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Combined electrical and thermal use of photovoltaic panels

Integrating photovoltaic panels (PV) into the roof allows to increase the energy efficiency by ventilating the underside of the panels. Investigations carried out at the research station ART Taenikon show that the heat production of the PV panels is four to five times higher than the electricity production. By ventilating the temperature decrease of the panels amounts to 15 °C, resulting in a 6 % increase in electricity production. Using the warm air for drying hay permits significant saving of energy by reducing the drying time. A numerical model has been developed and validated allowing the calculation of the thermal efficiency of the photovoltaic plant.

Keywords
Photovoltaic, heat production, energy efficiency, hay drying, energy saving

Abstract
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The PV installation consists out of 8 PV panels (Typ Megaslate 1.316 × 0.975 m, 136 Wp, 3S Swiss Solar Systems AG) integrated in the roof and connected to a DC/AC inverter (Sunny Boy 1100 LV), **figure 1**. The panels have been installed on purlins to form a roof of 0.83 m wide and 10.5 m long at an inclination of 20°. Particle boards have been fixed to the underside of the purlins, forming a collector channel between the PV panels, the purlins and the particle boards. The collector channel is ventilated by an axial fan (∅ 50 cm). The ventilation rate is controlled by a measuring fan (FANCOM). The air temperature is recorded at the collector inlet and outlet by 2 PT-100 sensors (precision 0.1 °C). The surface temperature of the panels is measured by a PT-100 sensor (precision 0.5 °C). A hot-wire anemometer (Schmidt SS20.502 300 428), installed about 1 m above the solar panels, records the wind speed (0.1–20 m/s, precision 0.06 m/s), and another one inside the collector measures the air speed: (0–10 m/s, precision 0.06 m/s). The global radiation is measured on a horizontal plane (Ahlborn Type FLA 613-GS, SN 6557/08, cos. correction < 3 %), ranging between 0–1200 W. The electrical power (0–2 kW) is recorded with a precision of 1 W at the DC/AC inverter outlet.

Fig. 1

Experimental PV plant, Photo: ART Taenikon

The electricity production measured after the inverter is 10 % lower because of the losses due to the transforming of the continuous current in alternative current.

Some of the parameters are measured each second; an average is calculated for each minute and registered in the computer. Other parameters are derived from the measured ones: The air flow is calculated depending on the air speed in the collector. The absorbed heat can be calculated from the difference of the air temperature at the beginning and at the end of the collector, the ventilation rate and the air density. The electrical and the heat efficiency result from the ratio of the electrical and the thermal power (W/m^2) for the global radiation (W/m^2) on a horizontal plane. During the measurements the roof was continuously oriented direction south.

Measurements

Measurements have been made for a period of 14 days in July, 6 days in August, 3 days in September and 2 days in October. The speed of the air in the collector varies between 0.2 m/s and 6.0 m/s (**table 1**).

According to the measurements, the amount of the sun's energy transformed into heat is five times greater than that trans-

Table 1

Data from the measurements made in July, August, September and October 2008

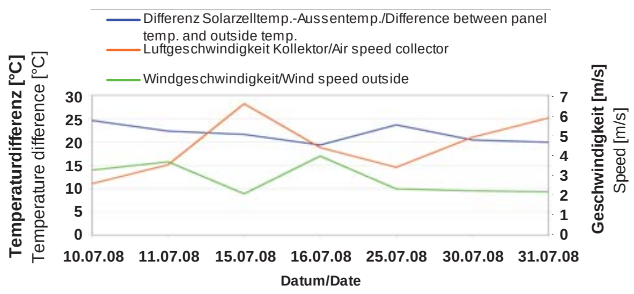
Datum *Date*	**Zeit** *Time*	**Wind** *Wind* **m/s**	**v Kollektor** *v collector* **m/s**	**PV-Temp.** *PV-temp.* **°C**	**E-solar** *E-solar* **kWh/m²**	**Electr. Wirk.** *Electr. effic.* **%**	**Term. Wirk.** *Heat effic.* **%**
01.07.08	11:00-17:05	1.71	-	51.9	5.15	9.18	-
02.07.08	07:56-16:46	1.69	-	47.9	6.58	9.33	-
04.07.08	07:42-16:05	1.99	3.85	32.6	5.25	9.81	54.29
08.07.08	07:53-16:45	3.97	4.26	27.6	5.26	9.83	46.77
10.07.08	07:22-16:25	2.32	2.18	41.6	6.80	9.50	44.71
11.07.08	10.07-16:25	2.42	2.95	47.2	5.23	9.58	48.37
15:07.08	08:13-16:07	1.81	5.60	35.4	6.25	10.13	63.84
16:07.08	07:50-16:34	2.81	3.76	36.8	6.54	10.05	49.54
21.07.08	07:50-16:34	3.52	4.37	25.4	4.14	10.22	46.86
23.07.08	08:10-23:59	1.80	6.00	26.2	7.56	10.09	50.26
24.07.08	00:00-24:00	1.51	5.45	21.6	7.72	9.97	44.95
25.07.08	00:00-16:06	1.22	2.84	25.2	6.02	10.00	11.52
28.07.08	08:11-16:44	2.01	2.03	43.0	5.60	9.54	41.96
29.07.08	08.14-16:52	1.89	3.35	39.8	5.52	9.82	45.83
30.07.08	08.09-16:25	1.56	4.24	39.7	5.21	9.94	54.51
31.07.08	07:58-16:22	1.65	5.08	40.7	6.03	9.98	57.55
Mittelwert/*Average*	**Juli**	**2.12**	**4.00**	**36.42**	**5.93**	**9.81**	**49.57**
06.08.08	08:40-16:55	1.57	3.57	39.9	5.59	10.21	51.04
07.08.08	13:02-16:22	2.82	3.54	41.5	1.93	9.79	49.84
11.08.08	10:05-16:06	1.37	5.79	36.2	3.51	10.14	56.81
13.08.08	13:18-16:42	3.16	3.54	35.4	2.18	10.55	48.62
18.08.08	10:09-17:48	2.52	4.38	39.0	5.31	10.98	52.69
21.08.08	11:00-16:13	1.61	0.20	42.9	3.31	10.15	-
27.08.08	10:11-12:49	1.63	4.28	37.3	1.88	11.44	64.04
Mittelwert/*Average*	**August**	**2.10**	**3.61**	**38.87**	**3.39**	**10.47**	**53.84**
08.09.08	07:48-17:05	1.02	4.44	34.8	3.84	12.27	63.28
09.09.08	08:18-16:43	1.27	3.52	35.5	4.84	12.06	61.16
30.09.08	14:09-16:05	2.26	2.09	18.3	0.42	11.03	33.33
Mittelwert/*Average*	September	1.52	3.35	29.53	**3.03**	**11.79**	**52.45**
14.10.08	12:12-17:18	2.50	3.37	30.76	1.23	14.40	53.7
15.10.08	11:45-17:42	2.60	4.08	28.26	1.41	14.80	51.2
Mittelwert/*Average*	**Oktober**	**2.59**	**3.73**	**28.5**	**1.32**	**14.60**	52.45

formed into electricity (measured after the inverter) [1; 2].The fluctuations in the efficiency are mainly due to the different wind speeds and air velocities in the collector.

Relation between the panel temperature and air speed

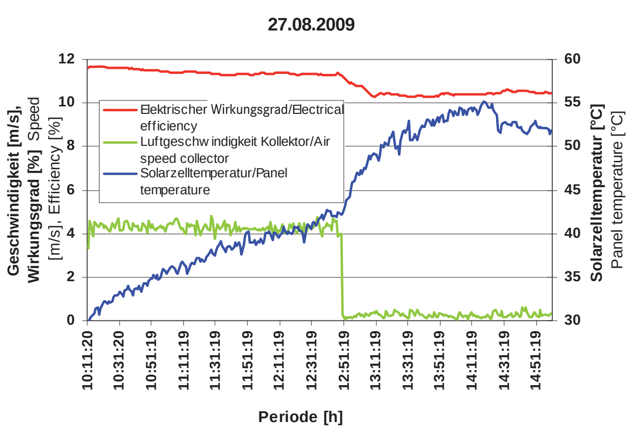
Based on the measurements, the temperature of the panels is influenced by the wind speed above the panels and the air speed in the collector. When the wind speed and the air speed increase, the temperature of the panels decreases (**figure 2**). On the 10th of July 2008 (13:00–13:30), the difference between the temperature of the panels and the outside temperature was 24.6 °C, at an average wind speed of 2.8 m/s and an air speed in the collector of 2.2 m/s. The minimal difference between the temperature of the panels and the environment was recorded on the 16th of July as 19.3 °C, at an average wind speed of 3.4 m/s and an air speed in the collector of 3.8 m/s.

Fig. 2



The difference between the panel temperature and the outside temperature shows a good correlation with the wind speed and the air speed in the collector

Fig. 3



Switching off the fan leads to a rapid increase in the panel temperature from 42 °C to 55 °C and a decrease in electrical efficiency from 11.2 to 10.4%

Relation between the panel temperature and electrical efficiency

The higher the temperature of the panels the lower the electrical efficiency. On the 27.08.2008 at 12:49 the ventilator is switched off (**figure 3**). The air speed in the collector drops from 5.2 m/s to 0.3 m/s. The remaining air speed in the collector is due to the wind outside and to the thermal buoyancy. Reducing the air speed leads within half an hour to an increase of the panel temperature from 42 °C to 51.6 °C. In the same time period the electrical efficiency decreases from 11.2 % at 42 °C to 10.4 % at 55 °C.

Relation between the air speed in the collector and heat efficiency

The higher the wind speed is the more heat will be dissipated to the surrounding environment and less heat can be recuperated in the collector. Hence, the greater the difference between the air speed in the collector and the wind speed, the greater the heat efficiency. At an air speed in the collector of 2.21 m/s and a wind speed of 2.79 m/s (difference between air speed and wind speed –0.58 m/s), the heat efficiency is 43.5 %. For an air speed of 5.64 m/s and a wind speed of 1.77 m/s (difference of 3.87 m/s), the heat efficiency increases to 59.5 %.

Numerical method

The energy balance of the solar panel for steady heat flow conditions is expressed by the following equation: absorbed sun's energy ($a_s G_{PV}$) – energy reflected by the solar panels ($Q_{IR,x}$) + energy absorbed by the solar panels due to sky reflection ($Q_{refl,x}$) – energy converted into electricity ($E_{el,x}$) – heat dissipated by the wind ($U'_{PV}(\theta_{PV,x}-\theta_a)$) – heat dissipated by the air flow in the collector $\alpha_{PV}(\theta_{PV,x}-\theta_{L,x}) = 0$ (**equation 1**).

$$[(a_s \cdot G_{PV} - Q_{IR,x} + Q_{refl,x} - E_{el,x} - U'_{PV} \cdot (\theta_{PV,x} - \theta_a)) \cdot B_{PV1} - \alpha_{PV} \cdot (\theta_{PV,x} - \theta_{L,x}) \cdot B_{PV2}] \cdot dx \cdot dt = 0 \qquad \text{(Eq. 1)}$$

To resolve this equation $\theta_{PV,x}$ needs to be expressed as a function of $\theta_{L,x}$. As this is not possible because of the interdependence between $Q_{IR,x}$ and $\theta_{PV,x}$, only approximate results can be obtained by assuming a constant value for $\theta_{PV,x}$ over the entire surface of the PV installation.

The problem of the interdependency between $Q_{IR,x}$ and $\theta_{PV,x}$ can be avoided by using a numerical method, dividing the length of the collector into n sections Δx [3]. The panel temperature $\theta_{PV,i}$ and the heat fluxes $Q_{PV,i}$ and $Q_{u,i}$ of each section Δx_i are calculated consecutively by using the air temperature ($\theta_{L,i-1}$) of the previous section (Δx_{i-1}). To achieve sufficient precision Δx should be less than 0.05 L (**equation 2**).

$$\theta_{PV,i} = \frac{(a_s \cdot G - Q_{IR,i} + Q_{refl} - E_{el} + U'_{PV} \cdot \theta_a) B_{PV1}}{\alpha_{PV} \cdot B_{PV2} + U'_{PV} \cdot B_{PV1}}$$

$$+ \frac{\alpha_{PV} \cdot \theta_{L,i-1} \cdot B_{PV2}}{\alpha_{PV} \cdot B_{PV2} + U'_{PV} \cdot B_{PV1}} \quad \text{(Eq. 2)}$$

The heat transfer (W) between the solar panels and the air in the section Δx_i is calculated from the temperature of the panels. The air temperature $\theta_{L,L}$, °C at the end of the collector is obtained by adding the air temperature of the previous section to the beginning temperature ($\theta_{L,o}$). The temperature increase for each section can be calculated dividing the heat transfer between the air and the underside of the panel ($\theta_{PV,I}$,W) and the underside of the collector ($Q_{u,i}$, W) by the ventilation rate (V, m³/h)), the specific heat (0.28 Wh/kg K) and the air density (ρ, kg/m³), (**equation 3**).

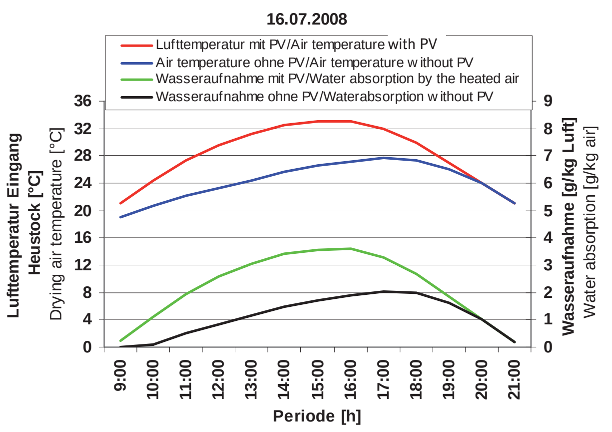
$$\theta_{L,L} = \theta_{L,0} + \sum_{i=0}^{i=n} \frac{Q_{PV,i} + Q_{u,i}}{V \cdot 0.28 \cdot \rho} \quad \text{(Eq. 3)}$$

Use of heat

The use of heat from the PV panels and in the same time of the electricity increases the profitability of the PV plant [3].

On sunny days, the heat production can amount to 4 kWh per m². Because of the temperature increase, the relative humidity of the air in the collector will decrease [4] and its humidity absorbing capacity will rise. A relatively small increase of the temperature, from 5 to 8 °C is sufficient to double the absorption capacity of the air (**figure 4**).

Fig. 4



Water absorption capacity of the outside air and of the air heated in the PV plant

When using the heated air of the photovoltaic plant for drying hay, the drying period can be halved.

The time and the energy need to dry hay can be calculated using a numerical method [5] based on the geometry of the plant and of the haystack (**table 2**). The results of the simulation show that using the heated air instead of the outside air for drying, the energy saving is estimated at 30 Wh per kg DM of hay.

Table 2

Comparison of the time and energy needed for hay drying with outside air (without PV) and with air heated by the PV plant (with PV) based on weather conditions in July 2008

PV-Fläche/*Surface of the PV plant* [m²]		300
Luftgeschwindigkeit Kollektor/*Air speed in the collector* [m/s]		3.8
Gesamtquerschnitt Kollektor/*Free section of the collector* [m²]		4.5
Luftrate Kollektor/*Air flow in the collector* [m³/h]		17.1
Heustockfläche/*Surface of the haystack* [m²]		155
Luftrate Heustock/*Air flow through the haystack* [m³/s m²]		0.11
Schichthöhe pro Füllung/*Thickness of the haystack per charge* [m]		1.5
Heumenge in TS pro Füllung/*Hay quantity* per charge [kg TS/*DM*]		18 655
TS-Gehalt des Heus vor Trocknung/ *DM content of the hay before drying* [%]		65
TS-Gehalt des Heus nach Trocknung/ *DM content of the hay after drying* [%]		87
Erforderlicher Wasserentzug/*Required dehydration* [kg/TS Heu *kg/DM hay*]		0.39
Erforderlicher Wasserentzug gesamt/*Total required dehydration* [kg]		7257
	Ohne/ *Without* PV	**Mit/ *With* PV**
Mittlerer Wasserentzug /*Average water absorption* [g/kg Luft/*Air*]	1.1	2,2
Wasserentzug pro Stunde/*Total water absorption* [kg/h]	76	150
Theoretische Trocknungszeit/*Theoretical drying time* [h]	96	48
Luftwiderstand/Total pressure drop [Pa]	450	525
Leistungsaufnahme Lüfter/*Fan power* [η = 0.60], [kW]	12.8	13,8
Energiebedarf Lüfter/*Energy demand of the fan* [kWh]	1 227	670
Energieeinsparung Lüfter/Saved energy for the fan [kWh]		-557
Zusätzliche Stromproduktion während der Belüftung/ *Additional electricity produced by the PV plant* [kWh]		38
Gesamter Energiegewinn/*Total energy gain* [kWh]		**595**
Mittlere Stromproduktion der Solarmodule/*Average electricity production:* 65 W/m² zwischen/*between* 09:00 und 21:00, Temperatursenkung der Solarzellen/*Temperature decrease of solar cells:* 10°C		

Conclusions

The heat which can be recuperated by ventilating the photovoltaic panels is four to five times higher than the electricity produced by the PV plant. When the wind speed above the panels and the air speed in the collector increase the temperature of the panels decreases. With the increase of the temperature of the panels, the electrical efficiency reduces. The higher the wind speed, the more heat will be dissipated to the surrounding environment and the less heat can be recuperated in the collector. Hence, the greater the difference between the air speed in the collector and the wind speed, the greater the heat efficiency. A numerical model has been developed and validated allowing the air temperature in the collector and the panel temperature to be calculated as a function of outside conditions, PV plant geometry, air speed and the thermal conductivity of the solar panels. Using the air heated in the PV plant instead of outside air for hay drying, the drying time can be halved. The energy saved by reducing the running time of the fan is estimated at 30 Wh per kg DM of hay. During the time when there is no demand for heat, minimal cooling of the panels by natural convection, on the underside as well as on the upper side should be ensured. Therefore, the collector should allow a stack effect (buoyancy).

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