The Pilot Photovoltaic/Thermal Plant at the University of Catania: description and preliminary characterization

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Abstract: The main objective of the present paper is to provide not only the description of a pilot cogenerative PVT Plant (PVTP) but also the results of preliminary electrical and thermal characterization. The PVTP is able to produce and store at the same time electrical and thermal energy, the main component is an uncovered (no air gap above the absorber) hybrid PVT module (PVTM), whose operating temperature has to be carefully chosen in such a way to reach the right compromise between cooling the PV cells (high electrical efficiency) and getting high water temperature (highest Carnot efficiency). The PVTM is the connection point between the two separate subsystems of the PVTP: the electrical subsystem (PVTE) and hydronic subsystem (PVTH). The design of experimental PVTP is very flexible to reproduce parallel and series connections of the PVTMs from both electrical and hydraulic point of view (so, for example, it would be possible to have an electrical series connection and a parallel hydraulic connection). The PVMT is installed in the campus of University of Catania, Catania, Italy (Lat.37.55N, Long.14.29E).

1. Introduction

PVT technology attracted numerous researchers during the last decades and many studies have been conducted to verify or quantify the effect of climatic, design and operational parameters on the performance of different types of PVT collectors.

A large number of investigations on PVT collectors/systems subsequently conducted. But few studies have been focused on experimental thermal modeling of a combined system of photovoltaic. The first study on a PVT system was presented by Martin Wolf in 1976 [1].

While Dubey and Tiwari Swapnil Dubey [2] have designed an integrated photovoltaic (glass-to-glass) thermal (PVT) solar water heater system and tested it in outdoor conditions of India. Furthermore, they have derived an analytical expression for characteristic equation of combined system of photovoltaic thermal (PVT) flat plate collectors which have been carried out and experimentally validated for various configurations in order to evaluate the performance of the systems as well.

Similarly, Erdil et al. [3] designed and tested a hybrid PVT system for energy collection at geographical conditions of Cyprus, where water was used as the cooling fluid. It was reported that 2.8-kWh thermal energy can be stored as pre-heated water for domestic utilization with 11.5 % electrical energy loss.

In 2012 Chao-Yang Huang et al [4] have carried out an experimental study on Photovoltaic/thermal system composed of a 240-W poly-crystalline silicon PVT collector, 120-L storage tank, pump controller and pump. The results indicated that the system thermal

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efficiency can reach 35.33% and photovoltaic conversion efficiency can reach 12.77% during the testing period. The water tank temperature can be risen from 26.2°C to 40.02°C.

Ozgoren et al [5] setup an experimental study with 190-W PV and 190-W PVT commercial water panels linked to a 175-L storage tank in order to establish the module's electrical and thermal performance. They experimetally found out a thermal performance of PVT collectorsof 51% and a maximum electrical efficiency of 13.6% for mass flow rate of 0.03 kg/s. In the case of the PV module temperature is 65°C, electrical efficiency of the PV module is 8%. They observed that for each 100-W/m^2 increase in solar radiation value the cell temperature increased about 1.2 °C for the PVT system and 5.4 °C for the PV system, respectively. Maximum cell temperature of PV module was 65 °C while PVT cell temperature is decreased to 32 °C at time 13:00 on 25th July 2011.

In 2015 Chao-Yang Huang and Hsien-Chao Sunga [6] investigated the performance of PVT system running during winter. The PVT system combined with six pieces 240-W un-glazed copper tube and sheet PVT module and a 500-L storage tank using water to cool the module and recycle the heat with circulate pump. The electricity efficiency was 13.264% and thermal efficiency was 17.342% in the zero reduction condition. The average performance ratio of the PVT system was 86%.

Aste et al [7] developed simulation model of PVT system and, in order to evaluate its accuracy, they carried out an experimental monitoring campaign on the prototype PVT. The collector was installed at the experimental station of the Politecnico di Milano, with tilt angle of 30° and azimuth equal to 0. The 125 W PVT unglazed collector was connected to an insulated storage tank with capacity of 200 l. They measured thermal and electrical performance in December. They found out a daily mean electrical efficiency of the PVT of 6.0% and thermal energy efficiency equal to 25 %.

2. Physical model of the PVT system

A numerical model was developed by the TRNSYS 17 software in order to test the transient behaviour of a PVT plant for three operating conditions, which are defined by fixing the temperatures within the thermal storage (30, 35 and 40°C). For each temperature both thermal and electrical energy have been calculated as well as the relative efficiency. The system consists essentially of two main subsystems (Fig. 1): solar loop (PVT systems with a hot water storage tank);chiller loop (including storage and consumption).

The user interface of TRNSYS allows connection of individual components (called type) such as model of solar collector, pump, controller, heat exchanger which are available in the program library. TRNSYS solves the set of algebraic and differential equations that describe the system at a user-selectable time step. The mathematical description of the used types can be found in TRNSYS manuals. It is worth noting that we do not use one of the type available in the TES library for simulating the PVT collector. Indeed, in this study the electrical efficiency of the PVTMs has been calculated using the data provided by the producer considering their dependence from the PV cell temperature that in turns can be linked with the temperature of the thermal fluid.

The study was carried out by using meteoclimatic data measured by the meteorological station located near the PVTP. These data are available from 1.1.2015 to 12.31.2015 (web site: http://www.moses.pvt.dieei.unict.it/). The acquired data originally in Microsoft Office Excel® have been converted into text format (.txt), so that they can be implemented within the Type 109; for this purpose, it was created a script in Matlab.

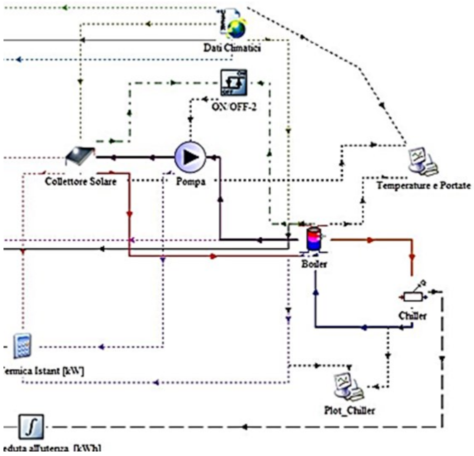


Fig. 1. TRNSYS model of the PVTP

Table 1. Types used in the TRNSYS model

Type	109	1b	3d	60d	2b	65c	92	24
Name	Weather data	Thermal Solar collector	Pump	Boiler	Controller	Plotter	Chiller	Integral operator

Output of Solar collector (Type 1b): outlet temperature, outlet flowrate and useful energy gain. The thermal efficiency is calculated by

$$\eta_{t=}a_0 - a_1\frac{(\Delta T)}{I_T} - a_2\frac{(\Delta T)^2}{I_T} \qquad \text{Eq. (1)}$$

where

$\boldsymbol{\Delta}T = T_{c1} - T_a$

T_{c1} = inlet solar collector temperature

T_a = outdoor temperature

I_T = modified solar radiation = I_b (1- η_{el})

It is calculated subtracting from the solar radiation "I_b" the amount of solar energy converted in the photovoltaic effect.

In this model, it is not used a type for describing the PV collector. Actually, an external operator is used for calculating the electrical efficiency in function of the cell temperature (T_c), which in turns is posed as a function of the average temperature between the inlet and the outlet temperature of the thermal fluid in the solar collector. The electrical efficiency is calculated by the following equation:

$$\eta_{el} = \eta_{STC} * [1 + \gamma * (T_c - 25)] \qquad \text{Eq. (2)}$$

$$T_c = \frac{T_{c2} + T_{c1}}{2} \qquad \text{Eq. (3)}$$

where T_{c2} is the outlet solar collector temperature.

The boiler (type 60d) is a stratified cylindrical vertical storage tank with an input and an output flow rate and two internal heat exchangers (1 and 2). The tank volume is 0.189 m^3. The heat exchanger sited in the lower part of the boiler is connected with the PVT collector circuit, while the heat exchanger sited in the upper part of the boiler is connected with the

auxiliary cooling device. It is necessary to define the flow rate at inlet 1 and inlet 2. The average temperature of the tank is connected to the input of the ON / OFF controller that operates the pump.
In this study, the auxiliary cooling device (type 92) has to simulate the DHW energy needs. At this phase of the study, this device has to maintain specific values of temperature inside the boiler, that are 30, 35 and 40 °C. The thermal flux exchanged with the boiler gives the useful thermal energy produced by the PVT circuit at the selected thermal level.
Through the Integral Operator (type 24) this type we have calculated the thermal energy provided to users, E_{term}, and the electricity produced, E_{el}, as

$$E_t = \int_{t1}^{t2} \dot{m}\, c_p \Delta T_2 \, dt \qquad \text{[kW h]} \qquad \text{Eq. (4)}$$

where

$\dot{m}$ =mass flow rate in the chiller loop $[kg/h]$

$c_p = 4.186$ $[kJ/kg\ \mathrm{K}]$

$\Delta T = \left|(t_{in,scamb2} - t_{in,scamb1})\right|$ [°C];

$$E_{el} = \int_{t1}^{t2} \mathrm{I_b} * \mathrm{A_{PV}} * \eta_{el}\, \mathrm{dt} \qquad \text{[kWh]} \qquad \text{Eq. (5)}$$

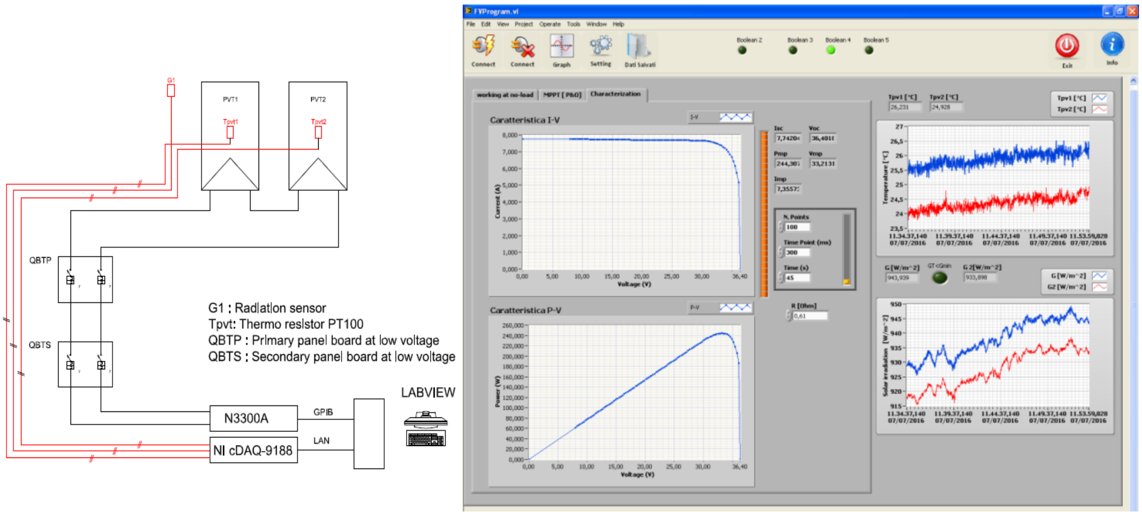
3. PVT module: main characteristics

The crucial element in the PVT system is the PVT module (PVTM), unglazed tube and sheet type, that is the connection point between the two separate subsystems: the electrical subsystem (PVTE) and hydronic subsystem (PVTH). The PVT modules have been manufactured by Dualsun™. A PVTM is cooled by water circulation on backside of the panel. The thermal energy is transferred to the operative fluid by means of a rigid ultra-thin heat exchanger, completely integrated into the panel. It allows an excellent heat transfer between PVM front side and water circulation on backside. The mounting structure for PVTMs is south oriented (azimuth angle γ=0°), whereas the tilt angle, β, is equal to 25°. The tilt angle can be changed manually from 15° a 60°, with an angle step, $\Delta\beta$, 5°. PVTMs can be connected in series or in parallel to form a string. The main electrical characteristics of each PVTM, measured by the manufacturer at STC (Standard Test Conditions) and of the string, with module in series or in parallel, are reported in Table 2.
Fig. 3.a shows the wiring diagram of the PVTE, in case of PVTMs in series. The connectors of the string, or just one PVTM, and the sensors cable are connected two separate sections of an electrical board installed on the roof (QBTP). Then cables that exit QBTP are connected to another electrical board, inside the electrical power system laboratories, where the electrical isolation and distribution is performed. In particular, the two connectors of the string are connected to a programmable electrical load, EL, (Agilent N3300A). The EL is connected by means of a GPIB cable/card to a Personal Computer (PC).

Table 2. Electric values for the PVTMs (measured at STC conditions) and series and parallel configuration (datasheet data).

Config.	I_{sc} (A)	V_{oc}(V)	I_{mpp} (A)	V_{mp} (V)	P_{mpp} (W)
PVTM 1	8.664	38.645	8.089	31.376	253.813
PVTM 2	8.654	38.607	8.103	31.545	255.597
Series	8.55	77	8.15	30.7	500
Parallel	17.1	38.5	16.3	61.4	500

In the PC there is a program developed in Labview environment that is able to control the EL in such way to measure the I-V curves. The measure of the irradiance on the plane of PVTMs and the two backside temperatures of the PVTMs are connected to a DAQ (NI cDAQ-9188) and shown in real time by means of the Labview program (see Fig. 3.b).



(a) (b)

Fig. 3. a) Wiring scheme of PVTE system; b) screenshot of the front panel of the Labview program.

The hydronic circuit of the PVTP was designed to obtain a very flexible system. Therefore, it is possible to manage and control the water temperature according to the meteorological conditions (irradiance, ambient temperature, wind speed) and to the thermal energy demand. Fig. 4a and 4b shows the PVT modules and the hydronic components along with the wiring boxes, respectively. Fig. 4c depicts the hydronic circuit and control and monitoring device of the PVTP. The main components of the PVTHS are listed here in after: N°2 PVT modules; N°1 boiler with two heat exchangers; N°1 water pump; N°10 temperatures sensors; N°4 flux meters; N°1 data acquisition system; safety components; hydraulic shut-off valves; N°2 mixing valves; heat pump. The main characteristics of PVTH are reported in Table 3. All the sensors are linked with a control unit placed on an external box and then the information is sent to the PC through Ethernet. Another box is placed on the roof and contains all the power supply for the electrical valve, for the chiller, the pump and all the components of the signal box. The data acquisition and control functions on the PVTP are performed by means of a Modbus/TCP protocol that makes perfect integration to SCADA software and web based applications [8].

In a first design step, the implemented logic of control of PVTH is straightforward and close to the one used for solar thermal systems. It is based onn the control of the temperature inside the boiler. The circulation of water starts when the water temperature in the PVTMs is higher than the one inside the boiler; on the contrary when the temperature inside the boiler is higher than the temperature of the module the flow is stopped. The PVTH designed scheme allows the connection in series or in parallel of the two PVTMs. Such configuration flexibility has a dual purpose: to test the operation of the two modules subjected to different conditions of shading (parallel connection), and to evaluate the changes in the electrical efficiency due to non-uniformity of temperature between the modules (series connection). The three-way valves allow to control the water flow inside the two modules in such a way as to limit the temperature differences due to different operating modes between the two modules.

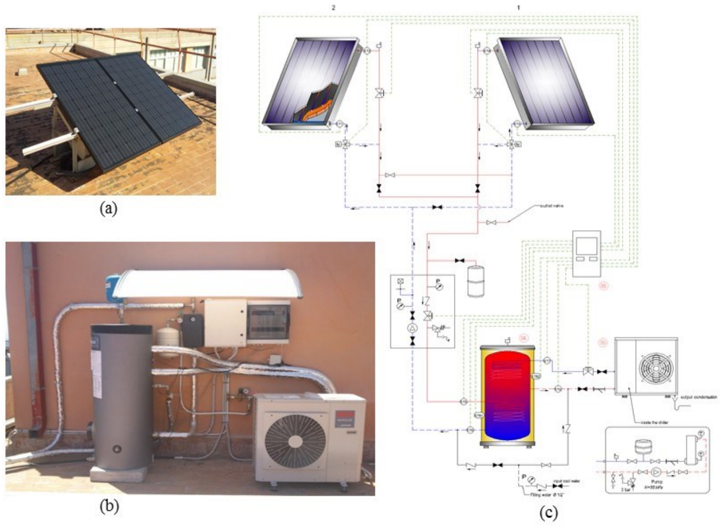


Fig. 4. A. PVT modules; b: hydronic components and wiring boxes; c: scheme of the hydronic section of the PVT plant

A preliminary version of the system provides for tuning of evaluation of thermal and electrical efficiencies of the PVT modules to vary the operating temperature. In this regard, we will proceed by setting the temperature inside the storage tank, the control of which is delegated to the operation of the chiller, and will evaluate the thermal and electrical efficiencies of the PVT modules. The temperature control inside the boiler is realized between the heat exchange with the heat pump that can simulate the heat demand from the users. Different scenarios of heat demand daily user's curves will be realized by choosing the set point for the temperature inside the boiler. Given a certain heat demand scenario and under given ambient conditions, the measured operative variables will allow to calculate the heat balances in each component (PVTM, Boiler, heat pump) of the Hydronic circuit and, consequently, to evaluate the partial and global efficiency in the PVTH.

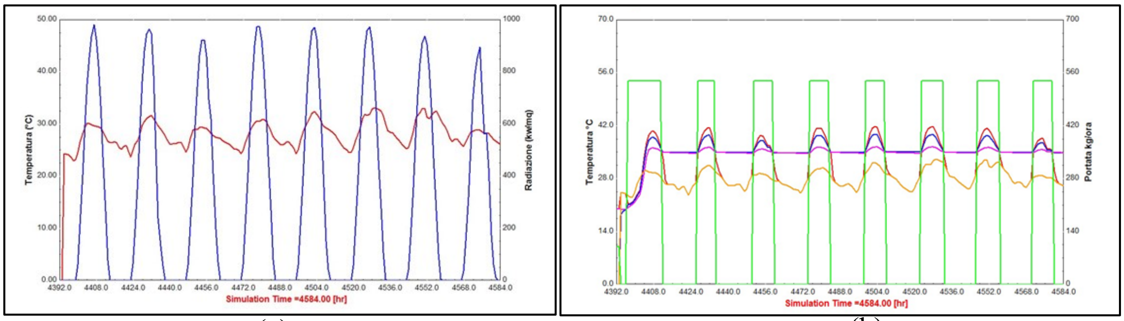
Table 3. PVTH main characteristics.

Pump		**Thermal boiler**		**Chiller**		**Pipes**	
Max. flow rate	Power	water in tank	water thermal cap.	nominal power	absorbed power	lenght	diameter
55 l/min	3-45 W	0.185 m^3	4.174 (KJ/Kg.K)	5000 W	1170 W	40 m	16 mm

4. Simulation Results

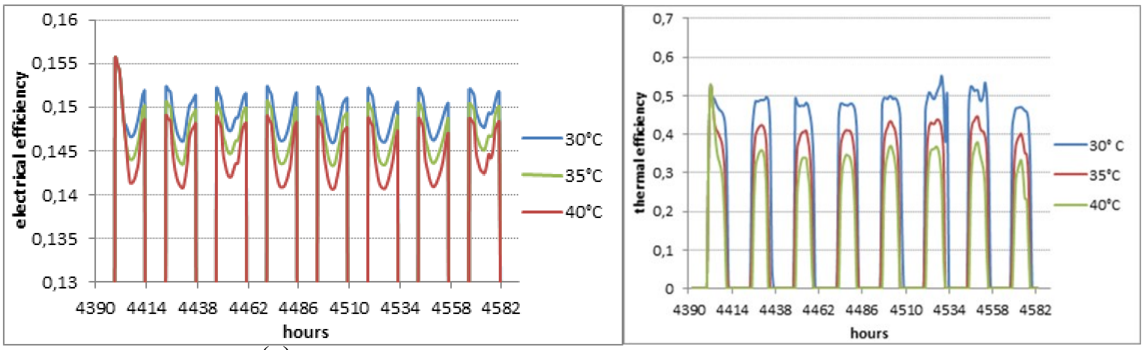
Figs. 6a) and 6b) report two examples of graphs concerning the simulations carried out using the meteorological data measured in Catania (Italy) in 2015 for the three operative temperatures investigated; specifically they refer to the period from July 3 (hour 4392) to July 10 (hour 4584).

Fig.s 7a and 7b show the electrical and the thermal efficiency of the PVTMs in function of the set point temperature within the thermal boiler.



(a) (b)

Fig. 6. a: Solar radiation I_b (blue line) and outdoor temperature T_a (red line); b: Simulated operative temperatures (tank temperature 35°C), Temperature outlet from solar collector T_{c2} (red line); Temperature outlet from tank reservoir (heat exchanger 1) T_{c1} (blue line), average temperature in the tank T_{mb} (purple line); outdoor temperature T_a (yellow line), mass flow rate in the solar circuit (green line).



(a) (b)

Fig. 7. A: PVTM electrical efficiency; b: PVTM thermal efficiency

The global efficiency of the PVT system has been calculated by Eq. (6):

$$\eta_{glob} = \eta_t + \frac{1}{0.46}\eta_{el} \qquad \text{Eq. (6)}$$

where 0.46 is the conversion coefficient for the electrical energy in primary energy.
Fig. 8 shows the global efficiency for three T set points.

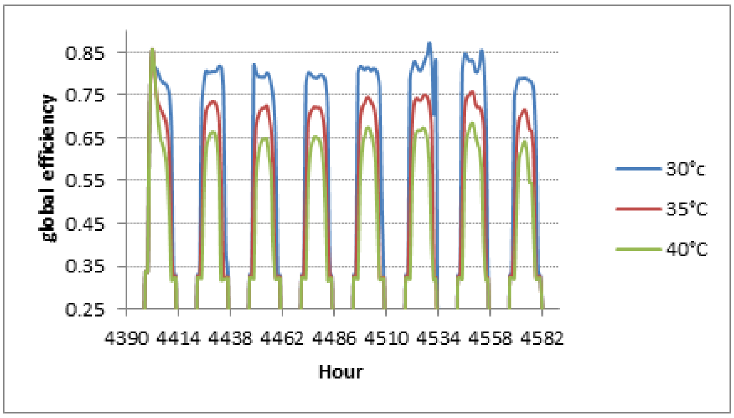


Fig. 8 – PVTM Global efficiency

Table 4 shows the electrical and the thermal energy as well as the energy available for domestic heat water (DHW) production during the analysed period for the three different simulation scenarios.

Table 4. Energy values in the PVTP

T set point	Thermal energy (kWh)	Electrical energy (kWh)	Energy for DHW production (kWh)
30° C	67	28.10	65
35° C	49	27.63	46
40° C	35	27.12	27

The analysis of this results clearly indicate that the highest electrical and thermal efficiency are obtained when the lowest temperature (30°C) is maintained inside the boiler. However, it is not the optimal choice, because of the exergy content of thermal energy is a function of its thermal level. Consequently, a second principle analysis is fundamental.

5. Conclusions

The present paper provides the description of a pilot cogenerative PVT Plant (PVTP) installed in the campus of University of Catania (Italy). Currently, all the components of the PVTP plant and the monitoring system have been installed. Preliminary tests about the operation of this plant are under development. In addition, the modeling of the PVTP with TRNSYS has been developed and the results of simulations showing the performance of the system as a function of the operative temperature have been reported.

6. References

[1] Wolf M. Performance analyses of combined heating and photovoltaic power systems for residences. Energy Convers 1976;16:79–90.

[2] Swapnil Dubey, G.N. Tiwari, Thermal modeling of a combined system of photovoltaic thermal (PV/T) solar water heater, Solar Energy, Volume 82, Issue 7, July 2008, Pages 602-612, ISSN 0038-092X

[3] E. Erdil, M. Ilkan, F. Egelioglu, "An experimental study on energy generation with a photovoltaic (PV)-solar thermal hybrid system," Energy, vol. 33, no. 8, pp. 1241–1245,

[4] Chao-Yang Huanga,, Hsien-Chao Sunga,c, Kun-Lung Yena Experimental Study of Photovoltaic/Thermal (PV/T) Hybrid System , International Journal of Smart Grid and Clean Energy 2012

[5] M. Ozgoren, M. H. Aksoy, C. Bakir and S. Dogan Experimental Performance Investigation of Photovoltaic/Thermal (PV-T) System EPJ Web of Conferences (2013)

[6] Chao-Yang Huanga,, Hsien-Chao Sunga, Performance monitoring of photovoltaic thermal hybrid system The 14th IFToMM World Congress, Taipei, Taiwan, October 25-30, 2015

[7] N. Aste et al. Design, modeling and performance monitoring of a photovoltaic–thermal (PVT) water collector Solar Energy 112 (2015) 85–99

[8] Tina, G.; Grasso, A.; Gagliano, A. Monitoring of solar cogenerative PVT power plants: Overview and a practical example. Sustain. Energy Technol. Assess. 2015, 10, 90–101.