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Feasibility of a Photovoltaic-Thermoelectric Generator: Performance Analysis and Simulation Results

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Feasibility of a Photovoltaic-thermoelectric generator: Performance Analysis and

2	Simulation Results								
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14	Abstract - The paper describes a theoretical approach to evaluate the performance of a								
15	hybrid solar system made with photovoltaic cells and thermoelectric modules. After a brief								
16	treatment of the integrated system, energy conversion and performance parameters are								
17	evaluated through numerical simulations depending on the global radiation and temperature								
18	distribution obtained by the Joint Research Centre of the European Commission and of the								
19	National Renewable Energy Laboratory. The contributes of thermoelectric module to total								
20	energy seems significant in southern Europe towns and less substantial when the locations								
21	considered are very distant from the equator and show the possibility of using thermoelectric								
22	devices for energy production.								
23									
24	Keywords – Solar cells, photovoltaic solar energy, photovoltaic cell model, thermoelectric								
25	conversion, thermoelectric module model, conversion efficiency.								
26	TERMINOLOGY								
27	α temperature coefficient for short-circuit current [A/K]								
28	A _p photovoltaic module surface [m ²]								
29	At thermo-element area [mm ²]								
30	E _g energy band gap [eV]								
31	ε_{STC} efficiency at Standard Test Conditions (STC)								
32	ε efficiency								
33	$\mathcal{E}_{_{PVTE}}$ efficiency of photovoltaic- thermoelectric module								
34	$\varepsilon_{_{TE}}$ efficiency of thermoelectric module $\varepsilon_{_{PV}}$ efficiency of photovoltaic module								

35	FF	fill factor
36	G_{ref}	irradiance at STC [W/m ²]
37	G	irradiance on horizontal surface [W/m ²]
38	Ι	thermo-module current [A]
39	I_L	photo-generated current [A]
40	$I_{OD1,}I_{OD2}$	reverse saturation diode current [A]
41	I_{sc}	short-circuit current in STC [A]
42	\mathbf{I}_{mp}	current at maximum power point [A]
43	k	Boltzmann's constant [J/K]
44	h_t	thermo-element length [mm]
45	h_c	copper contact length [mm]
46	h_p	ceramic element length [mm]
47	h_s	ratio between contact superficial electric resistivity and the thermo-element electric resistivity [mm]
48	A_t	thermo-element area [mm ²]
49	n_1, n_2	ideality factor
50	S	thermocouple Seebeck coefficient [V/K]
51	λ	thermocouple thermal conductivity [W/mm K]
52	ρ	thermocouple electric resistivity [Ω mm]
53	ρ_c	contact superficial resistivity [Ω mm ²]
54	λ_p	ceramic isolator thermal conductivity [W/mm K]
55	P _n	nominal power of the photovoltaic of the solar generator [W]
56	$P_{out_{PV}}$	electrical power output of the PV module [W]
57	$P_{out_{TE}}$	electrical power output of the TE module [W]
58	$P_{out_{PVTE}}$	electrical power output of the PV/TE system [W]
59	Q	rate of heat liberated by the thermoelectric module [W]
60	Q_{TE}	rate of heat liberated by the thermocouple [W]
61	\mathbf{R}_{in}	thermo-module resistance $[\Omega]$
62	R_L	electric load resistance $[\Omega]$
63	R _s	series resistance $[\Omega]$
64	\mathbf{R}_{Sh}	shunt resistance $[\Omega]$
65	T_{ref}	cell temperature at STC [K]
66	T_{max}	maximum photovoltaic module temperature [K]
67	T_{amb}	ambient temperature [K]
68	T_{m}	operating temperature [K]
69	T_{avg}	average temperature [K]
70	T'_h	hot junction temperature [K]
71	T'c	cold junction temperature [K]
72	Т	cell temperature [K]
73	V	voltage [V]

 Vo
 thermoelectric generator open-circuit voltage [V]

 Voc
 open-circuit voltage in STC [V]

76 V_T thermal voltage [V]

77 V_{mp} voltage at maximum power point [V]

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I. INTRODUCTION

In recent years, the fast development and the growing demand of comfort is rising the 81 82 energy consumption; surging oil and gas consumption and increasing environmental awareness has prompted more and more sustainable development [1]; originally born as a 83 problem of ethics and morality, the development of the alternative energy sources became a 84 pressing requirement since the global pollution problem has become relevant. In the last 85 decade, photovoltaic (PV) technology has attracted strong interest of the industry and of many 86 87 researchers [2]. Research on solar cell was made since 1960 and different technologies have been proposed in order to reduce the material and to increase the production capacity. 88

At present silicon modules represent the leading PV technology thanks to both their capability to provide high efficiency and the great availability of silicon material on the earth. In particular monocrystalline solar cells offer highest efficiency with more that 20% [3]. Two alternative typologies developed to reduce the cost in PV modules production are *(i)* the polycrystalline silicon which provides worse performance in terms of efficiency (13-16%) and *(ii)* the amorphous silicon which offer low efficiency (6-9%) but is less affected by high temperatures and shading.

With respect to the PV cells based on crystalline silicon, thin film technology is less expensive since it uses few materials and less manufacturing process. Depending on the technology, thin-film module prototypes have reached efficiencies between 7–13% [4], [5].

Despite PV is considered a commercially mature technology, the efficiency of the PV plants is still quite low, therefore in the best of cases about 80% of the potential energy available would be wasted. On the other hand, this technology reduces continuously its cost and requires technical advance and new research for efficiency increment [6], [7]. Therefore, many researches have focused on the reduction of the losses that affect solar panels such as losses caused by the sunlight, the conditioning circuit required, the energy storage system, the Joule effect and so on [8], [9].

In order to reduce these effects, researchers are focusing on two strategies: to develop new
 materials or to try recovering part of the energy lost as heat by Joule effect [10], [11].
 Therefore, nowadays, panel's manufacturers have high interest in combining thermoelectric

(TE) and photovoltaic effects to obtain higher performance. The low efficiency of TE energy 109 conversion has limited the use of TE in electric power generation but this technology is 110 evolving to a higher level of performance [12]. On the other hand, TE generators are preferred 111 to recovery large amounts of waste heat or when the thermal input is free. Common 112 113 applications of this conversion are the energy recovery from the waste heat of electronic hot components or cooling and heating PV elements in order to increase its efficiency or 114 115 powering autonomous sensors [13]-[16]. Latest applications of the TE conversion are addressed to PV systems as active cooling or additional power generation of PV panels both 116 using the difference between the ambient temperature and high panel temperature caused by 117 the solar irradiation. The performance of a TE module is represented by the so-called figure of 118 merit (Z) of the TE material or by the dimensionless ZT_{avg} product [23], [24], being T_{avg} the 119 average temperature of the TE module. 120

The figure of merit Z represents the conversion efficiency from thermal energy into electrical energy and is strongly TE materials dependent. To optimize this parameter a large Seebeck coefficient, high electrical conductivity and low thermal conductivity are required.

For near room temperature applications (300 K) bismuth chalcogenides such as Bi₂Te₃ or Bi₂Se₃ materials provides the greatest figure of merit; for mid temperatures (500-900 K) Magnesium group IV compounds are mainly preferred; instead for high temperatures silicon – germanium materials are typically used.

Typical values of ZT_{avg} range in [0.7-0.8] but materials currently available reach values of 1; ZT_{avg} goes beyond of 1.2 for nanostructured bismuth antimony telluride bulk alloys [25]. In TABLE I. standard values of figure of merit are listed for different thermoelectric materials.

A hybrid photovoltaic-thermoelectric (PVTE) system can be found in many configurations 131 where the two modules can be separated or integrated. No integrated hybrid systems are 132 retrievable in cars [27], in some systems of harvesting energy, in particular types of 133 telecommunication applications [28]; in some cases, these two modules are separated 134 requiring an electronic controller [29], [30]. The integrated panels combine these devices in 135 order to optimize the performance of both sources [9]. In this paper the performances of an 136 integrated PVTE system was analyzed varying the site and using solar irradiation, temperature 137 and sunshine hours available on solar energy database of the European Joint Research Centre 138 [31]. Using databases of irradiance, temperature and other climatic parameters the authors 139 evaluate the annual performance of the PVTE system at different European sites analyzing the 140 additional TE power; the consistency of data used, with a ten years coverage over most of the 141

regions considered, assure the reliability of the obtained results and can provide informationto investors, authorities and renewable energy market.

For this aim, first the theory of PV and TE conversion is shortly summarized; then the model and the estimation algorithms of both photovoltaic and thermoelectric modules are implemented with Matlab functions and verified by simulating commercial modules.

 TABLE I.
 FIGURE OF MERIT FOR DIFFERENT THERMOELECTRIC MATERIALS [26]

Thermoelectric material	Material name	Manufacturing type	ZT _{avg}	Scenario Temperature	
	Bi ₂ Te ₃	bulk	0.74	low	
Chalcogenides	$Bi_{0.52}Sb_{1.48}Te_3$	bulk	1.05	low	
enaleogenides	$Bi_{0.52}Sb_{1.48}Te_3$	nanobulk	0.52	low	
	$Na_{0.0283}Pb_{0.945}Te_{0.9733}$	nanobulk	1.45	high	
Silicon-	SiGe	bulk	0.3	high	
germanium	Si ₈₀ Ge ₂₀	banowire	0.53	high	
germannann	SiGe	nanobulk	0.22	low	
	CeFe ₄ Sb ₁₂	bulk	0.77	high	
Skutterudites	$Yb_{0.2}In_{0.2}Co_4Sb_{12}$	bulk	0.93	high	
	$Ca_{0.18}Co_{3.97}Ni_{0.03}Sb_{12.40}$	bulk	0.77	high	
Oxides	Ca2.4Bi0.3Na0.3Co4O9	bulk	0.13	high	

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II. THE MODEL

151 A. System Layout and Assumptions

A schematic representation of the PVTE system is reported in Fig.1 where the two blocks represent the PV and the TE modules; the thermal energy generated in the first block is converted to electricity by the second block. These elements can be reasonably considered separately, since the effects that lead to the generation of current can be considered independent of each other; indeed, even if the TE module is posteriorly integrated into the solar panel, and it exploits the temperature of the rear of the panel itself, this phenomenon affects the solar cell performance in a reasonably negligible way.



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Fig.1 - PVTE hybrid system representation

The system operates at room temperature having as input the solar radiation and as output the total electric power generated by the system. At high solar irradiance the PV module temperature (T_{max}) can reach 50-60 °C and differs from room temperature by about 30°- 40° C (ΔT). These values depend on the site, the type of the integration and of the period of year considered. To calculate the PV panel temperature (T), which strongly depends on the incident light, the working conditions and the installation conditions, the following relation was used [32]:

$$168 T = T_{amb} + c \cdot G (1)$$

being *G* [W/m²] the irradiance and *c* [K·m²/W] a coefficient, known as the Ross coefficient, which depends on the installation conditions of the PV panel. The values of *c* are 0.058 K· m²/W for roof PV panels integrated, 0.036 K·m²/W for top of roof with small roof-module distance (<10 cm), 0.027 K·m²/W for on top of roof with large roof-module distance (> 10cm), and 0.020 K·m²/W for free-standing.

In TABLE II. the obtained values for the six considered sites [31] are listed, where T_{max} represents the maximum value of the panel temperature and ΔT is the difference between T_{max} and T_{amb} at different *c* for each town considered.

- 177
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		T _{ma}	_x [°C]		ΔT [°C]					
City	c=0.058	c =0.036	c =0.027	c =0.020	c=0.058	c =0.036	c =0.027	c =0.020		
	$K \cdot m^2/W$	$K \cdot m^2/W$	$K \cdot m^2/W$	$K \cdot m^2/W$	$K \cdot m^2/W$	$K \cdot m^2/W$	$K \cdot m^2/W$	$K \cdot m^2/W$		
Pachino (Sicily)	60	48	43	39	32	20	15	11		
Taranto	58	46	41	38	31	19	14	11		
Rome	56	45	40	36	30	19	14	10		
Turin	50	41	37	34	26	16	12	9		
Glasgow	32	26	23	22	16	10	7	5		
Stockholm	37	30	28	25	18	11	8	6		

MAX VALUES OF MODULE TEMPERATURE AND TEMPERATURE DIFFERENCE AT DIFFERENT SITES FOR DIFFERENT PV INSTALLATION CONDITIONS

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The performance of the combined system should be given in terms of both generated electric power and overall system efficiency by highlighting their dependence on environmental conditions, such as temperature and radiation, and on physical properties of the used material.

Starting from these considerations the principle of superposition is therefore usable; then 186 the generated electrical power of the overall system will be the sum of the electric powers 187 generated by both modules. Under this assumption the overall efficiency of the system can be 188 calculated as the ratio between the sum of the generated electric powers by each module, and 189 the power of the input system, i.e. the solar radiation available to the PV module. In this case, 190 both the front face temperature (T) and operating temperature of TE (T_m) will determine the 191 PV and the TE module performance, respectively. Precisely, the temperature of the cells 192 within the PV module (T) will depend on the ambient temperature (T_{amb}) and on the incident 193 solar radiation flux (G); the operating TE temperature (T_m) will depend on rear panel 194 temperature (T_h) and on the ambient temperature (T_{amb}) . It is useful to note that there is a heat 195 flow (Q) going from the PV to the TE module which is dissipated through the latter. Finally, 196 in order to preserve the energy balance, the following losses should be considered: 197

inverter and other circuitries), which are not included in the model;

transformation losses due to conditioning circuits of the PV module (there are in fact

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- losses due to the Joule effect in the PV module;
- losses due to the Joule effect in the TE module;
- losses due to dispersion currents;
- convection losses.

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TABLE II.

205 B. PV MATHEMATICAL MODEL

The simplest equivalent circuit of a PV cell consists of p-n junctions with a current generator current having intensity dependent on the incident radiation power:

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$$I_{\rm L}(T,G) = I_{\rm SC}(T_{ref},G_{ref})\frac{G}{G_{ref}}\left[1 + \alpha \left(T - T_{ref}\right)\right]$$
(2)

where the parameter T points out the influence of the temperature on the solar cell. Both 209 simulation and characterization of PV cells require parametric estimation of the model's 210 parameters and many works are dedicated to this issue [33]; in [34] and an equivalent circuit 211 with its parameters evaluation is presented, whereas in [35] an equivalent circuit based on 212 double-diode representation is used. The mathematical model uses a current source having 213 intensity proportional to the incident radiance and two diodes simulating diffusion and 214 recombination processes. This accurate model highlights different physical characteristics 215 which are independent from each other: 216

217
$$I = I_{\rm L} - I_{0D1} \left[e^{\frac{(V+R_{\rm s}\cdot I)}{V_{\rm T}\cdot n_{\rm 1}}} - 1 \right] - I_{0D2} \left[e^{\frac{(V+R_{\rm s}\cdot I)}{V_{\rm T}\cdot n_{\rm 2}}} - 1 \right] - \frac{V+R_{\rm s}\cdot I}{R_{Sh}}$$
(3)

218 where:

219 •
$$V_T = k \cdot T/q$$

• q is the electron charge $(1.602 \cdot 10^{-19} \text{ C})$ and k the Boltzmann's constant $(1.38 \cdot 10^{-23} \text{ J/K})$;

- T is the absolute temperature (K) of the p-n junction
- *I*_{0D1} and *I*_{0D2} are the reverse saturation currents of the two diodes;
- n_1 and n_2 are the diodes ideality factors;
- R_s is the equivalent series resistance of the cell and R_{Sh} is the equivalent shunt resistance. 225

The saturation currents in model (3) depend on the intrinsic characteristics of the PV cell, 226 which in turn depend on several physical parameters that are not usually available for the 227 commercial PV arrays. The diode ideality factors values may be arbitrarily chosen but 228 generally the initial values $n_1=1$ and $n_2=2$ can be selected in order to identify the model. A 229 right estimation of these six parameters would be obtained by best fitting the model with a 230 real panel. In Fig.2 the first diode represents the recombination current in the almost-neutral 231 regions, while the second one represents recombination in the depletion region. In the same 232 figure, R_s is the series resistance including the silicon wafer, the contact resistance and, also, 233

the circuital resistance derived from connections to the terminals and thus, materially, represents losses by Joule effect. R_{sh} is the parallel resistance deriving from leakage currents at the solar cell edges and from the inhomogeneity of the surface's; it represents the losses due to leakage current towards ground. Both resistors make the characteristic curve less "rectangularly shaped" and they reduce the maximum output power. In an ideal solar cell, obviously the resistance values of R_s and R_{sh} should theoretically be zero and infinity respectively an assumption often used in the analysis and characterization of the panels.

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Fig.2 - Two diodes equivalent circuit of a PV cell



245
$$I_{\text{module}} = N_{\text{p}} \cdot I; V_{\text{module}} = N_{\text{s}} \cdot V$$

$$R_{\text{s} \text{ module}} = R_{\text{s}} \cdot N_{\text{s}} / N_{\text{p}}; R_{\text{sh module}} = R_{\text{sh}} \cdot N_{\text{s}} / N_{\text{p}}$$
(4)

where a string is made of N_s cells in series, and a module is composed by N_p strings in parallel with the hypothesis that all the cells are identical and are subjected to the same radiance and temperature. This kind of model, known in the literature as *seven-parameters model* (I_L , I_{OD1} , I_{OD2} , n_1 , n_2 , R_s , R_{sh}), was already analysed by the authors using the Newton-Raphson method and its applicability to different plants has been verified [37].

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252 C. TE MATHEMATICAL MODEL AND ITS VERIFICATION

The fundamental element of a TE module is the thermocouple which is realized with two legs of a different doped semiconductor material; they are made of n-type and p-type doped semiconductor doped and are connected to each other by a metal plate usually made of copper. In Fig.3 a generic TE module with N_{TE} thermocouples connected electrically in series and thermally in parallel is represented where h_p is the ceramic plate length, h_t and A_t are the length and the cross-sectional area of the thermo-elements and h_c represents the copper contact length.

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Fig.3 – Basic structure of a TE module

The thermal power extracted by a TE module is the result of the Peltier, Joule and Fourier effects which model this phenomenon by means of the Seebeck coefficient *s*, the electrical resistivity ρ and the thermal conductance λ of the material and of thermo-elements geometry as function of both hot-side T_h and cold-side T_c temperatures [38]:

269
$$Q_{TE} = N_{TE} \left[\lambda \frac{A_t}{h_t} \left(T_h - T_c \right) + s \cdot T_h \cdot I - \frac{1}{2} R \cdot I^2 \right]$$
(5)

being *I* the thermo-module current and $R = \rho \cdot h_t / A_t$. Equation (5) is a simplified model of a TE module which consists of two semiconductor thermo-elements connected by conducting copper strips. A more accurate and realistic model requires to consider the thermal and electrical contact resistances between the thermo-elements and the ceramic plates. Precisely, the effect associated with ceramic layers, reduces the effective temperature difference across the two ends of the thermocouple according to:

276
$$\Delta T = T'_{h} - T'_{c} = \frac{T_{h} - T_{c}}{\left(1 + 2\frac{\lambda \cdot h_{p}}{\lambda_{p} \cdot h_{t}}\right)}$$
(6)

where the effects related to the connected load should be considered. Really, if a resistive load is connected across the TE module terminals, an electrical current depending on the resistor value will flow in the load; low resistance values will produce an increment of the current and as a result the cooling of the hot junction and heating of the cold junction. The reduction of ΔT caused by this effect is dependent on the operating temperature and on the thermoelectric module properties and can be generally neglected.

Similarly, accounting for the electrical contact's contribution R_c , the total electrical resistance of TE module can be expressed as:

285
$$R_{TE} = R + R_c = \frac{\rho \cdot h_t}{A_t} + 2\frac{\rho_c}{A_t} = \frac{\rho(2 \cdot h_s + h_t)}{A_t}$$
 (7)

being ρ_c the contact superficial resistivity and putting $h_s = \rho_c / \rho$. Combining (5), (6) and (7) a more accurate expression of thermal power extracted by a TE module is obtained: $Q_{TE} = N_{TE} \left[\lambda \frac{A_i}{h_i} (T'_h - T_c') + s \cdot T'_h \cdot I - \frac{1}{2} R_{TE} \cdot I^2 \right]$ (8)

Considering m TE modules connected electrically in series and thermally in parallel, the expression:

$$291 \qquad Q = m \cdot Q_{TE} \tag{9}$$

takes into account the heat flow passing through the thermocouple in steady state calculatedas the sum of these three effects.

The first term in (8) accounts the heat conduction relevant to the temperature difference, the second one is the result of Peltier effects and the third term is representative of the Joule heating effect. Under these hypotheses, the current *I*, flowing in the electric load R_L connected to the TE generator, is given by:

298
$$I = m \frac{V_{TE}}{R_{in} + R_L} = \frac{V_o}{R_{in} + R_L}$$
(10)

where R_{in} is the internal electrical resistance of the TE generator, given by

$$300 R_{in} = m \cdot R_{TE} (11)$$

301 and
$$V_o = m \cdot V_{TE} = m \cdot s \cdot N_{TE} \left(T'_h - T'_c \right) = m \cdot s \cdot N_{TE} \frac{\left(T_h - T_c \right)}{\left(1 + 2 \frac{\lambda \cdot h_p}{\lambda_p \cdot h_t} \right)}$$
 (12)

the open-circuit voltage. The electric output power of the overall system is then [39]:

303
$$P_{out_{TE}} = \frac{V_o^2 \cdot R_L}{\left(R_L + R_{in}\right)^2}$$
 (13)

and varies with R_L having a maximum when the load resistance match the internal resistance. Therefore, the load resistance value affects both the power generation performance and the Peltier effect at the interface with a change of temperature across the module. Particularly, in the case $R_L = R_{in}$ the maximum power transfer is realized with a negligible Peltier contribution to temperature reduction.

The electrical quantities in (10)-(13) are defined in terms of three materials properties 309 (s, ρ, λ) that usually are not provided by manufacturers and vary with operating temperature. 310 Generally, every manufacturer specifies the TE module producing performance curves, 311 performance specifications $(Q_{TE_{max}}, I_{TE_{max}}, \Delta T_{max}, R_{TE})$ and some geometrical parameters. 312 The parameters (s, ρ, λ) can be accurately determined using experimental setup or using 313 some theoretical equations [24], [40], [41]. Alternatively, these TE coefficients can be 314 modelled, supposing a uniform temperature along the side of the module and using the 315 operating temperature $T_m = (T_c + T_h)/2$ of the TE, by means of a second-order polynomials 316 equation [42] depending on the manufacturer: 317

$$s = a(T_m - 23)^2 + b(T_m - 23) + c$$
318 $\rho = d(T_m - 23)^2 + e(T_m - 23) + f$
 $\lambda = g(T_m - 23)^2 + h(T_m - 23) + i$

$$a = -9.90 \cdot 10^{-10} [V/K^3]; b = 3.44 \cdot 10^{-7} [V/K^2]; c = 2.11 \cdot 10^{-4} [V/K];$$
(14)

$$d = -9.90 \cdot 10^{-10} [V/K]; b = 3.44 \cdot 10^{-10} [V/K]; c = 2.11 \cdot 10^{-10} [V/K];$$

319 with $d = 6.28 \cdot 10^{-11} [\Omega \cdot mm/K^2]; e = 5.35 \cdot 10^{-8} [\Omega \cdot mm/K]; f = 10.85 \cdot 10^{-6} [\Omega \cdot mm];$
 $g = 41.30 \cdot 10^{-6} [W / (mm \cdot K^3)]; h = -3.32 \cdot 10^{-3} [W / (mm \cdot K^2)]; i = 1.66 [W / (mm \cdot K)];$

where the values used are related to CP2-127-06 TE module [43]. The consistence of the values obtained throught (14) has been verified with Matlab simulations calculating the Seebeck coefficient *s*, the electrical resistivity ρ and the thermal conductance λ of the material on the basis the manufacturer's specifications ($Q_{TE_{max}}, I_{TE_{max}}, \Delta T_{max}, R_{TE}$); to this aim, three TE modules have been considered, i.e. Tellurex C2-30-1503, Marlov RC-12-4 and Kryotherm TB 127-1-1.0-1.3. They are designed for cooling and heating applications with geometrical, electrical and thermal parameters reported in TABLE III.

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TABLE III.

CHARACTERISTIC PARAMETERS OF THE CONSIDERED THERMOELECTRIC MODULES

Manufacturer	Model	Length [mm]	Width [mm]	Thickness [mm]	R _{TE} [Ω]	ΔT _{max} [K]	Qtemax [W]
Tellurex	C2-30-1503	30.00	30.00	3.70	3.85	341.15	34.1
Marlov	RC-12-4	29.97	29.97	3.43	3.20	339.15	36.0
Kryotherm	TB-127-1.0-1.3	30.00	30.00	3.60	3.20	342.15	34.5

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In TABLE IV. the values of (s, ρ, λ) estimated for the three TE module are reported.

331

TABLE IV. s, ρ, λ obtained by fitting manufacturer's specifications

Manufacturer	Model	S	ρ	λ
		[V/K]	$[\Omega mm]$	[W/mm K]
Tellurex	C2-30-1503	208.39e-6	10.07e-4	17.08e.3
Marlov	RC-12-4	209.24e-6	11.31e-4	16.07e.3
Kryotherm	TB-127-1.0-1.3	205.53e-6	10.06e-4	15.97e.3

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The goodness of the model has been verified using the specifications of the CP2-127-06 TE 333 module and comparing (see TABLE V. the results of (14) with the results obtained by using 334 the model in [44], [45] for different values of temperature; T_c values are the average 335 temperatures relevant to both coldest and the hottest month of the year and T_h values are the 336 front panel tempearature evaluated through (1) considering the environmental parameters of 337 the site (T_c, G) and PV panels installed on the top of roof with small roof-module distance 338 $(c=0.036 \text{ K} \cdot m^2/W)$. An in-depht analysis of the results shows that the maximum deviation of 339 the figure of merit $Z = s^2 / \rho \lambda$ between estimated using (14) and [44], [45] is less than 0.7%. 340

- 341 **TABLE V.** COMPARISON BETWEEN s, ρ, λ ESTIMATION BY (14) AND [44], [45] USING THE CP2-127-08 TE
- 342

SPECIFICATIONS

City	T₀ [°C]	Т _һ [°С]	<i>S</i> [V/K]	ρ [Ω mm]	λ [W/mm K]	<i>s</i> [V/K]	ρ [Ω mm]	λ [W/mm K]	
				Eq. (14)		[44], [45]			
Pachino	13	29	210.21e-6	10.74e-4	16.66e.3	210.26e-6	10.75e-4	16.66e.3	
(Sicily)	28	48	215.84e-6	11.64e-4	16.18e.3	215.89e-6	11.67e-4	16.19e.3	
Taranto	10	23	208.62e-6	10.50e-4	16.82e.3	208.67e-6	10.51e-4	16.83e.3	
i ai alitto	27	46	215.37e-6	11.56e-4	16.22e.3	215.41e-6	11.59e-4	16.22e.3	

Rome	9	21	208.08e-6	10.42e-4	16.88e.3	208.13e-6	10.43e-4	16.89e.3
Rome	26	45	215.05e-6	11.51e-4	16.24e.3	215.09e-6	11.53e-4	16.25e.3
Turin	5	17	206.63e-6	10.20e-4	17.05e.3	206.68e-6	10.22e-4	17.05e.3
Turm	25	41	214.25e-6	11.38e-4	16.30e.3	214.29e-6	11.40e-4	16.31e.3
Glasgow	5	9	205.14e-6	9.98e-4	17.23e.3	205.19e-6	10.02e-4	17.23e.3
on go	16	26	210.21e-6	10.74e-4	16.66e.3	210.26e-6	10.75e-4	16.66e.3
Stockholm	-1	3	202.85e-6	9.64e-4	17.52e.3	202.90e-6	9.71e-4	17.52e.3
Stockholm	19	30	211.41e-6	10.93e-4	16.54e.3	211.46e-6	10.94e-4	16.55e.3

344

Finally, substituting in (10) - (13) the parameters *s*, ρ , λ estimated throught (14) it is possible to obtain the electrical parameters of the TE module.

347 D. PVTE PERFORMANCE INDEXES

The mathematical model of the hybrid system is based on the integration of the PV cells with the TE modules previously described; the system combines radiation and thermal energy to produce electricity. In particular, the PV cells convert solar radiation into electricity whereas the TE modules transform the heat generated below the PV cells in electric power.

In this analysis it is assumed that the rear temperature of the panel almost equal to the temperature present on the front side of the panel itself and that the TE module posteriorly integrated into the PV panel with the hot junction at the same temperature of rear side of the panel and the cold junction at ambient temperature [14], [46], [47].

It is well known that when the PV module works at the maximum power point, its output power can be expressed as:

$$358 \qquad P_{out,max_{PV}} = I_{mp} \cdot V_{mp} \tag{15}$$

where I_{mp} and V_{mp} are the current and the voltage calculated at the maximum power point, respectively, even if environmental conditions can produce performances variation especially in PV plants where several modules are connected in string [48].

As regards the PV module, the efficiency assessed under the universally recognized standard test conditions (STC), is expressed in terms of the open-circuit voltage and the shortcircuit current, as:

$$365 \qquad \varepsilon_{_{PV_{STC\%}}} = \frac{FF \cdot I_{sc} \cdot V_{oc}}{A_{p} \cdot G_{STC}} \cdot 100 = \frac{I_{mp} \cdot V_{mp}}{A_{p} \cdot G_{STC}} \cdot 100 \tag{16}$$

where A_p and $FF = I_{mp} \cdot V_{mp} / I_{sc} \cdot V_{oc}$ are the area and fill factor of the PV panel, respectively. Under these assumptions, the efficiency of the PV module at a generic radiance (*G*) is expressed as:

$$369 \qquad \varepsilon_{_{PV_{\%}}} = \frac{I_{_{mp}} \cdot V_{_{mp}}}{A_{_p} \cdot G} \cdot 100 \tag{17}$$

while, the final yield, useful to compare different PV systems at the same operating site, is expressed as:

$$372 Y_{_{PV}} = \frac{E_{_{PV}}}{P_n} (18)$$

where E_{PV} is the average energy that the PV panel generates monthly or yearly and P_n is the 373 nominal power of the solar generator. TE performance varies significately with TE materials, 374 module geometry and contact properties; the maximum otput power depends on both the 375 amount of input heat and of the load resistance R_L which should be as close as possible to the 376 internal electrical resistance of the thermo-generator R_{in} . Moreover the conversion efficiency 377 increases with temperature difference and thermo-element length [49]. In relation to R_{in} , the 378 379 power output of the TE module increases with the number of the modules because the electric output power increases with "the square of m" while efficiency remains almost unchanged. 380

It could occur that when the current in the thermo-element increases, the component related to the Joule effect takes over on other energy components; this means a drastic performance reduction in terms of both efficiency and power. For this reason, when the TE module is forced to work under these conditions, it is preferred to increase *m*; obviously, this provides the physical limit for having no losses. However, where the space and the costs allow it, the use of multiple TE modules is advisable to increase the output power.

Finally, the TE global efficiency and the final yield can be expressed as:

388
$$\varepsilon_{TE} = \frac{P_{out_{TE}}}{Q}$$
(19)

In the proposed analysis m=37 TE modules integrated behind the PV panel have been considered. In this case the total generated power of the PVTE hybrid system is the sum of the power output of each system:

$$392 \qquad P_{out,max_{PVTE}} = P_{out,max_{PV}} + P_{out_{TE}}$$
(20)

393 with a conversion efficiency given by:

$$394 \qquad \mathcal{E}_{_{PVTE_{\%}}} = \frac{P_{out,max_{PV}} + P_{out_{TE}}}{G} \cdot 100 \tag{21}$$

Then, the energy generated by the PVTE hybrid system is calculated by summing the overall power at each single hour as:

$$397 \qquad E_{_{PVTE}} = P_{_{out,max_{PVTE}}} \cdot h \tag{22}$$

where h represents the hours of average radiance; so the final yield of the overall system performance is:

$$400 \qquad Y_{_{PVTE}} = \frac{E_{_{PVTE}}}{P_n} \tag{23}$$

401 according to IEC standard 61724 [50].

402

III. TEST PERFORMANCE AND RESULTS

The performance of the PVTE system was characterized considering global radiation data at different sites by evaluating power and energy generated, efficiency and final yield for PV, TE and integrated PVTE system.

The sites have been chosen to verify how performance varies when the irradiance and the temperature distributions reach higher values. The radiance (*G*), the sunshine hours (*d_h*) and the ambient temperature (T_{amb}) used in the model have been obtained by using the online database provided by the Joint Research Centre of the European Commission and of the National Renewable Energy Laboratory [31].

In order to have a global view of the performance of the system under consideration, the 411 data for each month of the year have been downloaded. For every day of each month the 412 system acquires the data at regular intervals of 15 minutes sunrises to sunset; for each 413 acquisition time the algorithm produces a mean of several measurements. TABLE VI. shows 414 the average data of global radiance, ambient temperature and hours of daily radiance for best 415 tilt solar panel. Data highlight that the towns closer to the equator have higher radiance and 416 temperature values with respect to northern one with very similar trends. Small differences 417 show Glasgow and Stockholm; in fact, during the coldest months of the year in Glasgow the 418 419 radiance and the temperature are higher than in Stockholm while in the warmer months it is the opposite. Finally, the average hours of radiance over a year shows that in the winter 420 months, the cities farthest from the equator have shorter days with respect to those in southern 421 Europe; vice versa in the summer months, the cities in northern Europe have longer days and 422 hence more hours of sunlight 423

In [38] an inclination angle of 0° was considered in order to verify the system performance with same initial conditions. Now, using best tilt angle, best performance should be estimated for each considered site.

	Stockholm		0	Hasgov	v	Turin		Rome		Taranto			Pachino (Sicily)					
Month	G [W/m ²]	T _{amb} [°C]	d _h [h]	G [W/m ²]	T _{amb} [∘C]	d _h [h]	G [W/m ²]	T _{amb} [°C]	d _h [h]	G [W/m ²]	T _{amb} [°C]	d _h [h]	G [W/m ²]	T_{amb} [°C]	d _h [h]	G [W/m ²]	T _{amb} [°C]	d _h [h]
Jan	98	-1,1	06:15	121	4,9	07:15	325	5,2	08:45	330	9,2	09:15	360	10,3	09:15	433	12,7	09:45
Feb	194	-0,8	08:45	187	5,4	09:15	436	7,3	09:45	409	9,9	10:15	417	10,6	10:15	490	13,0	10:15
Mar	253	1,3	11:15	259	6,8	11:15	441	10,9	11:45	426	11,9	11:45	444	12,3	11:45	497	14,4	11:45
Apr	303	6,2	14:15	310	8,6	13:30	411	13,5	13:15	446	14,4	12:45	459	15,1	12:45	508	16,5	12:45
May	352	11,1	16:00	313	11,6	15:30	402	18,6	14:15	449	19,6	14:15	458	20,4	14:15	497	21,0	13:45
Jun	300	16,0	17:30	276	14,2	16:30	403	22,7	15:00	460	23,8	14:45	468	24,7	14:45	496	25,3	14:15
Jul	309	19,2	17:00	273	16,1	16:00	445	24,6	14:30	509	26,0	14:15	507	27,3	14:15	541	27,8	13:45
Aug	293	19,1	14:45	263	16,2	14:30	437	24,0	13:45	524	26,0	13:15	527	27,0	13:15	546	28,0	13:15
Sep	269	14,4	12:15	242	14,3	12:15	437	24,0	13:45	478	22,1	12:15	481	23,0	12:15	517	24,8	12:15
Oct	196	8,8	09:45	186	11,0	10:15	354	15,8	10:45	424	18,9	10:45	448	19,6	10:45	506	21,9	10:45
Nov	127	3,7	07:15	159	7,7	07:45	302	9,9	09:15	363	14,1	09:15	367	15,0	09:45	461	17,8	09:45
Dec	61	0,2	05:45	113	4,9	06:45	333	6,0	08:15	331	10,5	08:45	383	11,7	08:45	437	14,4	09:15
Best Tilt [°]		41			38			39			35			34			33	
Azimut [°]	0			0			0			0			0			0		
Latitude	tude 59°19'44" North		"North 55°57'2" Nord		lord	45°4'15" North		41°53'34" North		40°27'56" Nord		36°42'43" North						
Longitu de	18°:	3'53" E	ast	4°6	34" Ov	vest	7 °4	41'8" E	ast	12°2	8'57" 1	East	17°	14'52 1	Est	15°	5'33" I	East

427 TABLE VI. GLOBAL IRRADIANCE, AVERAGE TEMPERATURE AND DAYLIGHT HOURS FOR THE CONSIDERED SITES

428

The tests have been conducted according to the hypotheses of *i*) solar module subjected to 429 uniform illumination without shadow zones, *ii*) equal rear and front panel temperature, *iii*) TE 430 431 hot junction temperature equal to rear temperature of the PV, iv) TE cold junction temperature equal to the ambient temperature (by assuming that the system is not working with an 432 additional cooling system). The PV panel front temperature is been calculated by equation (1) 433 using the value 0.036 K·m²/W for c and considering the monthly average data of temperature 434 and global radiation for each location at different times of the day. It is worth to underline that 435 there is a wide literature which analyses the correlation among temperature, weather 436 conditions and material properties and then several models for cell temperature have been 437 proposed as a function of the wind speed, solar radiation and ambient temperature in different 438 implicit and explicit equations [52]. The performance of the method has also been verified 439 using one PV panel and m=37 TE modules. The PV was a IP10P model by Istar Solar 440 consisting of $N_p = 2$ parallel-connected strings each composed by $N_s=36$ series-connected 441 polycrystalline silicon cells and provides a peak output of 10 W [53]; the dimensions of the 442

443 panel is 310 x 210 mm and its specifications in STC are listed in TABLE VII. The TE module 444 considered was a TGM 127-1.0-1.3 [54] composed by 127 thermocouples connected 445 thermally in parallel and electrically in series; the dimensions of the module is 30 x 30 mm; 446 the thermal and electrical parameters of TE are presented in TABLE VIII. The TE generator 447 was obtained considering thirty-seven TE modules connected electrically in series and 448 thermally in parallel so to cover about 2/3 of the rear side of the cells.

449

TABL	E VII. IP10P SPECIFICATION	S IN STC
Symbol	Parameter	Value
Рм	Maximum Power (MP)	10 W
V _{MP}	Voltage @MP	17 V
IMP	Current @MP	0.6 A
Voc	Open-circuit Voltage	21,6 V
Isc	Short-circuit Current	0.67 A
α	Current temperature coefficient	0.07 %/°C
β	Voltage temperature coefficient	-0.34 %/°C

450

451

TABLE VIII.TGM 127-1.0-1.3 PERFORMANCE

Symbol	Parameter	Value
$\Delta T_{\rm max}$	Maximum Temperature Difference	150 °C
T_c	Cold end Temperature	0° C
VTE	Voltage	2.5 V
ITE	Current	0.59 A
POUTTE	Power	21,6 V

452

In TABLE IX. annual power and energy have been reported for each site; the values are been obtained summing the monthly values of power and energy. The TE module is more performing and helpful in warmer countries and the latitude mainly affects the performance of the TE generator with respect to PV panel; in fact, the value of E_{PV} is halved moving from Pachino to Glasgow or Stockholm, whereas the E_{TE} is reduced by about 1/3.

458

459

	P _{PV} [W]	P _{TE} [W]	P _{PVTE} [W]	E _{PV} [Wh]	E _{TE} [Wh]	E _{PVTE} [Wh]
Pachino (Sicily)	1.737	239	1.976	20.198	2.792	22.989
Taranto	1.584	199	1.704	18.889	2.323	21.211
Rome	1.540	184	1.724	18.148	2.208	20.355
Turin	1.442	153	1.595	17.031	1.862	18.893
Glasgow	852	54	906	10.612	721	11.332
Stockholm	875	60	934	11.344	840	12.185

TABLE IX. ANNUAL POWER AND ENERGY CALCULATED FOR SITES CONDIDERED

460

These conclusions seem to be confirmed considering the effect of the power and energy 462 produced by TE with respect to PVTE system where the TE module contributes to total 463 energy from 12.2 % in Pachino to about 6.5 % in Glasgow and Stockholm (TABLE X.). It is 464 465 worth to note that the TE generator sited in Stockholm, in a time frame of an year, has better performance compared to the same TE generator in Glasgow despite Stockholm is more to 466 north of Glasgow. The final yield values reported in the same table, which represent the 467 annual produced energy normalised to rated power, are useful to compare the performance of 468 PVTE system for different configurations and sites. An in depth analysis of these data shows 469 that the final yield decrease no more than 45% for PV and up to 70% for TE. Same 470 performance can be achieved varying the number of thermo-modules. Other tests carried out 471 with the thermo-modules, and not reported in the paper for sake of brevity, seem to confirm 472 the exposed results. 473

474

TABLE X.

FINAL YIELD, POWER AND ENERGY CALCULATED FOR THE CONSIDERED SITES

	P _{TE} /P _{PVTE}	E _{TE} /E _{PVTE}	Y _{FTE}	Y_{FPV}
Pachino (Sicily)	12,11	12,14	50,30	2016,84
Taranto	11,70	10,95	41,85	1864,30
Rome	10,65	10,85	39,78	1815,46
Turin	9,57	9,86	33,55	1702,95
Glasgow	5,98	6,36	12,99	1061,98
Stockholm	6,39	6,90	15,14	1133,83

475

Finally, in TABLE XI. the values of the relative deviation percentage between the PV system and the hybrid system PVTE ($d_{_{PVTE}}$) calculated for each month of the year, are indicated.

479 The data highlight that $d_{_{PVTE}}$ ranges in the interval 7.78-16.08 for the cities of southern 480 Europe.

481

Month	Pachino (Sicily)	Taranto	Rome	Turin	Glasgow	Stockholm
Jan	11,69	9,16	8,51	8,39	3,85	2,31
Feb	12,90	10,80	10,37	11,16	4,91	4,48
Mar	13,37	11,93	11,26	11,33	6,21	6,08
Apr	13,79	15,55	12,09	10,62	7,50	7,54
May	14,05	12,89	12,50	10,67	8,37	9,44
Jun	14,03	13,64	13,19	10,98	7,05	8,22
Jul	15,70	14,48	14,82	12,51	7,23	8,17
Aug	16,08	14,97	14,93	12,06	6,59	7,76
Sep	15,03	13,61	13,64	12,06	6,07	7,25
Oct	13,90	12,50	11,35	9,73	5,17	4,79
Nov	12,55	10,00	9,41	7,78	4,43	3,63
Dec	11,75	9,92	8,55	8,22	4,18	0,98

 TABLE XI.
 PERCENTAGE PERFORMANCE " PVTE /PV" DEVIATION

The best performances are obtained in August in the Pachino city (green cell) even if the 484 TE power contribution is considerable in each site in the spring and summer months. Lower 485 performance are obtained in northern towns (Glasgow and Stockholm), especially in the 486 winter months; this unfavourable phenomenon happens in the particularly cold months of 487 January and December in the city of Stockholm (red cells). In the same table, cells in yellow 488 highlight that the maximum values are obtained, in all the cities, in the month of July or 489 August except in Glasgow and Stockholm in which they are obtained in May. Although the 490 TE module enhances annual PV performance, the extra cost of this device should be balanced 491 by the energy produced. TE devices price varies from manufactures to manufacturer and TE 492 493 materials keeps changing on with changing times. So, new products to the market bring fluctuation in TE price. Commercial modules are available in many size and with different 494 power; generally, the price reduces when the power increases and for large quantities. 495 Typical costs for TE generating modules varies from 2.40 to 6.80 \$/W, which is higher than 496 normal solar price of 0.58-1.28 \$/W [55]; so the global extra cost of about four-five times 497 higher than PV module makes less attractive current TE technology for this application and 498 requires new researches in order to increase the efficiency and reduce the cost of these 499 devices. However, the results suggest that to obtain systems with good reliability and cost-500 effective the design of a PVTE system should be tailored to location, individual requirements 501 and meteorological condition and that the optimal number of TE module is dependent on the 502 resistance of PV panel, on the type of components used and on the environmental parameters 503 of the site. 504

IV. CONCLUSIONS

In the paper a complete model to evaluate the performance of a PVTE hybrid system is 507 proposed and verified by simulation results. The obtained results seem to shown that the PV 508 module is the primary source of energy of the system, even if the TE contribution is 509 significant in southern Europe towns and that best performance are obtained for the locations 510 having high radiance and low ambient temperature. A detailed analysis of the results indicated 511 that the TE module produce good performance in the spring and summer months assuring 512 513 promising contribution of energy even if the load resistance, the meteorological conditions and site should be carefully considered. New further research in TE material seem to promise 514 high values of the figure of merit Z so to increase the TE efficiency up to 50%.; under this 515 assumption the TE technology would be a viable candidate for alternative power generation. 516

517

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