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Thermo – Photo – Voltaic Generator Development

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Abstract

The growing demand of energy coupled with an increasing attention to the environmental impact have forced, in the last decades, toward the study and the development of new strategies in order to reduce primary energy consumptions.

The cogeneration (CHP) and the on-site generation (also known as distributed generation) could be the key strategy to achieve this goal; CHP systems allow to reduce the fuel consumption and pollutant emissions (in particular the greenhouse gases) compared to separate generation; moreover on-site-generation contributes to the reduction of the energy which is lost in electricity transmission, and increases the security in the energy supply.

In this scenario the Thermo–Photo–Voltaic generation (TPV) is obtaining an increasing attention; TPV is a system to convert into electrical energy the radiation emitted from an artificial heat source (i.e. the combustion of fuel) by the use of photovoltaic cells.

A domestic gas furnace based on this technology can provide the entire thermal need of an apartment and can also contributes to satisfy the electrical demand.

In this paper, the main research activities on thermophotovoltaic generation developed in the last years at Institute of Materials for Electronics and Magnetism (IMEM) of Italian National Research Council (CNR), of will be presented and discussed.

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Keywords: thermophotovoltaic generation, combined heat and power, efficiency optimization

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1. Introduction

A Thermo-Photo-Voltaic generator (TPV) is an innovative system to convert into electrical energy the radiation emitted from an artificial heat source (i.e. the combustion of fuel) by the use of photovoltaic cells. A scheme of a TPV is presented in Figure 1, in which the main components and energy fluxes are highlighted.

A TPV generator consists of an heat source, an emitter (EM), a filter (F) and a photovoltaic cells (PV) array; in Figure 1 also the combustion air pre-heating system using combustion products is sketched.

The main advantages of this energy system can be found in the (*i*) high fuel utilization factor (close to the unity thanks to its devices which allow the recovery of the most of the thermal losses and makes possible the use of TPV as a combined heat and power system), (*ii*) in the low produced noise levels (due to the absence of moving parts), (*iii*) in the easy maintenance (similar to a common domestic boiler) and in its (*iv*) great fuel flexibility. In fact, on this regard, it can be observed that the heat source of a TPV system can be provided by various fuel typologies such as fossil fuels (natural gas, oil, coke, etc.) municipal solid waste, nuclear fuels, etc; also the concentrated solar radiation can be used as TPV heat source [1, 2].

The main use of a TPV generator can be in the distributed combined heat and power generation, but also its application in the automotive sector, glass or other high temperatures industries has been analyzed in literature [3].

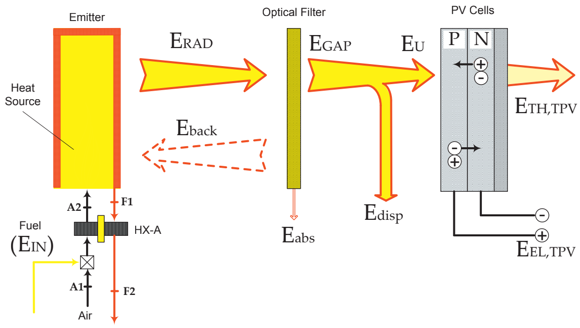


Fig. 1. Schematics of a Thermo-photovoltaic generator

The introduced heat source is converted into radiant energy (E_{RAD} in Figure 1) by the emitter; it can be observed that the radiant energy density can be up to 300-400 kW/m^2 (considering the emitter temperature from 1200 °C to 1400 °C). This last value is very high considering that the radiant energy density of the sun is equal to 1 kW/ m^2 at 45° latitude. The achievement of high temperature is a very important aspect since, according to Planck's law, radiation power density scales with temperature to the fourth power. Therefore, most heat sources used in TPV systems are based on combustion systems; various types of *premixed* and *not-premixed* combustors [4] or radiant tube burner [5, 6] have been developed in the last years. It should be considered that the aim toward high temperatures burner is limited by the NOx production; due to this evidence, the temperatures are usually limited up to 1300-1400 °C.

The radiant energy from the emitter has to be characterized by an emission spectrum suitable for the adopted photovoltaic cells; in fact only the photon energy in a narrow band above the bandgap of the photovoltaic cells can be converted into electrical energy. It follows that selective emission is required; in order to achieve this goal a *selective emitter* [7-10] or a *broadband emitter* with a filter can be used. In the first case the emitter is made with materials such as rare earth oxides which are characterized by an emission spectrum centred on specific wavelength; in the second case, many of the emitted photons, due to their lower energy on the respect of the bandgap of photovoltaic cells result unusable. It results imperative to send this photons back to the radiator in order to conserve heat and to reduce the fuel consumption to achieve the required emitter temperatures. Many types of filters have been developed such as plasma filters, dielectric stacks or back-surface reflectors [11-14]; also filters based on multiple layer of SiO2 have been realized [15, 16]. In conclusion, with reference to Figure 1, from the entire emitted energy (E_{RAD}) a portion (E_{GAP}) is filtered towards the photovoltaic cells and the remaining part (E_{back}) is reflected towards the emitter itself. The photovoltaic cells are the device which convert the incident radiation (E_U) into electrical energy ($E_{EL,TPV}$); in fact, as presented in Figure 1, it is observed that a fraction (E_{disp}) of the convertible radiant emission is not incident on the cells. The cells adopted in TPV generator are not similar to the traditional photovoltaic ones due to the different nature of the photon source. The need of absorbing the large amount of photons that is possible requires the use of semiconductors with low bandgap. Silicon based cells show a relative high bandgap (E_{gap}=1.11 eV, λ_{gap}=1.13 μm) and thus are not suitable for this application although their relative low cost [17-19]; others semiconducting materials such as Ga, GaSb, GaInAs, GaInAsSb show a lower bandgap [20-25]. Nevertheless these cells are actually very expensive and/or contain toxic components. Nowadays, the best compromise between costs and energy gap value is represented by Germanium (Ge) based cells, which results the most suitable for TPV applications. The amount of incident energy on photovoltaic cells which cannot be converted into electrical energy contributes to increase their temperature ($E_{TH,TPV}$ in Figure 1); this should be avoided because the conversion efficiency of the cells rapidly falls with the increase of temperature.

A comprehensive analysis about the current state of the art of TPV generation and a critical review of the prototypes which have been realized in the last years can be found in [26-28].

2. Electrical performance of a TPV generator

The scheme of a TPV generator in CHP configuration with the power balance of the system is presented in Figure 2. The introduced power with fuel (P_{in}), unless the thermal losses ($P_{fuel,loss}$) of the combustion process, is converted by the emitter and by the optical filter into radiant power ($P'_{GAP} = P_{RAD} - P_{back}$) and thermal power discharged with the gases ($Q_{TH,gas}$ in Figure 2 and sec. F_2 in Figure 1). A fraction of the radiant power (P'_{GAP}), which is in the useful range of wavelengths for the photovoltaic conversion (due to the optical filter selection), can be lost due to the absorption of the optical filter (P_{abs}, even if this term can be usually neglected) and for the view factor between filter and PV cells (P_{loss} this term can be reduced achieving values very close to zero with a optimal design of the system geometry). The radiant power incident on the photovoltaic cells ($P_U = P_{GAP} - P_{loss} = P'_{GAP} - P_{loss} - P_{abs}$) is then converted into continuous current ($P_{el,dc}$) and thermal power ($Q_{th,pv}$); except for the losses ($P_{el,loss}$) due to the inverter (INV in Figure 2) efficiency, the electrical power ($P_{el,ac}$) can be obtained from the system. On the other hand, the enthalpy content of the gases at the emitter exit ($Q_{TH,gas}$ and sec. F_2 in Figure 2) can be partially recovered ($Q_{TH,cp}$) while the remaining part is discharged to the ambient ($Q_{th,d}$).

The electrical efficiency of a TPV generator can be written as:

$$\eta_{EL,TPV} = \eta_{CC} \cdot \eta_{RAD} \cdot \eta_{GAP} \cdot \eta_F \cdot \eta_{VF} \cdot \eta_{PV} \cdot \eta_{dc/ac} \cdot \quad (1)$$

where: η_{CC}: combustion efficiency; η_{RAD}: radiant efficiency; η_{GAP}: spectral efficiency; η_F: filter efficiency; η_{VF}: view factor efficiency; η_{PV}: cell efficiency $\eta_{dc/ac}$: inverter efficiency. From Eq. 1 it can be seen that in order to maximize the electrical efficiency of a TPV generator, two main strategies can be followed: the maximization of the spectral efficiency (which is defined as the product of the two partial efficiencies η_{RAD} and η_{GAP} in Eq. 1) and the maximization of the cell efficiency (η_{PV} in Eq. 1).

2.1. Optimization of emitter surface

One of the parameters that strongly influences the spectral efficiency in TPV generator is the emitter's surface [29-32]. As well known, in order to increase the electrical efficiency of the system is necessary the maximization of the power density of the system. Figure 3 from *a* to *d* shows the trend of spectral efficiency and emitter temperature as function of the emitter's surface for four configurations: (*i*) no optical filter and no air pre-heater, (Figure 3 *a*), (*ii*) perfect optical filter and no air pre-heater (Figure 3 *b*), (*iii*) no optical filter but air pre-heater, assuming the heat exchange efficiency (E) equal to 10%, 25% and 50% (Figure 3 *c*) and (*iv*) perfect optical filter and air pre-heater (Figure 3 *d*).

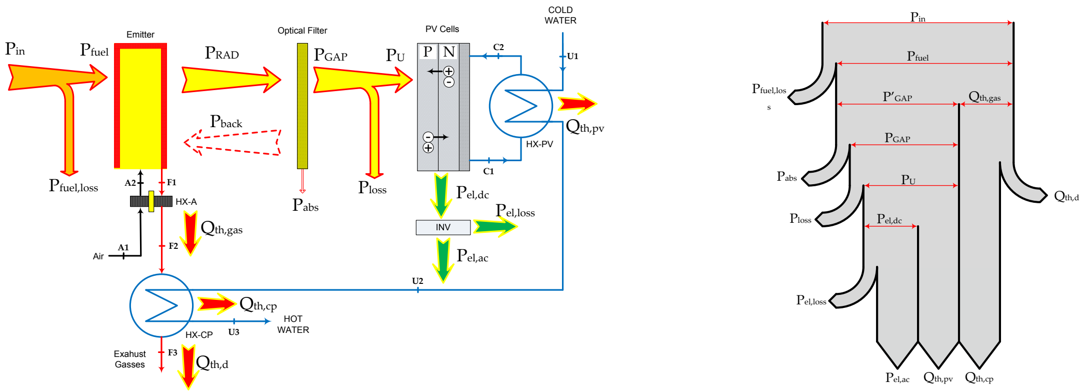
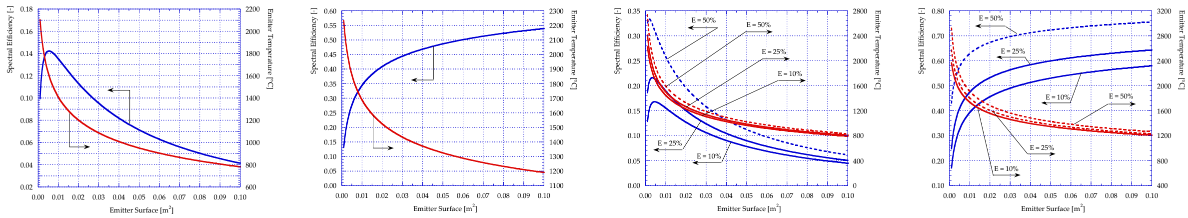


Fig. 2. Power balance of a TPV generator

In Figure 3 *a*, a maximum of the spectral efficiency equal to about the 14.20% can be found for an emitter surface equal to about 55 cm^2; these values correspond to a power density (also called burning rate and defined as the ratio between the introduced power with fuel and the emitter surface) of 1826 kW/m^2 and to an emitter temperature of approximately 1600 °C; further, it can be observed that the efficiency rapidly decreases as the emitter surface increases. In Figure 3 *b*, the obtained trend of the spectral efficiency does not show a maximum but a value equal to about 50.10% is reached for an emitter surface of about 600 cm^2 (corresponding to a power density of 167 kW/m^2 and an emitter temperature equal to 1288 °C); by further increasing the emitter surface, the efficiency increases only by a few percentage points. In Figure 3 *c*, considering the efficiency of the air-combustion products heat exchanger equal to 10%, a maximum value of spectral efficiency of 16.80% can be reached with an emitter surface of about 45 cm^2; the corresponding power density rises up to more than 2200 kW/m^2 achieving an emitter's temperature lightly greater than 1700 °C. If the efficiency of the considered heat exchanger grows up to 25%, a maximum value of the spectral efficiency of 21.61% can be found with an emitter's surface of about 35 cm2; a power density of about 2867 kW/m2 and an emitter temperature close to 1900 °C are obtained. It can be observed that in these cases the efficiency is rapidly decaying with the increase of the emitter area. Finally, in Figure 3 *d*, the results show very high value for what regards the spectral efficiency (more than 58% and up to 64% respectively for the efficiency of the air-combustion products heat exchanger equal to 10% and to 25%); the spectral efficiency is increasing slowly with the emitter surface but already with an emitter surface of 400 cm2 and a power density 250 kW/m2 a spectral efficiency of 58.44% (if E=25%) or of 51.35% (if E=10%) can be obtained with a value of emitter temperature of about 1429°C and 1394°C respectively.

On the basis of these observations, the developed analysis suggests that to improve the spectral efficiency, a TPV converter should be realized with a small area of the emitter surface in order to maximize the power density. In radiant burners this is usually equivalent to the firing rate that rarely exceeds 300 kW/m^2. This suggests that in an optimized TPV converter the combustion process should be separated by the emission process. Clearly the reduction of the emitter surface can affect its thermal exchange; this issue needs to be taken into account in the design process of emitter geometry. Another important observation is that optimized TPV generators with reduced emitter area may need less photocell area. Since the cost of the generator is essentially determined by the photocell area [33], the use of a smaller emitter area may reduce the estimated cost of the TPV converter and the corresponding payback time. This would also open the possibility of using more expensive and more efficient PV cells, such as, for instance, GaSb, or InGaAs MQW based PC cells.

The research activity on the emitter section of a TPV generator has been also conducted under the experimental point of view. As example, in Figure 4, a common domestic boiler with 28 kW of power introduced with fuel (Figure 4 *a*) with a radiant burner (Figure 4 *b*) modified with a quartz window for the emission spectrum measurements (Figure 4 *c*) is presented. It can be observed from that the maximum of radiant intensity is found at about 2000 nm of wavelength on the respect of the 500 nm of the solar radiation.



(*a*) (*b*) (*c*) (*d*)

Fig. 3. TPV electrical efficiency: (*a*) no optical filter and no air pre– heater; (*b*) perfect optical filter and no air pre– heater; (*c*) no optical filter but air pre– heater; (*d*) perfect optical filter and air pre– heater

(a) (b) (c)

Fig. 4. (a) TPV test facility, (b) radiant burner emitter, (c) measured spectra of radiant burner emitter in case of domestic boiler

2.2. Germanium Cells

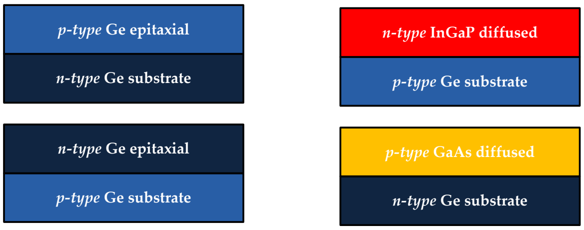
As previously said, the second approach that allows to increase the electrical efficiency of a TPV generator is the maximization of the PV cells conversion efficiency. in order to realize a system which is economically sustainable, Germanium based cells have been realized.

Germanium (Ge) cells are obtained by low-pressure Metal Organic Vapor Phase Epitaxy (MOVPE) deposition technique using H_2 as carrier gas. Two different methods were tested to fabricate the low-bandgap photovoltaic cells:

- homoepitaxial growth of *p-type* or *n-type* Ge onto, respetively, *n-type* or *p-type* Ge substrates (see Figure 5 *a*). In this case a dedicated Ge source (iso-butyle-germane) was used but the main drawback of this approach was the difficult of doping control of the epitaxial structure and the excessive diffusion of the dopant in the substrate, that results in a p/n junction not perfectly sharp. Also, it is difficult to reduce the background Ge doping below 5-10 x 1017 cm-3 and to growth both n-type and p-type germanium in the same growth run;
- because of reasons explained above, a more traditional approach is the heteroepitaxial growth of GaAs *p-type* or InGaP *n-type* on a Ge substrate doped respectively *n-type* or *p-type* (see Figure 5 *b*). In this case the layers are grown at high temperature (650-700°C) and the elements that constitutes the epitaxial layer diffuse in the Ge substrate during the growth itself, thus forming the p/n or n/p junction needed for the photovoltaic cell.

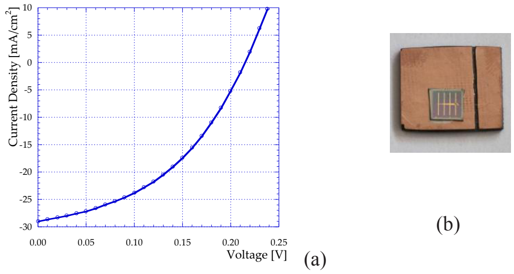
Once the junction is formed, electrical contacts are deposited on the structure by means of standard photolitography techniques and evaporation of AuZn or AuGe metal layers.

As example of the realized TPV cells, in Figure 6 *a* and *b* a Ge n-pyte cells doped with GaAs is presented togheter with the corresponding I-V characteristic. The realized cells, as presented in Figure 6 *a* shows a value of short circuit current lightly less than 30 mA/cm^2 and an open circuit voltage equal to 0.215 V; the resulting fill factor is equal to about 45% with a conversion efficiency (in standard AM1.5 conditions) less than 3%; this performance are consistent with the best PV cells realized up to now and reported in literature.



(a) (b)

Fig. 5. TPV cells structures obtainable with MOVPE



(a) (b)

Fig. 6. Realized TPV GE based cell

3. Combined heat and power performance of a TPV generator

From Figure 2 it can be seen that the thermal power produced by a TPV generator is based on heat recovery from both the cooling circuit of the PV cells ($Q_{TH,HX\text{-}PV}$) and the combustion products ($Q_{TH,HX\text{-}CP}$).

The thermal efficiency ($\eta_{TH,TPV}$) of a TPV generator can be expressed as:

$$\eta_{TH,TPV} = \frac{Q_{TH,HX-CP} + Q_{TH,HX-PV}}{P_{in}} \tag{2}$$

With reference to Figure 2, it can be written:

$$Q_{TH,HX-CP} = \dot{m}_{CP} \cdot \left(h_{gas,F2} - h_{gas,F3}\right) = \varepsilon \cdot \left(\dot{m}_{gas} h_{gas,F2} - \dot{m}_{air} h_{gas,F3}\right)$$
(3)

where ε is efficiency of the heat exchanger HX-CP; m_{gas} and m_{air} are respectively the mass flow rate of combustion products and of air; $h_{gas,F2}$, $h_{gas,F3}$ and $h_{air,A1}$ are the specific enthalpy of combustion products and air.

The previous relationship can be also written as:

$$Q_{TH,HX-CP} = \varepsilon \cdot Q_{TH,gas} \tag{4}$$

It follows, expressing $Q_{TH,gas}$ in Eq. 4, that:

$$Q_{TH,HX-CP} = \varepsilon \cdot \left(P_{fuel} - P'_{GAP}\right) \tag{5}$$

Further it can be obtained:

$$Q_{TH,HX-CP} = \varepsilon \cdot \eta_{CC} \cdot \left(1 - \eta_{RAD} \cdot \eta_{GAP}\right) \cdot P_{fuel} \tag{6}$$

The thermal power recovered from the cells cooling is equal (see Figure 2) to:

$$Q_{TH,HX-PV} = \left(1 - \eta_{PV}\right) \cdot P_U \tag{7}$$

The thermal power recovered from the PV cells array can be also written as:

$$Q_{TH,HX-PV} = (1-\eta_{PV}) \cdot \eta_{CC} \cdot \eta_{RAD} \cdot \eta_{GAP} \cdot \eta_{F} \cdot \eta_{VF} \cdot P_{in} \tag{8}$$

By introducing Eqs. 6 and 7 in Eq. 2, it can be obtained that:

$$\eta_{TH,TPV} = \frac{Q_{TH,HX-CP} + Q_{TH,HX-PV}}{P_{in}} = \eta_{CC} \cdot \left[\varepsilon \cdot (1-\eta_{RAD} \cdot \eta_{GAP}) + (1-\eta_{PV}) \cdot \eta_{RAD} \cdot \eta_{GAP} \cdot \eta_{F} \cdot \eta_{VF}\right] \tag{9}$$

The combined heat and power efficiency of a TPV generator is equal to:

$$\eta_{CHP,TPV} = \eta_{EL,TPV} + \eta_{TH,TPV} \tag{10}$$

which leads to:

$$\eta_{CHP,TPV} = \eta_{CC} \cdot \begin{bmatrix} \eta_{RAD} \cdot \eta_{GAP} \cdot \eta_{F} \cdot \eta_{VF} \cdot \eta_{PV} \cdot \eta_{dc/ac} + \\ + \varepsilon \cdot (1-\eta_{RAD} \cdot \eta_{GAP}) + (1-\eta_{PV}) \cdot \eta_{RAD} \cdot \eta_{GAP} \cdot \eta_{F} \cdot \eta_{VF} \end{bmatrix} \tag{11}$$

by introducing Eqs. 1 and 10 in Eq. 11.

3.1. Performance of a TPV generator in household sector

In order to understand the behavior of a TPV in CHP application in case of residential buildings, under both the energetic and economical point of view a parametrical analysis has been developed and discussed varying the TPV electrical efficiency, the thermal request and the apartment typology [34]. More in details, in this analysis two TPV generators have been considered (respectively named TPV#1, with an electrical efficiency equal to 10.0% and a thermal efficiency equal to 81.0% and TPV#2 with an electrical efficiency equal to 5.0% and a thermal efficiency equal to 86.5%) and two different electrical loads (named scenario#1 and scenario#2 characterized by an yearly electrical demand equal to 20 kWh_{EL}/m^2/year and 40 kWh_{EL}/m^2/year respectively) which are typical of Italian household sector. Some of the results of the developed simulations conducted with an hourly basis for an entire year, are presented in Figure 7 *a* and *b* in which the values of the primary energy saving (PES) as function of the yearly primary energy consumption (PEC) for space heating and hot water are presented with reference to the considered cases. It can be noted that due to the assumptions regarding the TPV generator performance, the value of PES, for a given thermal and electrical efficiency is only influenced by the fraction of the total produced electrical energy which is self-consumed or sold to the network [34]. TPV#1 (Figure 7 *a*) shows a PES always greater than 10% for all the considered scenarios, but this value decreases with the diminution of the fraction of the produced electrical energy which is self consumed; in case of TPV#2, the value of PES results close to 6.8% as shown in Figure 7 *b*.

The same study [34] also shows that according to the tariff scenario which was taken into account, the yearly money saving in case of TPV#1 ranges from 2.5 €/m^2 (PEC=50 kWh/m2/year) to about 3.9 €/m^2 (PEC=150 kWh/m2/year) with an electrical load equal to 40 kWh_{EL}/m^2/year. The reduction of TPV electrical efficiency (TPV#2) heavily influences the yearly money saving which ranges from 1.8 €/m^2 (PEC=50 kWh/m^2/year) to less than 2.7 €/m^2 (PEC=150 kWh/m^2/year), always with reference to 40 kWhEL/m2/year of electrical load. Nevertheless these values can be considered significant for the analyzed cases. The results also show that the reduction of the user's electrical load (passing from 40 to 20 kWh_{EL}/m^2/year) produces a sensible decrease in the yearly money saving which assume a maximum value equal to 1.2 €/m^2 (TPV#2, PEC=150 kWh/m^2/year).

3.2. TPV integration with an Organic Rankine Cycle

In a TPV generator the produced electrical power is strictly connected to the thermal one as their ratio is almost constant and cannot be changed without severe loss in performance; the coupling between TPV and ORC [35, 36] allows to overcome this limitation and to realize a cogenerative system which can be regulated with a large degree of freedom changing the ratio between the produced electrical and thermal power.

The proposed system (Figure 8) TORCIS (***T***hermophotovoltaic ***O***rganic ***R***ankine ***C***ycle ***I***ntegrated ***S***ystem) is based on the integration of two energy systems: a thermo-photovoltaic generator and an organic Rankine cycle. This system was conceived by the three unity involved in this project which belong to the Institute of Materials for Electronics and Magnetism (IMEM) of the National Research Council (CNR), to the Department of Industrial Engineering (ENDIF) of University of Ferrara and to the Department of Mechanical Engineering (DIN) of University of Bologna.

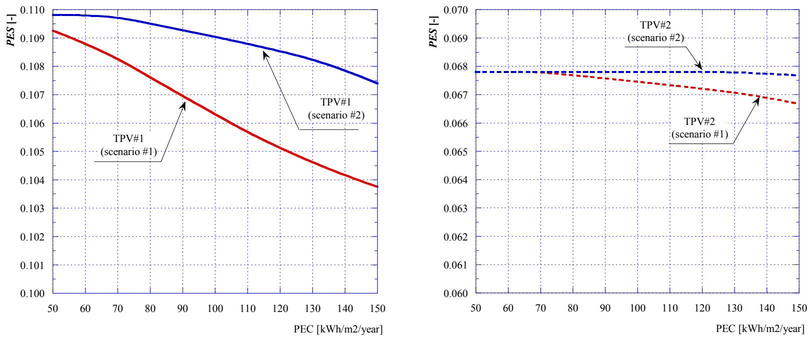


Fig. 7. Primary Energy Saving

With reference to Figure 8, it can be observed that TORCIS consists in a *topping* section (i.e. the thermo-photovoltaic generator) and a bottoming section (i.e. the organic Rankine cycle); the two section are coupled by a thermal energy storage (TS).

Combustion products from the regenerative heat exchanger (sec. F2) can be sent to the thermal energy storage and can be used for thermal energy production and/or electrical energy production by the use of the organic Rankine cycle. Thermal energy production is also realized by recovering the heat from the organic Rankine cycle condenser (COND in Figure 8) and from the photovoltaic cells cooling circuit (HX-PV in Figure 8). This last device requires further observations. It is well known that photovoltaic cells decrease their conversion efficiency with the increase of temperature: the fraction of radiant energy which cannot be converted into electrical energy results into heat. In order to maintain as constant as possible the performance of these devices a cooling circuit for the photovoltaic cells is required. This circuit concurs to the increase of the fuel utilization factor by increasing the conversion into electrical energy of the cells, on one hand, and by recovering the heat on the other hand. The disposition of the heat exchangers COND and HX-PV and of the thermal energy storage is realized in order to maximize the heat recovery efficiency for the hot water production for residential applications. The ORC allows the production of electrical energy by converting the enthalpy content of combustion products if they are not used for the thermal production.

The integration of the thermo-photovoltaic generator and of the organic Rankine cycle allows the achievement of great flexibility for what regards the ratio between the produced electrical and thermal energy. In fact, two operating configurations can be taken into account in order to represent respectively the system "*maximum thermal*" (MAX TH LOAD) and "*maximum electrical*" (MAX EL LOAD) production. In the first configuration (MAX TH LOAD), the heat recovery from the combustion products is completely used for the hot water production; it follows that the ORC is switched off and the electrical production is only realized by the thermo-photovoltaic furnace. In this case the TORCIS electrical efficiency coincides with the TPV electrical efficiency. In the second configuration (MAX EL LOAD) the whole enthalpy content of the combustion products is converted into electrical energy by the ORC system; as consequence, the hot water production is realized due to the heat discharged by both ORC and photovoltaic cells by the means of respectively ORC condenser and PV cooling circuit. On the respect of the previous configuration, the system electrical efficiency rises due to the ORC electrical efficiency while the thermal performance of the system obviously decreases.

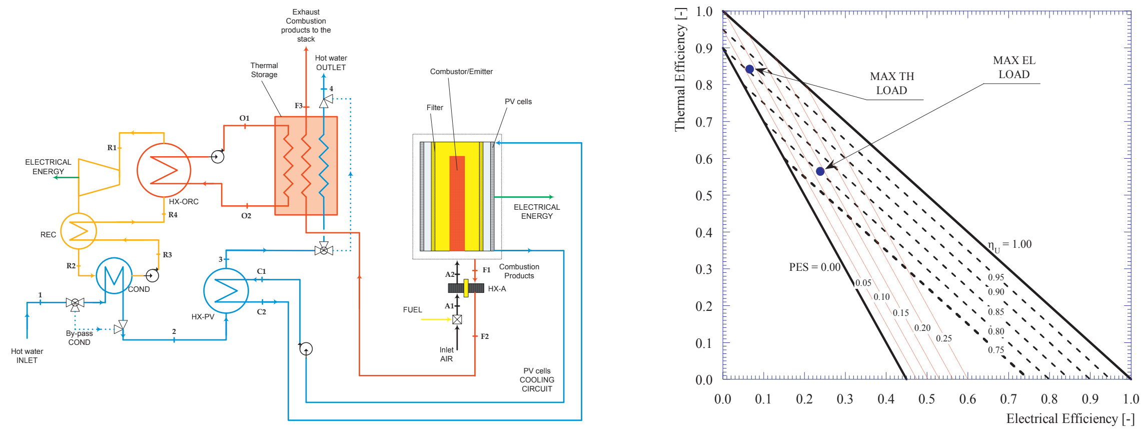


Fig. 8. Thermophotovoltaic Organic Rankine Cycle Integrated System – TORCIS – lay-out

4. Concluding Remarks

This paper highlights the main topics which have been developed in the last years for what regards the research activity on the thermo-photo-voltaic generation at the Institute of Materials for Electronics and Magnetism (IMEM) of the Italian National Research Council (CNR). The research has been conducted under both the experimental and the theoretical point of view. The main researches activities were directed through the developments of the TPV components (with a particular attention to the emitter and to the PV cells) but also to the analysis of the TPV generator performance in CHP configuration with reference to the domestic scenario. Further a novel system, based on the integration of a TPV generator with an organic Rankin Cycle has been defined, analyzed and discussed.

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