the biomass fuel cost variations was found to be above €0·3/kWh as shown in Table 2. In previous studies, the LCOE of the state-of-the art hybrid CSP–biomass power plant was found to be in the range of €0·139–€0·175/kWh (Hussain, 2019; Servert and Miguel, 2011; Soares *et al.*, 2018). Thus, an LCOE above €0·3/kWh

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Table 2. LCOE in €/kWh of different hybrid TPV power plant configurations with varying economic parameters

Operating temperature	**400°C**	**800°C**	**1200°C**
Annual biomass fuel cost	€132/kW	€264/kW	€396/kW
TPV cell price			
€1·25/cm^2	0·16	0·18	0·20
€5/cm^2	0·17	0·19	0·21
€10/cm^2	0·19	0·21	0·23
€50/cm^2	0·31	0·33	0·35

Table 3. Variation of LCOE of different TPV hybrid plant configurations with fixed fuel price

	Annual fuel expenditure: €264/kW, operating temperature at 800°C								
	TPV cost: €1·25/cm^2			TPV cost: €5/cm^2			TPV cost: €10/cm^2		
	Lower limit	Base-case	Upper limit	Lower limit	Base-case	Upper limit	Lower limit	Base-case	Upper limit
Capacity factor: %	*90*	**80**	*70*	*90*	**80**	*70*	*90*	**80**	*70*
LCOE: €/kWh	*0·166*	**0·183**	*0·194*	*0·177*	**0·195**	*0·217*	*0·191*	**0·210**	*0·234*
Discount rate: %	*14*	**9**	*4*	*14*	**9**	*4*	*14*	**9**	*4*
LCOE: €/kWh	*0·150*	**0·183**	*0·219*	*0·160*	**0·195**	*0·236*	*0·170*	**0·210**	*0·257*
Capital cost: €/kW	*6534*	**7260**	*7986*	*7237*	**8041**	*8845*	*8175*	**9083**	*9991*
LCOE: €/kWh	*0·163*	**0·183**	*0·193*	*0·183*	**0·195**	*0·207*	*0·197*	**0·210**	*0·223*

Bold/italic numbers indicate installed TPV cell cost obtained from validated results as presented in Figure 3

might not be economically viable for TPV technology to be integrated into a commercial-scale hybrid power plant. TPV cell price at €10/cm^2 with an annual biomass fuel price of €396/kW (for 1200°C) gave an LCOE of €0·23 /kWh. The reduction of the annual fuel price of €132/kW (when operated at 400°C) could give a better LCOE of €0·19/kWh. A TPV cell price of €5/cm^2 with an annual biomass fuel expenditure of €396/kW produced an LCOE of 0·21/kWh that was found to be higher than the LCOE of the state-of-the-art hybrid CSP–biomass power plant. However, the LCOE was found to be much more economically competitive when the system operated at lower temperatures. For example, the LCOE with a TPV cell price of €5/cm^2 was found to be €0·19/kWh when it was operated at 800°C and €0·17/kWh when operated at 400°C. A TPV price of €1·25/cm^2 with lower TPV temperatures further improved the LCOE.

Although an annual fuel expenditure of €132/kW (at an operating temperature of 400°C) produced a lower LCOE, a TPV cell operating at such a lower TPV temperature is not commercially available. A low-band-gap TPV cell is under development that could enable a TPV operation at a low temperature under 800°C (Krier *et al.*, 2016). Therefore, in Table 3 systems with different TPV cell prices were compared along with a moderate fuel price of €264 applied at an operating temperature at 800°C.

The 'base-case' column presents the LCOE obtained with an 80% capacity factor and a 9% discount rate. The columns 'upper limit' and 'lower limit' indicate realistic upper and lower limits, respectively, for LCOE, when the capacity factor is varied by 10%, the discount rate is varied by 5% and the capital cost is varied by 10%. The base-case LCOE of hybrid TPV power plants was approximately 31–51% (from €0·183 kWh for €1·25/cm^2 to €0·21 kWh for €10/cm^2) higher than the base-case LCOE of the hybrid CSP–biomass Rankine cycle power plant (€0·139 kWh). A discount rate of 14% reduced the difference to between 8 and 22% (from €0·150 to €0·170 kWh) as shown in Table 3. A 10% variation of the capacity factor and the initial capital cost did not affect LCOE as significantly as it was affected by the change in the discount rate. Percentage variations of LCOE due to the changes in different techno-economic parameters are presented in Figure 4. As it can be seen, the best case was found with the TPV cell being operated at 800°C at a price of €1·25/cm^2.

For a €5/cm^2 TPV cell price, the changes in LCOE from different annual biomass fuel expenditures due to different temperature operations are shown in Table 4. Annual biomass fuel expenditure of €396/kW produced an LCOE of €0·215/kWh as shown in Table 4. The LCOE is low when the cost of fuel consumed is low; an LCOE of €0·195/kWh corresponded to an annual fuel expenditure of €264/kW, while an

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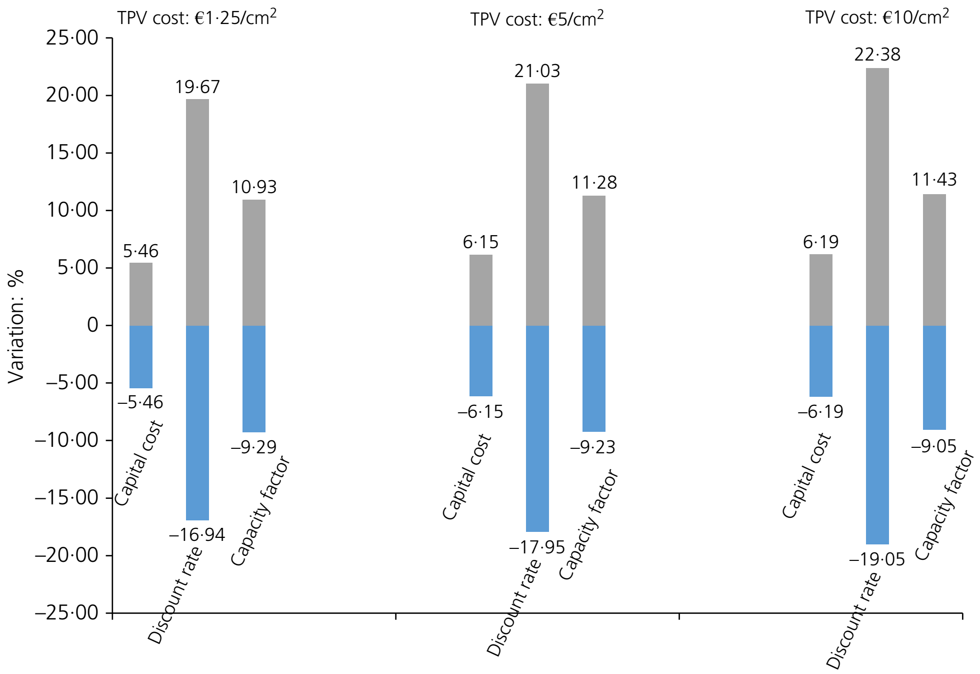

Figure 4. Percentage variation of LCOE of a hybrid TPV power plant with variable TPV cell price at an operating temperature of 800°C

Table 4. Variation of LCOE of different TPV hybrid plant configurations with fixed TPV cell price

	TPV cost: €5/cm²								
	Annual fuel expenditure: €132/kW (operating at 400°C)			Annual fuel expenditure: €264/kW (operating at 800°C)			Annual fuel expenditure: €396/kW (operating at 1200°C)		
	Lower limit	Base case	Upper limit	Lower limit	Base case	Upper limit	Lower limit	Base case	Upper limit
Capacity factor: %	*90*	**80**	*70*	*90*	**80**	*70*	*90*	**80**	*70*
LCOE: €/kWh	*0·159*	**0·175**	*0·194*	*0·177*	**0·195**	*0·217*	*0·196*	**0·215**	*0·239*
Discount rate: %	*14*	**9**	*4*	*14*	**9**	*4*	*14*	**9**	*4*
LCOE: €/kWh	*0·139*	**0·175**	*0·216*	*0·160*	**0·195**	*0·236*	*0·181*	**0·215**	*0·255*
Capital cost: €/kW	*7237*	**8041**	*8845*	*7237*	**8041**	*8845*	*7237*	**8041**	*8845*
LCOE: €/kWh	*0·163*	**0·175**	*0·187*	*0·183*	**0·195**	*0·207*	*0·203*	**0·215**	*0·227*

Bold/italic numbers indicate installed TPV cell cost obtained from validated results as presented in Figure 3

LCOE of €0·175/kWh corresponded to an annual fuel expenditure of €132/kW.

When the annual fuel cost of €132/kW was chosen, a 20·57% reduction from base-case LCOE of €0·175/kWh could make a solar–biomass TPV power plant potentially economically viable in the present hybrid power generation scenario (with a low LCOE of €0·139/kW), as can be seen in Figure 5. Variations of the capacity factor and the capital cost produced comparatively minor changes to the LCOE.

4.3 Rankine cycle and TPV systems comparison for solar–biomass hybridisation

The LCOE of a hybrid CSP–biomass Rankine cycle power generation system was compared with the LCOEs of a TPV-based hybrid solar–biomass power generation system. For the comparison, the two most promising TPV options given in Tables 3 and 4 were compared with the base-case LCOE of €0·139/kWh for the hybrid CSP–biomass Rankine cycle power plant (Hussain, 2019). The comparative results for two hybrid TPV–biomass systems and one

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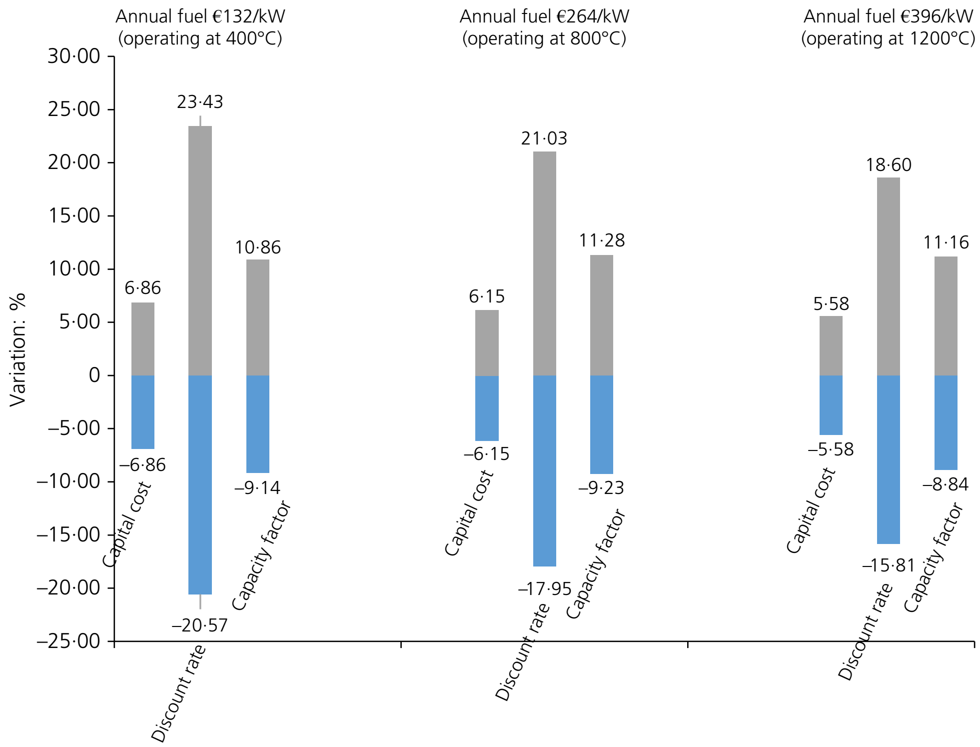

Figure 5. Percentage variation of LCOE of a hybrid TPV power plant with variable fuel expenditure

Table 5. LCOE comparison of CSP and TPV-based hybrid power plant

	CSP–biomass Rankine cycle			Solar–biomass TPV					
				TPV cost: €1·25/cm²			TPV cost: €5/cm²		
				Annual fuel expenditure: €264/kW (operating at 800°C)			Annual fuel expenditure: €132/kW (operating at 400°C)		
	Lower limit	Base-case	Upper limit	Lower limit	Base-case	Upper limit	Lower limit	Base-case	Upper limit
Capacity factor: %	*90*	**80**	*70*	*90*	**80**	*70*	*90*	**80**	*70*
LCOE: €/kWh	*0·126*	**0·139**	*0·154*	*0·166*	**0·183**	*0·194*	*0·159*	**0·175**	*0·194*
Discount rate: %	*14*	**9**	*4*	*14*	**9**	*4*	*14*	**9**	*4*
LCOE: €/kWh	*0·112*	**0·139**	*0·169*	*0·150*	**0·183**	*0·219*	*0·139*	**0·175**	*0·216*
Capital cost: €/kW	*5400*	**6000**	*6600*	*6534*	**7260**	*7986*	*7237*	**8041**	*8845*
LCOE: €/kWh	*0·130*	**0·139**	*0·147*	*0·163*	**0·183**	*0·193*	*0·163*	**0·175**	*0·187*

Bold/italic numbers indicate installed TPV cell cost obtained from validated results as presented in Figure 3

hybrid CSP–biomass Rankine cycle system are illustrated in Table 5.

The base-case LCOE of both hybrid TPV–biomass power plants were higher than the CSP Rankine cycle hybrid power plant in Table 5. However, the lower-limit LCOEs of both TPV-based power plant configurations were economically competitive with the hybrid economical power plant with an LCOE of €0·139/kWh. The lowest LCOE of €0·139/kWh for a TPV-based hybrid solar–biomass power plant was found at a TPV cell cost of €5/cm^2 when operated at a lower operating temperature of 400°C, leading to a lower annual fuel expenditure of €132/kW at a discount rate of 14%.

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5. Conclusions

Biomass fuel consumption is directly related to the temperature required to use specific TPV cells. Therefore, using a low-band-gap TPV cell to operate a TPV system below 800°C incurs lower annual biomass fuel expenditure. Assuming other economic factors remain constant, a TPV cell which costs below €5/cm^2 is essential before solar TPV technology can be viable for deployment for solar thermal electric power generation.

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