Data in Brief 49 (2023) 109417

Contents lists available at ScienceDirect

Data in Brief

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Data Article

Measurement data from real operation of a hybrid photovoltaic-thermal solar collectors, used for the development of a data-driven model

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ARTICLE INFO

Article history:
Received 4 July 2023
Accepted 11 July 2023
Available online 16 July 2023

Dataset link: easurement dataset from real operation of a hybrid photovoltaic-thermal solar collectors, used for the development of a data-driven model (Original data)

Keywords:
Hybrid photovoltaic thermal (PVT) solar collector
Wind and infrared sensitive collector (WISC)
Summer operation temperate climate
Detailed weather data
Detailed solar resource data
High time resolution
Data-driven parameter identification

ABSTRACT

This article presents a measurement dataset from real operation of a hybrid photovoltaic-thermal solar collector. The data is from a summer period, when the collector works at its higher temperature limit, with low thermal efficiency. The dataset characterizes the output of the collector: thermal (heat transfer fluid flowrate, inlet and outlet temperatures) and electrical (raw current and voltage, Hampel filtered power). Further information on the collector are the PV cell temperature and the back surface temperature (in three points). It provides detailed weather information: ambient temperature, solar resource (direct normal, global and diffuse horizontal, global tilted in the collector plane), equivalent radiative sky temperature (calculated from a pyrgeometer), wind speed and direction both horizontal and in the tilted collector plane. The calculated sun position with Duffie and Beckmann method is also given (elevation and azimuth) . The dataset covers 58 summer days from 11th July to 6th September, with a 5 second time step. The data is available as .mat file (MATLAB) and .csv file. A selection of variables from this dataset has already been used in the development of a data-driven model (see related article) [1]. The extended data presented in this article offers mode detailed weather information, opening further investigations opportunities. Further

DOI of original article: 10.1016/j.enbuild.2023.113277
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https://doi.org/10.1016/j.dib.2023.109417

options for data-driven modelling of PVT collectors could be investigated. The correlation of wind related losses to horizontal wind measurements could be compared to a model with wind measurements in the collector plane. The dataset could support the validation of solar models, with direct and diffuse shares on the horizontal or in the tilted plane.

Specifications Table

Subject	Renewable Energy, Sustainability and the Environment
Specific subject area	Real operating data from hybrid photovoltaic and thermal solar collector including weather data, in high time resolution, for data-driven modelling.
Type of data	Table
How the data were acquired	This experimental dataset has been obtained through real operation of a hybrid photovoltaic and thermal (PVT) solar collector on a test bench in Austria. The measurement data has been collected automatically with a time step of 5 seconds (in average). One acquisition system records data from the weather station: pyranometers, pyrgeometer and pyrheliometer (KIPP&ZONEN), ultrasound wind sensor (LUFFT), NTC temperature sensor for ambient air. The other acquisition system monitors the collector test bench: PT100 temperature sensors, voltage and current meters, MID flow meter, pyranometer (KIPP&ZONEN), ultrasound wind sensor (LUFFT). The data has been compiled, resampled and filtered in MATLAB.
Data format	Resampled Filtered Calculated
Description of data collection	The dataset is resampled to a regular 5 s time step. Wind data are 10 s average of 1 s measurements. The collector is tilted by 20 °, towards South. Errors are corrected: global tilted irradiance above 5000 W/m^2 is set to 0; wind values over 400 (tilted) or 1000 (horizontal) are set to 0; abnormally falling output power is corrected with a Hampel filter. The sky temperature is calculated from the measured downward longwave irradiance. The sun position is calculated.
Data source location	• *Institution: Fachhochschule Burgenland* • *City/Town/Region: Eisenstadt* • *Country: Austria* • *Latitude and longitude (and GPS coordinates, if possible) for collected samples/data:* 47.358162 ° latitude (North) and 16.128405 ° longitude (East).
Data accessibility	Repository name: Dataset or other products (fh-burgenland.at) Data identification number: DOI: 10.57739/3720 Direct URL to data: http://hdl.handle.net/20.500.11790/3720
Related research article	[1] F. Veynandt, P. Klanatsky, H. Plank, C. Heschl, Hybrid photovoltaic-thermal solar collector modelling with parameter identification using operation data, Energy and Buildings. 295 (2023) 113277. https://doi.org/10.1016/j.enbuild.2023.113277.

Value of the Data

- These real operating data of an uncovered hybrid photovoltaic and thermal (PVT) solar collector with associated weather is useful to test and validate PVT collector models.
- The high time resolution with 5 s time step captures precisely the dynamics of the system.
- The dataset provides operating data from a summer period with high heat sink temperature. This represents working conditions with low thermal efficiency.
- Solar technology researchers and control system developers can be interested in the data.

- Designer and planning engineers of heating systems and special hybrid concepts, to study possible system integration, for example for domestic hot water preheating or combinations with heat pumps, especially applications with direct return boosting or PVT with heat pump booster, as well as regeneration of ice storage or ground heat exchanger…
- The dataset is provided for transparency. It can be used for further modeling work of PVT collectors, especially with data-driven approach.
- The detailed weather information opens opportunities to further develop the model. Refining the influence of wind, infrared and solar resource, depending on the available measurement information could be interesting.

1. Objective

To optimise the use of renewable energy in buildings, an accurate model to forecast the energy production from renewable energy is critical. To scale up model-based control solutions, data-driven approaches enable the model to self-adjust to any situation, through parameter identification based on historical data. Here focusing on the (potentially) most surface efficient solar technology, a hybrid photovoltaic and thermal solar collector, an experiment has been designed to produce this dataset. This supports testing and validation of the promising data-driven modeling approach.

2. Data Description

The dataset has been obtained through real operation of a hybrid photovoltaic-thermal (PVT) solar collector on a test bench in Austria. The measured variables presented in the dataset are illustrated in Fig. 10, shown in the following section.

Measurements from the PVT test bench and from the weather station are defined in Tables 1 and 2. The variables that are mostly relevant for data-driven parameter identification of a PVT collector model are marked with a * symbol in the last column labelled "For model" (as used in the related research article [1].

The data is provided in two formats: *datetime* in MATLAB and csv.

A sample of the table can be seen in Table 3. A graphical overview of the twenty-two variables is also provided in six figures (Figs. 1 to 6).

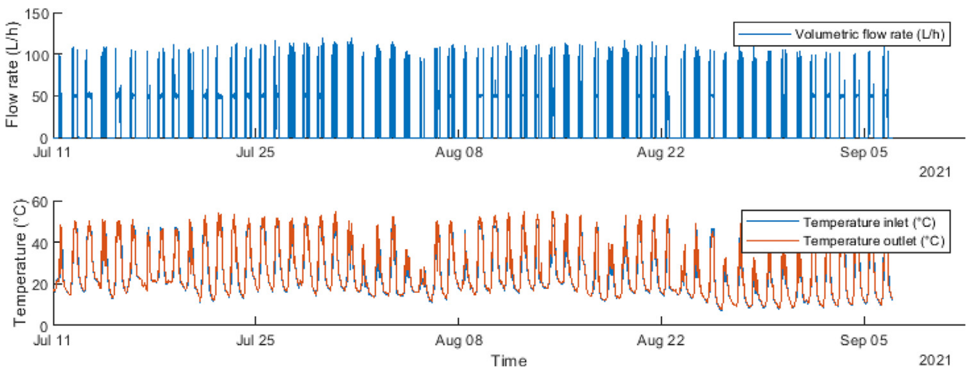

Fig. 1. Overview of variables (1/6)

Table 1
Description of measured variables on the PVT collector test bench and the weather station (1/2).

Measured variable	Name	Unit	Details	For model
Collector				
Inlet temperature	*T_fluid_in*	°C	of the heat transfer fluid at the collector inlet (PT100).	*
Volume flow rate	*flow_rate_fluid*	L/h	of the heat transfer fluid flowing through the collector. The very small negative values (no flow) are corrected to zero. (Magnetic-inductive flow meter (MID) from manufacturer KRONE)	*
Collector back surface temperature	*T_back_surf*	°C	Selected sensor on the backside, 70 cm from the lower edge (see Fig. 12) (PT100).	*
Collector back surface temperature (left)	*T_back_surf_left*	°C	Other sensor on the backside, 35.5 cm from upper edge, left side (see Fig. 12) (PT100).	*
Collector back surface temperature (right)	*T_back_surf_right*	°C	Other sensor on the backside, 35.5 cm from upper edge, right side (see Fig. 12) (PT100).	*
PV cell temperature	*T_PV*	°C	At the back of the PV panel, 14.5 cm from the lower edge of the collector (PT100).	*
Collector output				
Outlet temperature	*T_fluid_out*	°C	of the heat transfer fluid at the collector outlet (PT100).	*
PV current	*I_PV*	A	To calculate the PV panel electrical power output.	
PV voltage	*U_PV*	V	To calculate the PV panel electrical power output.	
Electrical power	*P_el*	W	Calculated from the measured current and voltage at the PV panel terminals. Corrected unexpected events of falling power through a Hampel filter.	*
Weather data at the collector				
Global tilted irradiance	*I_g_t*	W/m^2	in the tilted collector plane. An occasional error occurs at night, with values above 5000 W/m^2: these are corrected to 0 W/m^2. From SMP10 pyranometer (manufacturer KIPP&ZONEN)	*
Ambient air temperature	*T_air*	°C	Outside air temperature (NTC sensor).	*
Wind speed in the collector plane	*v_wind_t*	m/s	"Actual wind speed": 10 s average of second measurements, from WS200 sensor (manufacturer Lufft)	*
Wind direction in the collector plane	*d_wind_t*	°	"Actual wind direction": 10 s average of second measurements, from WS200 sensor (manufacturer Lufft)	

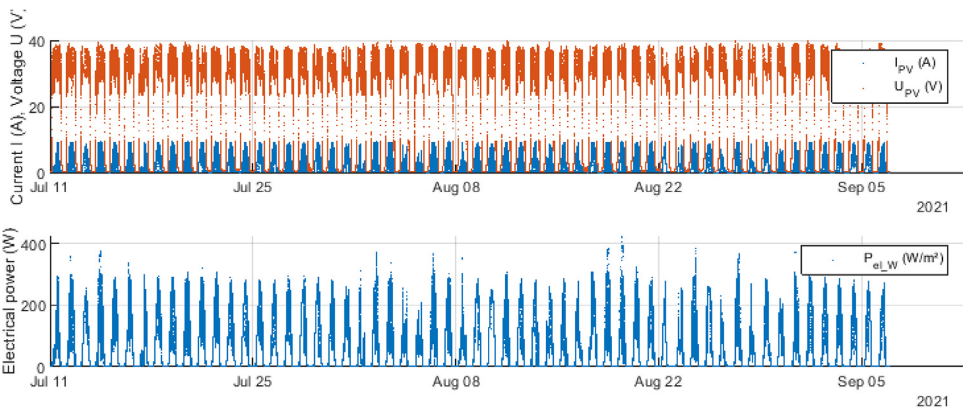

Fig. 2. Overview of variables (3/6)

Table 2
Description of measured variables on the PVT collector test bench and the weather station (2/2).

Measured variable	Name	Unit	Details	For model
Weather data from weather station (65 m away from the collector)				
Global horizontal solar irradiance	*I_g_h*	W/m^2	in the horizontal plane. From SMP21 pyranometer (manufacturer KIPP&ZONEN)	*
Diffuse horizontal solar irradiance	*I_d_h*	W/m^2	in the horizontal plane. From SMP21 pyranometer (manufacturer KIPP&ZONEN) with ball shadow	*
Direct normal solar irradiance	*I_b*	W/m^2	"beam" irradiance. From pyrheliometer (manufacturer KIPP&ZONEN)	
Equivalent radiative temperature of the sky	*T_sky*	°C	Calculated from $I_{ir_{sensor1}}$ downward longwave radiation, from SGR4 pyrgeometer (manufacturer KIPP&ZONEN)	*
Wind speed horizontal	*v_wind_h*	m/s	in the horizontal plane, WS600 sensor (manufacturer Lufft).	
Wind direction horizontal	*d_wind_h*	°	in the horizontal plane: 0 or 360 ° indicate North, 90 ° East, WS600 sensor (manufacturer Lufft).	
Sun elevation	*alpha_sun*	°	Sun position: elevation from the horizon (90 ° is vertical).	
Sun azimuth	*azimuth_sun*	°	Sun position: azimuth, starting at 0 ° from the North, positive to the East.	

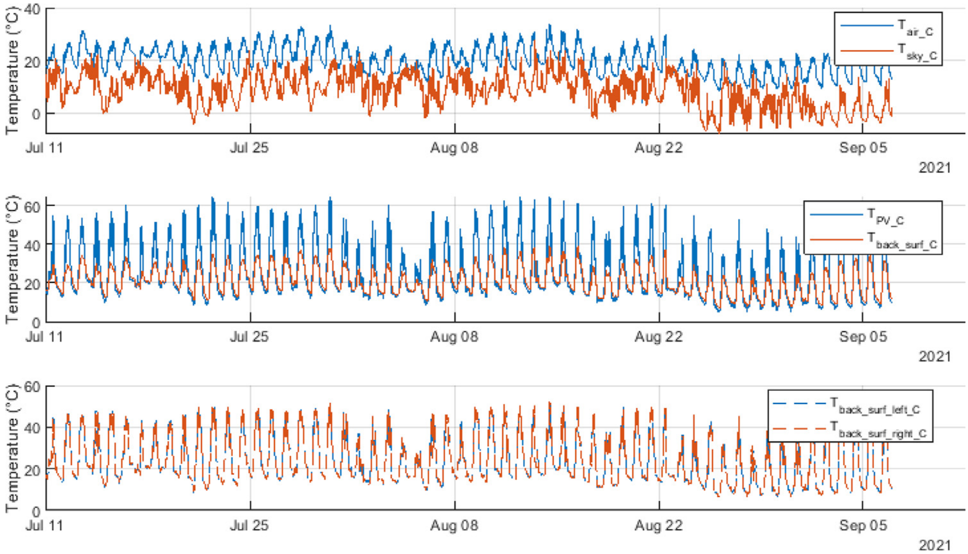

Fig. 3. Overview of variables (2/6)

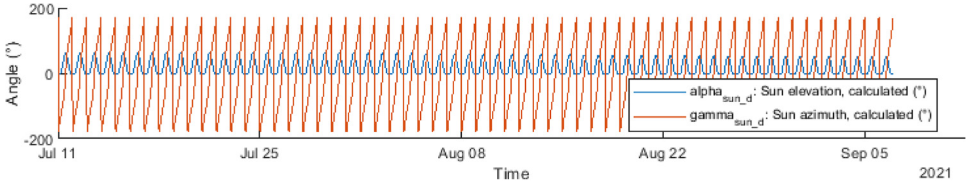

Fig. 4. Overview of variables (4/6)

Table 3
Sample of the dataset with PVT solar collector operation and the associated weather measurements.

date_time	T_fluid_ in_C	flow_rate_ fluid_lph	I_g_t_ Wpm2	T_air _C	T_PV _C	T_back _surf_C	T_back_ surf_left_C	T_back_ surf_right_C	v_wind_ t_mps	d_wind_ t_d	T_fluid_ out_C	I_PV _A	U_PV _V	alpha _sun_d	gamma_ sun_d	d_wind _h_d	v_wind _h_mps	P_el _W	I_b_ Wpm2	I_d_ Wpm2	I_g_ Wpm2	T_sky _C
’11-Jul-2021 00:00:00′	16.63	0	0	17.20	14.41	16.28	15.26	15.47	1.9	358.9	17.09	0	0.040	0	170.27	314.3	0.6	0	-4	-5	-6	5.33
’11-Jul-2021 00:00:05′	16.64	0	0	17.20	14.41	16.27	15.27	15.46	1.9	358.9	17.10	0	0.040	0	-170.24	314.3	0.6	0	-4	-5	-6	5.33
’11-Jul-2021 00:00:10′	16.63	0	0	17.21	14.41	16.28	15.26	15.46	2.2	352.8	17.09	0	0.037	0	-170.26	314.3	0.6	0	-4	-5	-6	5.33
’11-Jul-2021 00:00:15′	16.63	0	0	17.19	14.42	16.27	15.29	15.48	2.2	352.8	17.09	0	0.037	0	-170.28	314.3	0.6	0	-4	-5	-6	5.33
’11-Jul-2021 00:00:20′	16.64	0	0	17.21	14.43	16.29	15.27	15.47	1.9	340.2	17.10	0	0.037	0	-170.30	314.3	0.6	0	-4	-5	-6	5.33
’11-Jul-2021 00:00:25′	16.63	0	0	17.21	14.42	16.27	15.28	15.47	1.2	341.2	17.10	0	0.037	0	-170.32	314.3	0.6	0	-4	-5	-6	5.33
’11-Jul-2021 00:00:30′	16.63	0	0	17.22	14.43	16.28	15.27	15.48	1.2	341.2	17.09	0	0.040	0	-170.34	314.3	0.6	0	-4	-5	-6	5.33
’11-Jul-2021 00:00:35′	16.62	0	0	17.21	14.43	16.28	15.26	15.48	0.8	3.6	17.08	0	0.037	0	-170.36	314.3	0.6	0	-4	-5	-6	5.33
’11-Jul-2021 00:00:40′	16.62	0	0	17.20	14.43	16.27	15.26	15.49	0.8	3.6	17.09	0	0.040	0	-170.38	314.3	0.6	0	-4	-5	-6	5.33
’11-Jul-2021 00:00:45′	16.64	0	0	17.21	14.43	16.26	15.27	15.49	0.9	3.9	17.09	0	0.037	0	-170.40	314.3	0.6	0	-4	-5	-6	5.33

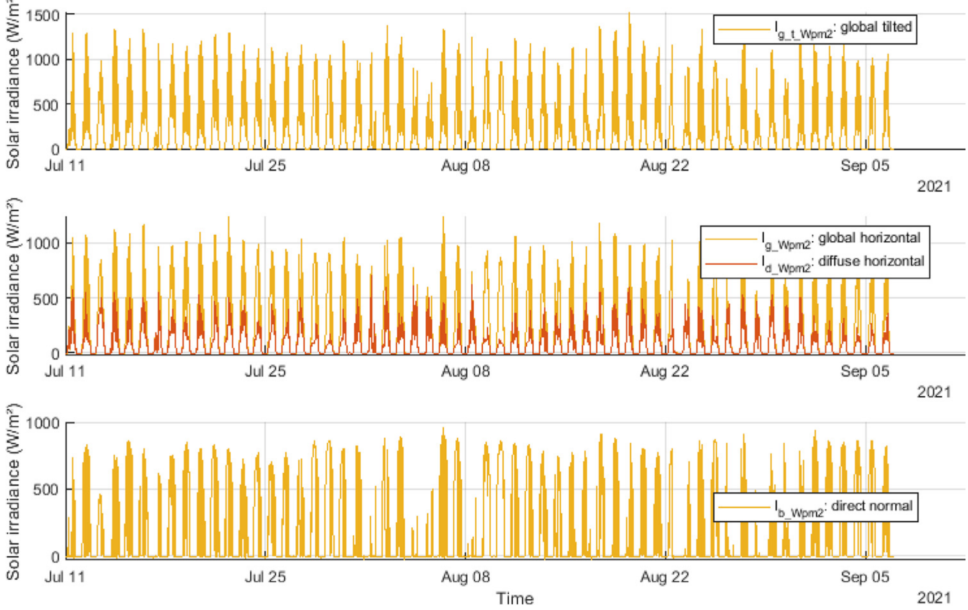

Fig. 5. Overview of variables (5/6)

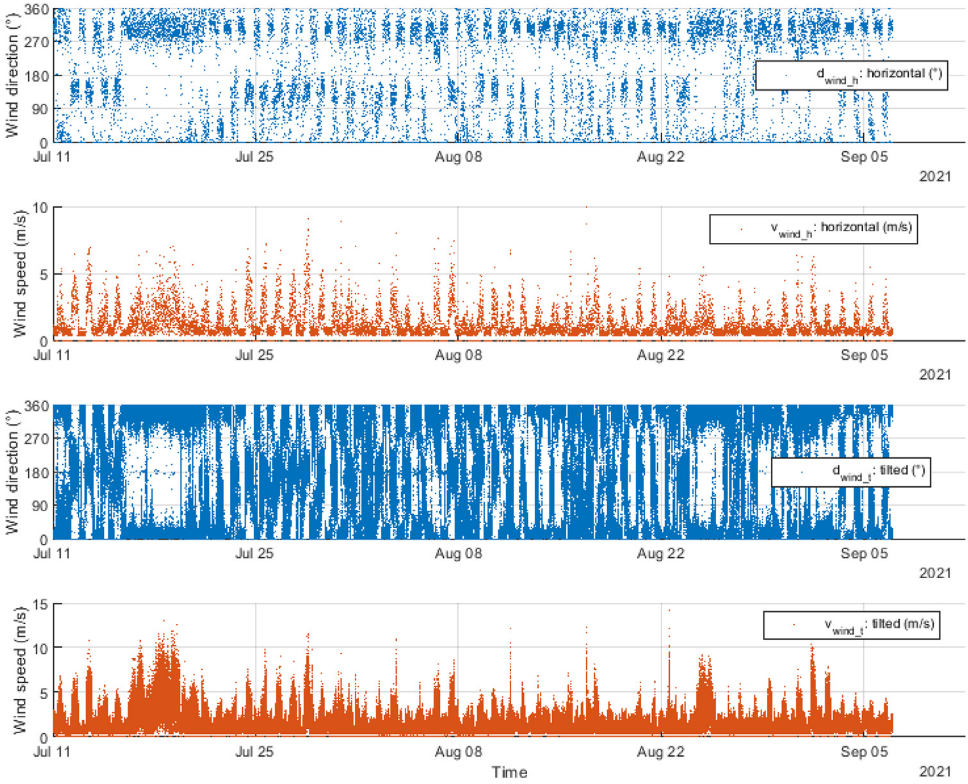

Fig. 6. Overview of variables (6/6)

3. Experimental Design, Materials and Methods

The following details the experimental setup, the sensors and the related variables monitored. The pre-processing of the data is detailed in an exhaustive way, exposing all steps followed to clean the raw measurement data, so as to obtain a useful dataset.

3.1. Experimental setup with PVT collector test bench

A PVT collector has been tested under real summer operating conditions. The photos in Fig. 7 show the collector test bench on the rooftop: the PVT collector is placed in the middle. To measure the wind speed and direction in the collector plane, yellow boards have been installed around the collector to extend the plane. This homogenises the convection fluxes around the collector and facilitates the integration of the wind sensor without shading the collector. The hydraulic circuit is located in the labor hall right underneath, as illustrated in Fig. 8 (left). The weather station, including a solar tracker, shown in Fig. 8 (right), is also on a flat rooftop.

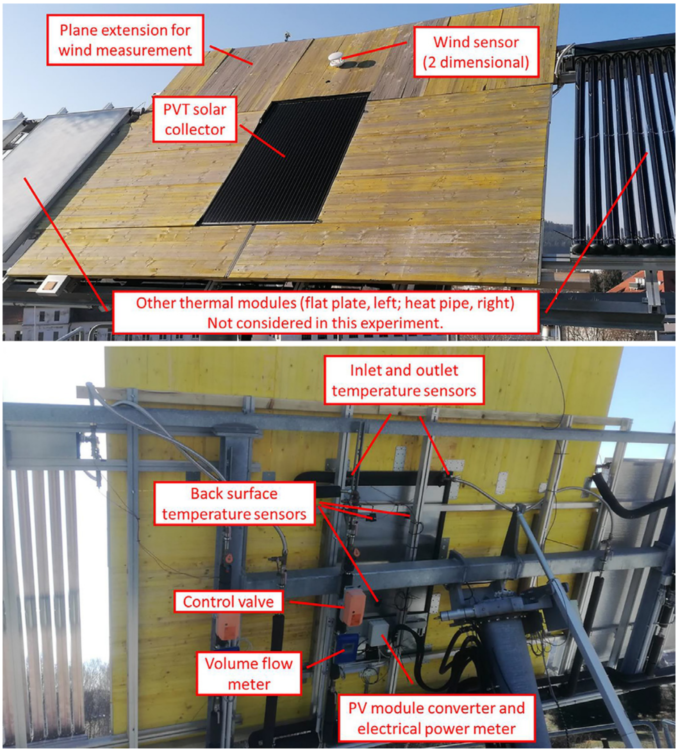

Fig. 7. Photos of the PVT collector test rig: front (top) and rear (bottom) views (with a different slope than in the experiment).

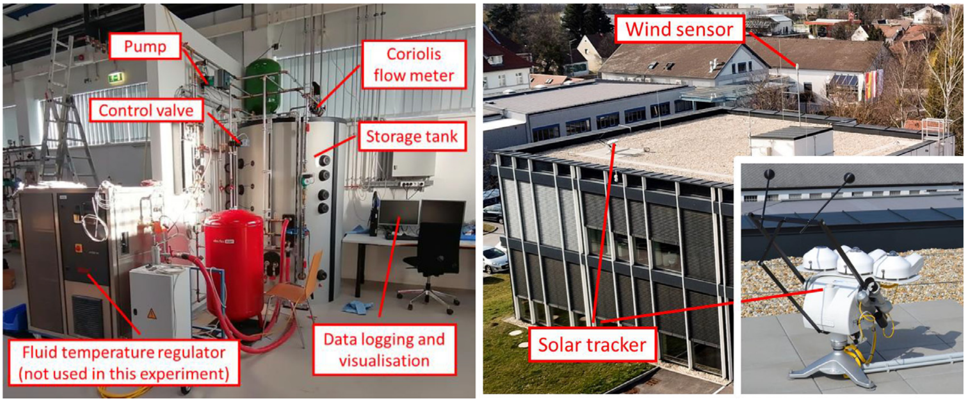

Fig. 8. Photos of the hydraulic circuit (left) and of the weather station nearby (right) with zoom on the solar tracker.

The tested PVT collector design is flat plate, non-covered, as schematized in Fig. 9: in the front is the glass of the PV panel (no air gap with additional glazed cover), in the back is the hydraulic heat exchanger (without back insulation). The schematic diagram of the experimental setup is presented in Fig. 10, with the hydraulic circuit connecting the PVT collector. The thermal storage tank reaches relatively high temperatures, because it is loaded by other solar collectors, running in parallel. Therefore, the PVT collector is brought to its highest temperature limit, with low thermal efficiency. The thermal energy is transferred to a buffer tank with the

Fig. 9. Principle section schema of the PVT collector used in the experiment

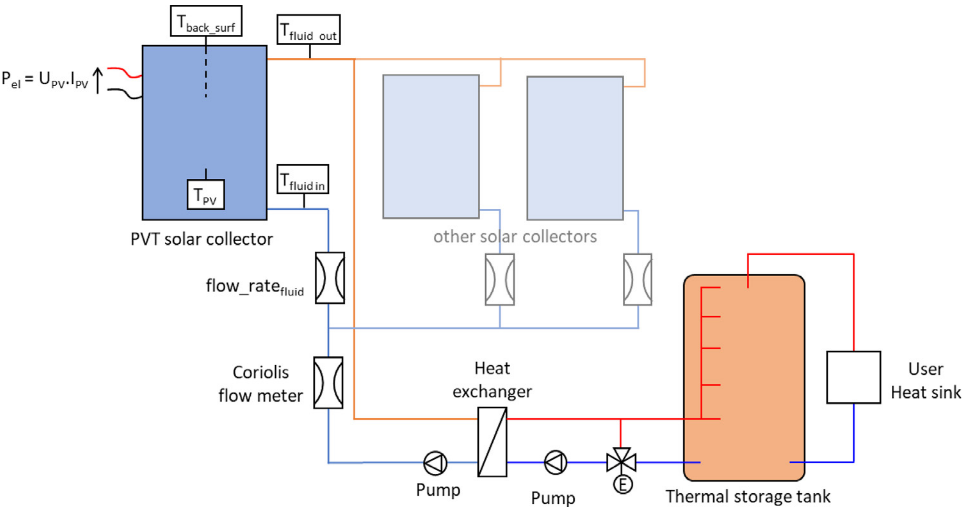

Fig. 10. Simplified hydraulic circuit and main sensors of the test bench with the hybrid PVT solar collector.

help of a pump, controlled with a variable mass flow rate. A Coriolis flow meter measures the total mass flow through all collectors of the test bench. By comparing with the volumetric flow measurements from the magnetic-inductive flow meters (MID), it is possible to determine the heat transfer fluid density. The photovoltaic (PV) panel in the PVT collector is controlled with Maximum Power Point Tracking (MPPT), ensuring the highest power output for any solar irradiance.

3.2. Time period and time step

The time range covers 58 days, from the 11th of July to the 6th of September 2021. Data from the PVT test bench are labelled with the Central European Summer Time (CEST) and Central European Time (CET). For the time period presented here, between July and September, the relevant time zone is CEST. It is converted to the Coordinated Universal Time (UTC) time zone for consistency with the measurements from the weather station, which are directly monitored in UTC time zone.

The data acquisition system is set to record measurements every 5 seconds. The actual recording time step vary slightly around this 5 s average, as Fig. 11 shows. The longest time step observed is 24 s, but only 276 time steps are longer than 7 s (less than 0.03 % of all time steps) and 2 longer than 10 s. The shortest time step is 2 s and it is the only time step below 3 s. Only 46 time steps are shorter than 4 s (less than 0.005 % of all time steps). The data represented in the dataset has been resampled to a regular time step of 5 s. This eases the analysis without altering significantly the raw data.

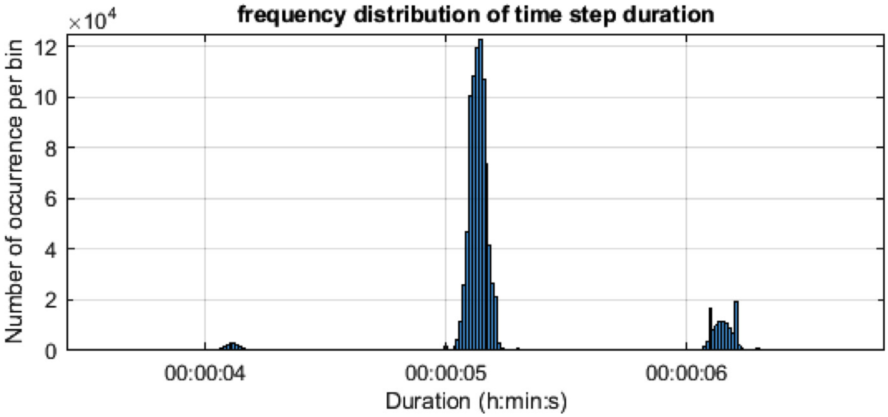

Fig. 11. Frequency distribution of time step in raw data acquired.

The raw data is imported from the monitoring system in daily files. If the time step is 00:00, it happens that this time step is stored as the last time step in the file of the previous day. When setting the date based on the file number, it is wrongly defined for this time step, which should be the first of its day. The correction of this issue is implemented. In this small collector field, the time delay between inlet and outlet is short, but it should not be overseen, when using the 5 s time step.

At some isolated time steps, no data has been stored. As these are punctual events of single time steps, the missing data is filled with an average value of the previous and next time steps.

3.3. Geographical parameters and weather data

The location of the experiment is Pinkafeld, in Austria: 47.358162 ° latitude (North) and 16.128405 ° longitude (East), at an altitude of 400 m over sea level.

The collector is mounted on a biaxial sun-tracker, on the roof of the laboratory hall. Nevertheless, the data presented here are with a fixed position of the tracker, corresponding to most PVT collector applications. The position of the collector is defined by two angles, set as follow:

- tilt (from horizontal): $Slope\_PVT\_d = 20\,^\circ$
- azimuth (from North, ascending to the East): $Azimuth\_PVT\_d = 180\,^\circ$

Measurements of the slope and azimuth of the collector confirm that the collector remained in a fixed position during the selected time period. These measurements are raw values, given in mA, so they are not directly exploitable.

Global solar irradiance I_g_t (W/m^2) is measured in the tilted collector plane. Complementarily, global horizontal irradiance I_g_h (W/m^2) and diffuse horizontal irradiance I_d_h (W/m^2) are provided. The direct normal irradiance I_b (W/m^2) (from the sun beam) is also measured with a high quality pyrheliometer. This enables to test various situations, with different available information on the solar resource.

On the global solar irradiance in the collector plane, punctual occurrence of very high values ($>$ 5000 W/m^2) are observed in the night. These values are corrected to zero.

In complement, the coordinates of the sun position are calculated based on the Duffie und Beckmann model [2]. The sun position is given by its elevation $alpha\_S$ (°) and its azimuth $gamma\_S$ (°).

Beside the solar resource, important weather variables are the ambient air temperature T_air (°C) and the wind speed v_wind_t (m/s) in the collector plane (t for tilted). These boundary conditions are directly related to the thermal losses of the collector. The wind direction d_wind_t (°) is also measured in the collector plane.

To support stability of the measurements, wind speed and directions are 10 s averages of second measurements: the stored values are averages of 10 measurements. Both wind speed and direction are corrected to zero, when irregular values over 400 are observed.

The wind speed v_wind_h (m/s) and direction d_wind_h (°) from the weather station are measured in the horizontal plane (h for horizontal). Values over 1000 are corrected to zero. These variables are not used in the model, but are provided here. This complementary information could be of interest for further investigations, to establish models relying only on horizontal wind data from a weather station, instead of data specifically measured in the collector plane.

The radiative equivalent sky temperature T_sky (°C) is derived from measurements of a SGR4 pyrgeometer (manufacturer KIPP&ZONEN). This measuring device provides directly the downward longwave irradiance $I_{ir\_sensor1}$ (W/m^2). The temperature T_sky is calculated as:

$$T\_sky = \left(\frac{I_{ir\_sensor1}}{\sigma}\right)^{\frac{1}{4}} - 273.15$$

with $\sigma = 5.67 \times 10^{-8} W/(m^2K^4)$ Stefan-Bolzmann constant.

3.4. Collector data and pre-processing

Key boundary conditions are the inlet temperature T_fluid_in (°C) and flow rate $flow\_rate\_fluid$ (L/h) of the heat transfer fluid through the collector.

The temperature at the back of the collector helps assess the thermal losses of the collector. The back surface temperature is measured in three points, as presented in Fig. 12. Two are placed in the upper half: $T\_back\_surf\_left$ and $T\_back\_surf\_right$ (°C). The third one T_back_surf (°C) is more centrally placed, at 70 cm from the lower edge of the collector. This third sensor is selected for modelling to best represent the back surface temperature.

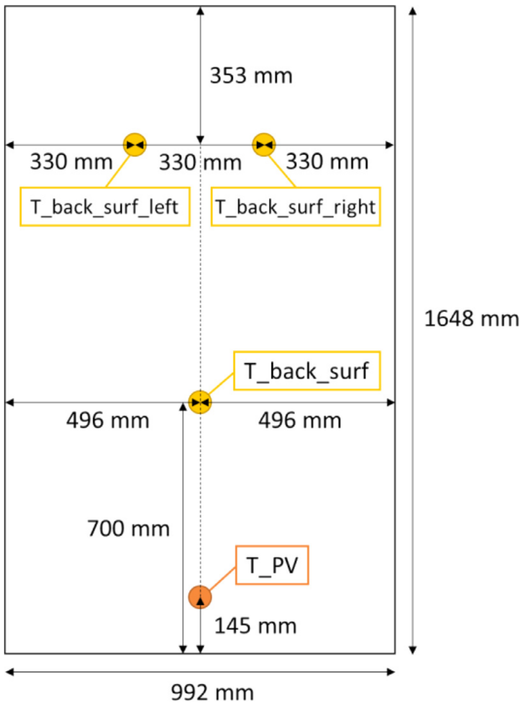

Fig. 12. Position of temperature sensors on the collector back surface and on the back side of the PV panel.

The temperature of the PV absorber *T_PV* (°C) is also an important variable, related to the PV efficiency. But it might not be necessary to use it as input of a model. It is measured directly at the backside of the PV panel, the closest to the PV cells. It is measured in the lower part of the collector (14.5 cm from the lower edge).

The energy production of the collector has to be calculated from several measurements:

- the electrical power *P_el* (W), produced by the collector, calculated from the current *I_PV* (A) and voltage *U_PV* (V) at the PV collector terminals as:

$$P\_el = I\_PV.U\_PV$$

- the thermal power *Q_dot_u* (W), produced by the collector, calculated in particular in function of the temperature *T_fluid_out* (°C) and knowing the characteristics of the heat transfer fluid: a mixture of demineralised water with 43 % mono-propylene-glycol by mass, having a thermal capacity of $c_{p_{fluid}} = 3650 J/(kg.K)$ and density of $density\_fluid = 1040\ kg/m^3$:

$$Q\_dot\_u = flow\_rate\_fluid.density\_fluid.c\_p\_fluid.(T\_fluid\_out - T\_fluid\_in)$$

The electrical power regularly happens to fall to zero for a short period of time and then ramp back up, without any corresponding change in the solar radiation. These events of reduced power output of the PV panel typically last about one minute, sometimes up to five minutes. This failure is measured on the current output, which supports the hypothesis of a malfunction of the PV control system (Maximum Power Point Tracker (MPPT), or inverter). This irregular behaviour of the PV panel is not modelled. On the one hand because the failure occurs at unpredictable times, independent on the solar irradiance or other (measured) environment parameters. On the other hand because the objective is to model the normal behaviour of the PV system. A deviation from the expected output can therefore be interpreted as a system failure, indicating a need for maintenance. Therefore, the electrical power is filtered to correct for these irregular events. A Hampel identifier [3] is applied on the ratio *P_el* / *I_g_t* of the electrical power *P_el* over the global solar irradiance in the collector plane *I_g_t* (when $I\_g\_t > 0$) to correct outlier values. The neighbours within a 30 minutes time span, centred on the observed time step, are used, corresponding to 360 values with the 5 second time step. Two standard deviations are considered to define an outlier, slightly sharper than the default three standard deviations. The values of *P_el* greater than 2 W are corrected according to this Hampel filter. Fig. 13 shows the effect of the Hampel filter on *P_el* by comparing raw data and corrected data. The corrected data of *P_el* are presented in the dataset. The PV panel current *I_PV* and voltage *U_PV* are provided as raw data: this enables to visualise the failure on *I_PV*.

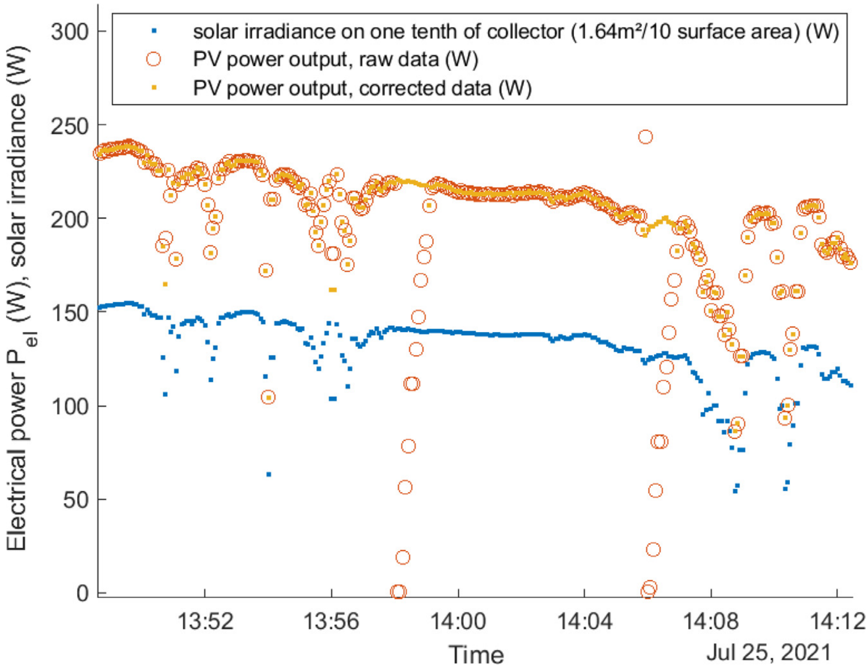

Fig. 13. Effect of the Hampel filter on the PV electrical power

Small negative values of the fluid flow rate ($flow\_rate\_fluid > -0.2\ L/h$) are corrected to zero.

Ethics Statements

This work respects ethics in science.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Measurement dataset from real operation of a hybrid photovoltaic-thermal solar collectors, used for the development of a data-driven model (Original data) (Dataset or other products (fh-burgenland.at)).

CRediT Author Statement

François Veynandt: Data curation, Visualization, Writing – original draft; **Franz Inschlag:** Methodology, Investigation, Writing – review & editing; **Christian Seidl:** Software, Investigation; **Christian Heschl:** Conceptualization, Methodology, Supervision, Funding acquisition.

Acknowledgments

Thank you to Helmut Plank for his help in designing the experiment. Thank you to Patrick Luif, Markus Brenner, Lukas Klein and Mark Grill for their support in building the test bench and running the experiment.

This work was elaborated within the PVadapt project and has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 818342.

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