PERFORMANCE OPTIMIZATION OF A PVT THAT IS INTEGRATED INTO AN INDUSTRIAL COMPANY

Prof. Eng. **Aneta HAZI,** PhD[1], Prof. Eng. **Gheorghe HAZI** PhD[1],
Lecturer. Eng. **Roxana GRIGORE** PhD[1]

[1]„Vasile Alecsandri" University of Bacau.

REZUMAT. In lucrare este prezentat un model matematic de optimizare a unui sistem PVT integrat într-o unitate industrială, în care este folosită continuu caldura obținută din sistem. Funcția obiectiv a modelului este eficiența energetică globală şi eficiența exergetică globală a sistemului. Tinând seama de posibilitatea de variație, s-au ales 3 parametri independenți: înclinarea panourilor, debitul de apă în PVT şi configuratia serie-paralel a modulelor. Sunt prezentate câteva din restricțiile de tip egalitate care sunt relații de definiție a diferiților parametri dependenți. Restricțiile de tip inegalitate sunt date de domeniul de variație al parametrilor independenți. Este prezentată o simulare numerică care stă la baza concluziilor obținute în lucrare.

Cuvinte cheie: PVT, optim, eficiență energetică şi exergetică.

ABSTRACT. The paper presents a mathematical optimization model of a PVT system which is integrated in an industrial company, where the heat obtained from the PVT system is continuously used. The objective function of the model is given by the overall energy efficiency and overall exergy efficiency of the PVT system. Given the possibility of variation three independent parameters were chosen: inclination of panels, water flow in PVT and series-parallel configuration of PVT modules. Some equality constrains are presented as they define the various dependent parameters. The inequality constraints are given by the variation domain of the independent parameters. Based on the conclusions obtained in this work numerical simulation is presented.

Keywords: PVT, optimum energy and exergy efficiency.

1. INTRODUCTION

Solar energy as a renewable energy source is usually used for heat or electricity, in separate systems. Electrical efficiency of a PV system decreases due to the temperature increase in the module. Therefore, water or air was used to cool the modules. Heat obtained by these agents was used in various applications.

Different theoretical and experimental studies were performed on PVT systems that simultaneously produce electricity and heat. Most of these relate to the integration of PVT systems in buildings, where the heat obtained from the panels is used to heat the air in the building, [2], hot water heater, or, in combination with heat pumps, in heating systems [3].

This paper presents a mathematical model for optimizing the overall thermal and exergetic efficiency of a PVT system, considering as independent variables: the inclination of photovoltaic panels, the water flow in the PVT and the modules series-parallel configuration.

To understand the influence of the independent parameters on cell temperature, plate temperature and water temperature, relations for their calculation are presented, [4].

A numerical simulation is performed for the 12 panels, arranged in series-parallel configurations for 4 plane inclinations and 10 values of water flow in PVT. The simulation leads to useful conclusions for integrating such systems in industry.

2. MATHEMATICAL OPTIMIZATION MODEL

The mathematical optimization model is based on relations for calculating the electrical and thermal parameters of the system.

The cell temperature, t_c, the plate temperature, t_p and the outlet water temperature at the end of the collector t_{fe}, are calculated as in reference [4]:

$$t_c = \frac{(\alpha\tau)_1 \cdot G + U_{tc,a} \cdot t_a + h_{c,p} \cdot t_p}{U_{tc,a} + h_{c,p}} \quad (1)$$

$$t_p = \frac{(\alpha\tau)_2 \cdot G + h_{p1} \cdot (\alpha\tau)_1 \cdot G + U_{L1} \cdot t_a + h_{p,f} \cdot t_f}{U_{L1} + h_{p,f}} \quad (2)$$

$$t_{fe} = \left[\frac{h_{p2} \cdot (\alpha\tau)_m \cdot G}{U_{L,m}} + t_a \right] \cdot \left[1 - \exp\left(- \frac{F' \cdot S \cdot U_{L,m}}{D \cdot c_p} \right) \right] + t_{fi} \cdot \exp\left(- \frac{F' \cdot S \cdot U_{L,m}}{D \cdot c_p} \right) \quad [^0C] \quad (3)$$

where: $U_{tc,a}$ – heat transfer coefficient from top surface of cell to ambient, in W/(m^2 ^{0}C); $h_{c,p}$ - heat transfer coefficient from cell to absorber, in W/(m^2 ^{0}C); $h_{c,f}$ -heat transfer coefficient from blackened plate to flowing fluid, in W/(m^2 ^{0}C);); t_{fi} – inlet water temperature, in ^{0}C; G –global irradiance on a cell surface, in W/m^2; S- cell surface, in m^2; D – water flow in PVT, in kg/s; c_p – heat capacity of water, [J/(kg^{0}C)]; $(\alpha\tau)_1$, $(\alpha\tau)_2$, $(\alpha\tau)_m$, h_{p1}, h_{p2}, U_{L1}, $U_{L,m}$, F' – coefficiens that are determined with the relations presented in reference [1].

If several modules are connected in series, the inlet temperature of the next module is determined as a function of the outlet temperature of the previous module, with the following relation:

$$t_{fi2} = t_{fe1} - \frac{\Delta\Phi_{mm}}{D \cdot c_p} \quad [^0C] \quad (4)$$

where $\Delta\Phi_{mm}$ is the heat flux lost to air from the pipe connecting the modules, in [W].

The heat flux generated by the modules, ϕ_{pvt}, is computed with the relation:

$$\Phi_{pvt} = n_r \cdot \sum_{j=1}^{n_p} D \cdot c_p \cdot \left(t_{fe,j} - t_{fi,j} \right) \quad [W] \quad (5)$$

where: n_r is the number of rows in parallel; n_p – the number of modules in series in a row; j – number of the module in series.

The useful heat flux, ϕ_u, is taken from the heat exchanger, [5]:

$$\Phi_u = \eta_s \cdot \left(\Phi_{pvt} - \Delta\Phi_{ms} \right) = D_s \cdot c_{ps} \cdot \left(t_{se} - t_{si} \right) \quad [W] (6)$$

where: η_s is the efficiency of the heat exchanger, $\Delta\Phi_{ms}$ is the heat flux lost to air from the pipe connecting the modules to the heat exchanger, in [W]; D_s – water flow taken from the heat exchanger, in kg/s; c_{ps} – heat capacity of water, [J/(kg^{0}C)]; t_{si}, t_{se} – inlet and outlet water temperature, in ^{0}C.

The exergy flux taken from the heat exchanger, $\phi_{ex,c}$,is calculated with relation, [6]:

$$\Phi_{ex,c} = D_s \cdot c_{ps} \cdot \left[\left(t_{se} - t_{si} \right) - \left(273 + t_{r,ex} \right) \cdot \ln\left(\frac{t_{se} + 273}{t_{si} + 273} \right) \right] \quad [W] \quad (7)$$

where $t_{r,ex}$ is the reference temperature for the exergetic calculus, in ^{0}C.

Exergy of solar radiation is determined as in reference [7].

The average electric power produced by the PVT in a period τ, is determined as ,[4]:

$$P_{pvt} = G \cdot S \cdot \eta_{e,r} \cdot \left[1 - \beta \cdot \left(t_c - t_r \right) \right] \quad [W] \quad (8)$$

where: P_{pvt} – electric power generated by a PVT module, [W]; $\eta_{e,r}$ – electrical efficiency at the reference temperature; β - correction coefficient of efficiency; t_r - reference temperature, [^{0}C].

Monthly heat generated by PVT is calculated with the relation:

$$Q_{pvt,m} = 10^{-3} \cdot n_z \cdot \sum_{h=\tau 1}^{\tau 2} \Phi_{pvt,h} \quad [kWh/month] \quad (9)$$

where: m – number of the month, n_z – number of days in month, τ_1, τ_2 – solar radiation for the first, respectively the last hour of the day, $\Phi_{pnt,h}$ – heat generated by the PVT in an hour h, [Wh].

The other energy values (electricity, electric and heat loss, etc.) are calculated with relations of the form (9). Yearly energy is determined as the sum of monthly energy.

Overall energy efficiency of the system is calculated considering the average efficiency of electricity production in the power plant, $\eta_{CET} = 0.38$, with relation, [8]:

$$Ef = \frac{\eta_e}{\eta_{CET}} + \eta_t \quad (10)$$

where: η_e and η_t – electrical and thermal efficiency of the PVT system. The total energy is calculated with a similar relationship.

The total exergy is:

$$Ex_t = W_u + Ex_{cu} \quad [kWh] \quad (11)$$

where W_u – useful electricity, delivered to grid, in [kWh]; Ex_{cu} – exergy of useful heat, Q_u, in [kWh].

Losses of electricity and heat, electric and thermal efficiency, overall energy efficiency are determined with the relations from [8].

Overall exergy efficiency is calculated as:

$$Ef_{ex} = \frac{Ex_t}{C_{exs} \cdot G_{an}} \quad [kWh] \quad (12)$$

where C_{exs} is exergy coefficient of the solar radiation, [6].

The purpose of a PVT system is to generate electricity and heat. The correct information is that of the energy related to the same effect (as in rel.10).

To take into account the heat quality (the temperature of it) its exergy must be taken into account, rel (11). Electricity completely represents exergy.

Thus, taking into account the purpose of PVT systems, the objective function of the optimization process is to maximize energy and exergy efficiency.

Depending on location, the climate data (temperature) and the solar radiation available in a given period are known. This solar irradiation depends on the inclination of the PVT plane. Thus, the inclination angle is an independent parameter for the optimization procedure.

Water flow passing through the panel determines the cell temperature and the outlet water temperature.

Connecting different panels, series-parallel, leads to different electrical and thermal parameters.

Thus, the angle of inclination of the panels, water flow and connection panels can be modified and they are independent parameters in the optimization process.

Starting from these independent variables and using the above relations, other parameters are determined that, ultimately, lead to the overall energy and exergy efficiency that we want to maximize.

In conclusion, the optimization problem is formulated as:

-objective function:

$$Maximize = \begin{bmatrix} Ef = Eq.(10) \\ Ef_{ex} = Eq.(12) \end{bmatrix} \quad (13)$$

subject to:

$17^0 < \varphi < 50^0$

$0.02 < D < 0.2$

$(1/12) < (n_r/n_p) < (4/3)$

t_c, t_p, t_{fe}, ϕ_{pvt}, ϕ_u, $\phi_{ex,c}$, P_{pvt}, G_{an}, Q_u, Ex_{cu}, Ef_{ex}, *etc.*>0

and other constraint equations.

were: φ is the inclination of the plane, *D* and *np/nr* are independent variables and t_c, t_p, t_{fe}, ϕ_{pvt}, ϕ_u, $\phi_{ex,c}$, P_{pvt}, G_{an}, Q_u, Ex_{cu}, Ef_{ex}, *etc.* are dependent variables in the optimization process.

5. NUMERICAL RESULTS

Based on the mathematical model presented above, a numerical simulation was performed for a PVT of 12 modules of 190W electrictricity and 2320 W heat each. Heat is taken from the PVT system with a heat exchanger which provides hot water to the technological process in the industrial unit, as long as there is solar radiation. At other times, water circulation pumps are stopped. The numerical results obtained for the dependent parameters and for the objective function representing the variation of the three independent parameters are presented in the following tables and graphs. There are shown yearly values. The reference temperature for the exergetic calculus is 10 ^{0}C.

Table 1 shows the parameters variation for 4 of panel inclinations relative to the horizontal plane. Solar radiation values are valid for Bacau, Romania. The calculation is performed for a flow of water in PVT of 0.06 kg / s and a configuration of 2 rows / 6 panels.

Table 1

Variation of indicators depending on the inclination of the plane

Indicator	Symbol	U.M	Inclination, [^{0}]			
			17	**27**	**37**	**47**
Solar radiation	G_{an}	kWh	22488	23244	23492	23191
Electricity generated by PVT	W_{pvt}	kWh	3389	3500	3537	3496
Electricity for pumping	W_p	kWh	81	80	81	81
Loss of electricity	ΔW	kWh	48	49	49	49
Useful electricity	W_u	kWh	3263	3374	3410	3369
Heat generated by PVT	Q_{pvt}	kWh	8630	8879	8989	8880
Loss of heat from pipeline	ΔQ	kWh	13	15	15	14
Useful heat	Q_u	kWh	7762	7985	8085	7988
Exergy of useful heat	Ex_{cu}	kWh	44	45	46	44
Overall exergy	Ex_t	kWh	3352	3465	3502	3459
Overall energy	W_t	kWh	16349	16864	17060	16855
Electrical efficiency of the system	η_e	%	14.51	14.52	14.52	14.53
Thermal efficiency of the system	η_t	%	34.52	34.35	34.42	34.44
Exergy efficiency of the heat	η_{ex}	%	0.21	0.21	0.21	0.20
Overall energy efficiency of the system	Ef	%	72.70	72.55	72.62	72.68
Overall exergy efficiency of the system	Ef_{ex}	%	15.91	15.91	15.91	15.92

Table 2

Variation of indicators depending on the water flow in PVT

Indicator	**Symbol**	**U.M**	**Water flow, [kg/s]**									
			0.02	**0.04**	**0.06**	**0.08**	**0.1**	**0.12**	**0.14**	**0.16**	**0.18**	**0.2**
Electricity generated by PVT	W_{pvt}	kWh	3398	3497	3537	3560	3574	3584	3591	3597	3602	3605
Electricity for pumping	W_p	kWh	65	72	81	92	107	126	153	180	217	261
Loss of electricity	ΔW	kWh	46	48	49	51	52	54	57	60	63	68
Useful electricity	W_u	kWh	3289	3379	3410	3421	3420	3411	3393	3369	3336	3294

Heat generated by PVT	Q_{pvt}	kWh	7009	8399	8989	9324	9543	9698	9816	9908	9983	10043
Loss of heat from pipeline	ΔQ	kWh	56	28	15	8	4	1	-1	-2	-4	-4
Useful heat o	Q_u	kWh	6294	7552	8086	8388	8586	8728	8833	8916	8984	9041
Exergy of useful heat	Ex_{cu}	kWh	28	40	46	49	51	53	54	55	56	57
Overall exergy	Ex_t	kWh	3317	3419	3456	3470	3471	3464	3448	3424	3392	3351
Overall energy	W_t	kWh	14949	16445	17060	17391	17586	17703	17763	17781	17762	17710
Electrical efficiency of the system	η_e	%	14.63	15.03	15.17	15.21	15.21	15.17	15.09	14.98	14.83	14.65
Thermal efficiency of the system	η_t	%	27.99	33.58	35.96	37.30	38.18	38.81	39.28	39.65	39.95	40.20
Exergy efficiency of the heat	η_{ex}	%	0.13	0.19	0.22	0.23	0.24	0.25	0.26	0.26	0.27	0.27
Overall energy efficiency of the system	Ef	%	66.48	73.13	75.86	77.33	78.20	78.72	78.99	79.07	78.98	78.75
Overall exergy efficiency of the system	Ef_{ex}	%	15.74	16.23	16.40	16.47	16.47	16.44	16.36	16.25	16.10	15.90

Table 3

Variation of the indicators depending on the panel configuration

Indicator	Symbol	U.M	Number of rows/number of panels			
			1/12	**2/6**	**3/4**	**4/3**
Electricity generated by PVT	W_{pvt}	kWh	3581	3574	3568	3563
Electricity for pumping	W_p	kWh	221	107	88	80
Loss of electricity	ΔW	kWh	64	52	50	50
Useful electricity	W_u	kWh	3311	3420	3434	3437
Heat generated by PVT	Q_{pvt}	kWh	9663	9543	9466	9411
Loss of heat from pipeline	ΔQ	kWh	3	4	5	6
Useful heat	Q_u	kWh	8696	8586	8515	8465
Exergy of useful heat	Ex_{cu}	kWh	53	51	51	50
Overall exergy	Ex_t	kWh	3364	3471	3484	3487
Overall energy	W_t	kWh	17410	17586	17551	17509
Electrical efficiency of the system	η_e	%	14.72	15.21	15.27	15.28
Thermal efficiency of the system	η_t	%	38.67	38.18	37.87	37.64
Exergy efficiency of the heat	η_{ex}	%	0.25	0.24	0.24	0.24
Overall energy efficiency of the system	Ef	%	77.42	78.20	78.05	77.86
Overall exergy efficiency of the system	Ef_{ex}	%	15.96	16.47	16.54	16.55

Note that solar radiation is maximum for an inclination of 37^0. Corresponding to this inclination, the useful and generated electricity, heat and heat exergy of the panels have maximum values, fig.1. The total energy and exergy of the system are maximal for the inclination of 37^0. The electrical and thermal efficiency, which are expressed as the ratio between electricity, useful heat and solar radiation, that have the same sense of variation, do not highlight the advantage of optimum inclination. Energy efficiency has a maximum value for 17^0 of inclination and the exergy efficiency – for 47^0, fig.2. So, the objective function does not lead to correct conclusions if the variable parameter is the inclination of the plane.

In Table 2 and fig. 3 and 4 there are shown the parameter variations when considering the water flow in the PVT as an independent parameter. For these calculations, the inclination of 37^0 and the configuration of 2 rows / 6 panels was considered.

Electricity generated by the PVT increases because

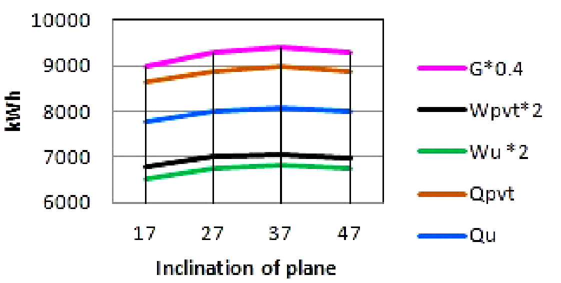

Fig. 1. Variation of indicators depending on the inclination of the plane: G – solar radiation; W_{pvt} – electricity generated by PVT; W_u – useful electricity; Q_{pvt} – heat generated by PVT; Q_u – useful heat.

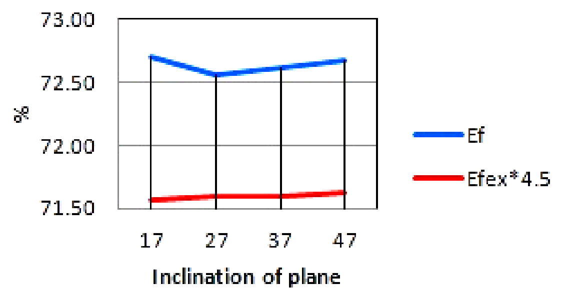

Fig. 2. Variation of indicators depending on the inclination of the plane: Ef – overall energy efficiency; Ef_{ex} – overall exergy efficiency.

the panels are cooled better when the water flow of the PVT increases, fig.3. But this also increases the electricity consumption for pumping. Thus, the useful electricity reaches a maximum value at a water flow of 0.1 kg/s.

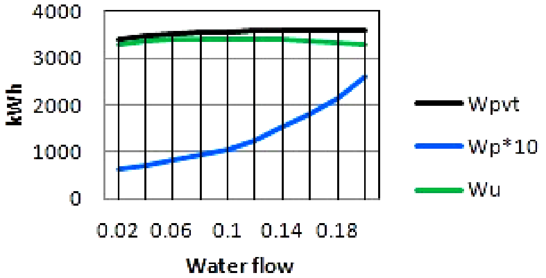

Fig. 3. Variation of indicators depending on the water flow in PVT: W_{pvt} – electricity generated by PVT; W_p – electricity consumed for pumping; W_u – useful electricity.

Useful heat and heat exergy of the system increases due to increased flow although the water temperature is lower. The minus sign for the heat loss indicates that the water receives heat from the environment. It should be noted that ground water is used which has an average temperature of 10 ^{0}C.

The total energy of the system is maximum for a water flow value of 0.16 kg/s and the total exergy - for a water flow value of 0.1 kg/s. Note that the objective function reaches optimal value for the same flow, fig.4.

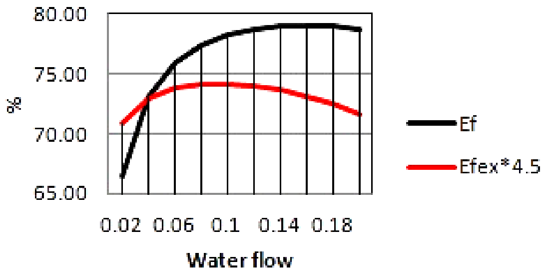

Fig. 4. Variation of indicators depending on the water flow in PVT: *Ef* – overall energy efficiency; Ef_{ex} – overall exergy efficiency.

The influence of modifying the PVT configuration with a different number of panels in series-parallel, is presented in Table 3 and fig. 5 and 6. For these calculations, an inclination of 37^0 and a water flow of 0.1 kg/s was considered. Note that electricity and heat generated by the PVT panels have maximum values for the one line configuration because the water flow through the PVT is maximum in this case. The pumping electricity consumption, on the other hand, is lower as the flow decreases in the PVT, and so the maximum useful power is obtained for the panels configured on several rows (4/3), fig.5.

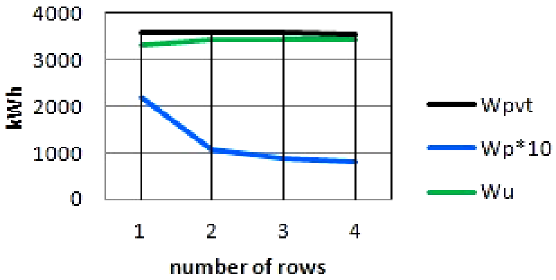

Fig. 5. Variation of indicators depending on the rows number: W_{pvt} – electricity generated by PVT; W_p – electricity consumed for pumping; W_u – useful electricity.

The heat exergy is maximum for a configuration of the panels on one line, when a maximum water temperature in the PVT is obtained, fig.6.

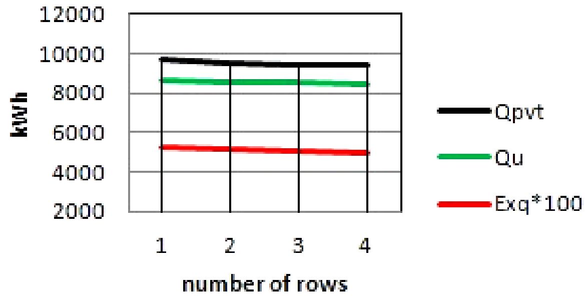

Fig. 6. Variation of indicators depending on the rows number: Q_{pvt} – heat generated by PVT; Q_u – useful heat; Ex_q – exergy of useful heat.

The overall energy efficiency is maximum for a configuration on two rows of six panels and the maximum overall exergy efficiency as well as the maximum useful electricity are obtained for a configuration of 4 rows /3 panels, fig.7.

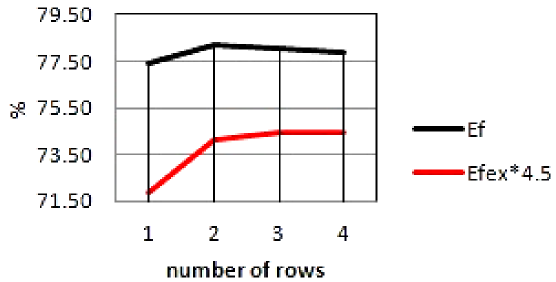

Fig. 7. Variation of indicators depending on the rows number: *Ef* – overall energy efficiency; Ef_{ex} – overall energy efficiency.

6. CONCLUSIONS

From the numerical results presented in this paper, the following conclusions can be drawn:

- Using the overall energy and exergy efficiency as an objective function does not lead to a correct conclusion when using inclination of plane as an independent parameter. In this case, the maximum useful energy and exergy give accurate indications of the optimum inclination advantage.
- Since electricity is fully exergy, using the overall exergetic efficiency of the system as an objective function we obtain maximization of useful electricity. If we are interested in the temperature of the heat, then we must maximize the exergetic efficiency of the heat.
- The maximum overall energy efficiency of the system, of 79.07, was obtained for the inclination of 37^0, a PVT water flow of 0.16 kg/s and a configuration of 2 rows / 6 panels;
- The maximum overall exergy efficiency of the system, of 16.55, was obtained for the inclination of 37^0, a PVT water flow of 0.1 kg/s and a configuration of 4 rows / 3 panels.

Optimizing the efficiency of a PVT system must be made both in terms of quantity - energy efficiency and quality - exergy efficiency. The optimal solution is primarily chosen depending on the interest.

BIBLIOGRAPHY

[1] **Boubekri, M., Chaker, A., Cheknane**, A., *Numerical approach for performance study of hybrid PV/Thermal collector,* Revue des Energies Renouvelables, vol.12, no.3, 2009.

[2] **Mishra, R.K., Tiwari, G.N**., *Evaluation of an integrated photovoltaic thermal solar (IPVTS) water heating system for various configurations at constant collection temperature*, World Renewable Energy Congress 2011 - Sweden, 8-13 May 2011, Linkoping, Swedwn.

[3] **Bakker** M., et al. *Performance and costs of a roof-sized PV/thermal array combined with a ground coupled heat pump*, Solar Energy 2004.

[4] **Tiwari, G.N., Dubey, S**.,*Fundamentals of photovoltaic modeles and their applications*, The Royal Society of Chemistry, Cambridge, 2005.

[5] **F. Sarhaddi,** et al., *Non-Sensitive Solutions in Multi-Objective Optimization of a Solar Photovoltaic/Thermal (PV/T) Air Collector*, World Academy of Science, Engineering and Technology 74, 2011.

[6] **Arif Hepbasli**, *A key review on exergetic analysis and assessment of renewable energy resources for a sustainable future*, Renewable and Sustainable Energy Reviews, 12, 2008.

[7] **Farahat S., Sarhaddi F., Ajam H.**, *Exergetic optimization of flat plate solar collectors*, Renewable Energy 34, 2009

[8] **Huang B.J., Lin T.H, Hung W.C, Sun F.S**, *Performance evaluation of solar photovoltaic/thermal systems* , Solar Energy, Volume 70, Issue 5,2001.

About the authors

Prof. Eng. **Aneta HAZI,** PhD
“Vasile Alecsandri” University of Bacau
email:ahazi@ub.ro

Graduated at the „Gh.Asachi”University of Iasi, Faculty of Electrotechnics, study program - Industrial Power Engineering in 1982. In 1999 obtained the scientific title of doctor engineer of the “Politehnica” University of Bucharest, specialization Thermo Power Engineering. Since 1993 teacher at the Power Engineering Department, Faculty of Engineering, “Vasile Alecsandri” University of Bacau and has an intense teaching and scientific activity in the fields of thermal installations, energy generation, electrical substation and energy efficiency.

Prof. Eng. **Gheorghe HAZI,** PhD
“Vasile Alecsandri” University of Bacau
email:gheorghe.hazi@ub.ro

Graduated at the „Gh.Asachi” University of Iasi, Faculty of Electrotechnics, study program – Electro Power Engineering in 1982. In 1997 obtained the scientific title of doctor engineer of the „Gh.Asachi” University of Iasi, specialization Electro Power Engineering. Since 1990 teacher at the Power Engineering Department, Faculty of Engineering, “Vasile Alecsandri” University of Bacau and has an intense teaching and scientific activity in the fields of networks, optimization and reliability of energy systems.

Lecturer Eng. **Roxana GRIGORE,** PhD
“Vasile Alecsandri” University of Bacau
email:rgrigore@ub.ro

Graduated at the “Politehnica” University of Bucharest, Faculty of Power Engineerig, study program - Thermoelectric Power Plants in 1991. In 2008 obtained the scientific title of doctor engineer of the “Politehnica” University of Bucharest, specialization Power Engineering. Since 1992 teacher at the Power Engineering Department, Faculty of Engineering, “Vasile Alecsandri” University of Bacau and has an intense teaching and scientific activity in the fields of generation, transmission and distribution of heat, reliability, maintenance and diagnosis of thermal installations.