Comparison of PV and PVT Energy Yield for Low-Temperature Process Heat: a Case Study

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Abstract

Solar energy's integration for industrial decarbonization remains in its early stages. Limited cases of its use in brewing processes are found within medium to large breweries. Brewing, requiring low-temperature heat and cold, suits a solar-assisted polygeneration system well. Unlike larger breweries, microbreweries commonly lack steam boilers, often using gas burners or electric resistors for heat and small vapor-compression chillers for cold. A proposed solution involves a hybrid photovoltaic-thermal (PVT) system preheating brewing water and generating electricity, curbing CO_2 emissions. Research assessed PV and PVT systems' energy output atop a Spanish microbrewery using real load profiles and simulations in TRNSYS. Results indicate the PVT system covering up to 17% to 30% of electric consumption and 20% to 35% of heat demand, for a Central Europe and a Mediterranean location. Notably, the PVT system outperforms PV by 8% to 31% in energy yield, accounting for electricity and useful heat. Despite its energy advantages, the current market conditions render the PVT system less cost-effective than PV systems due to high initial investment and maintenance costs. Recommendations for enhancing its cost-effectiveness are proposed to stimulate further research in this area.

Keywords: SHIP, PVT, microbrewery, solar industrial heat, cogeneration

1. Introduction

Hybrid photovoltaic-thermal (PVT) solar collectors prove advantageous for cogeneration, particularly in situations with limited space, as they occupy less area compared to separate PV and thermal systems. This makes them a viable choice for industries constrained by roof space. Additionally, PVT solar collectors demonstrate the capability to yield higher energy outputs than separated PV and solar thermal systems. Consequently, they emerge as an appealing solution for small-scale industries such as the microbrewery under which require both heat and electricity. However, their operational temperature upper limit for the fluid circuit remains low, typically below 70°C, thus narrowing down their potential applications in contrast to solar thermal collectors. Therefore, therefore it is possible to use the low-grade heat as heat source for heat pumps, what allows higher efficiency and performance (Coca-Ortegón et al., 2023; Herrando et al., 2023). However, the economic assessment it vital to decide if this configuration is cost-effective. On the other hand, the low-grade heat can be used directly to preheat a fluid for an industrial process. Various PVT technologies exist with different cooling approaches, currently at varying stages of development (Ghazy et al., 2022). Among these, flat-plate collector types with water or air as cooling fluids stand as the most prevalent options.

In the last 20 years, the rise of microbreweries, i.e., producing under 5,000 hL annually, has been consistent, indicating ongoing market growth (Garavaglia & Swinnen, 2017). In the US, microbreweries surged from 1,596 in 2009 (Brewers Association, 2015) to 8,895 in 2021 (Brewers Association, 2022). Similarly, in Europe, they grew from 3,020 in 2011 to 8,937 in 2020 (The Brewers of Europe, 2021). Brewing demands high energy, especially in small-scale setups with higher specific energy consumption and increased energy costs. Thus, integrating solar energy seems a cost-effective fit for small breweries and microbreweries.

Roughly fifteen solar heat plants for industrial processes (SHIP) have been established to supply heat to breweries and cider makers (AEE INTEC, 2023). Primarily situated in Central Europe, notably in Germany (Schmitt et al., 2012) and Austria (Mauthner et al., 2014), these plants received partial subsidies. In September

10.18086/swc.2023.04.11 Available at http://proceedings.ises.org

2023, a 30 MWth SHIP plant (the largest of Europe), was inaugurated in Seville, supplying up to 60% of the annual heat demand for the Heineken brewery (Engie España, 2023). However, high upfront and upkeep expenses often deter clients from adopting solar thermal solutions without subsidies. In contrast, breweries, including microbreweries, have installed over 100 photovoltaic (PV) systems due to lower initial costs and simpler maintenance (van der Linden & Wolf, 2019). Likely underreported, the actual number of PV systems in breweries surpasses reported figures. While relatively low compared to total breweries, the inclination towards PV adoption is anticipated to persist. No literature references PVT system integration in breweries.

The present research assesses the energy output of three PVT system sizes in contrasting climates: Malaga, Spain, and Stuttgart, Germany, and compared these results with ones obtained for standard PV systems. A PVT system could potentially decrease heat demands by raising initial water temperatures, cut grid electricity usage through self-generation, and reduce the electric peaks due to use of heat storage (only possible including a thermal storage tank). Employing a TRNSYS simulation model the energy demand and the PVT and PV systems' energy yield is obtained. Finally, from the results of the energy assessment an economic analysis is performed, considering real energy expenses for these small industries and the market prices of components and installation for system analysis.

2. Methodology

The study's methodology involves simulating the heat, cold, and electricity requirements for brewing, computing the energy needed to meet these demands, evaluating energy generation from PV and PVT systems, and conducting an economic assessment concerning payback periods and return on investment. TRNSYS 18 (Klein et al., 2017) calculates brewing energy needs and models PV/PVT system performance using local weather data, system parameters, and component specifics. In this case recommendations to model and simulate SHIP systems to reduce uncertainty in the results have been taken into account (Cardemil et al., 2022). The economic analysis relies on MS Excel for assessment.

2.1. Base Case and PV and PVT integration

The brewery components' energy interactions are simulated in TRNSYS 18, employing a model validated with a Jerez de la Frontera microbrewery's data (Pino et al., 2023). The case study brewery relies solely on electricity, even for process heat (immersed electric heaters: resistors). The analysis includes two locations: Malaga and Stuttgart (Table 1). The brewery produces 650 L batches three times per week, totaling 1000 hL yearly. Brewing days drive higher energy use; continuous electric demand maintains fermenter and maturer temperatures via an air-water chiller and a 1.3 m^3 cold storage tank. An ACHP system maintains a constant 20°C for beer conditioning throughout the year.

Tab. 1: Main climate characteristics and electric rates for the two locations.

PV	**Malaga**	**Stuttgart**	
Global Horizontal Irradiation (GHI), kWh/m^2	1832	1088	
Direct Normal Irradiation (DNI), kWh/m^2	2001	880	
Ambient temperature range, °C	1 to 41	-13 to 32	
Average ambient temperature, °C	18	9	
Temperature of the water from the, °C	16.7 -28	6.1 - 14	
Electricity Price, cent€/kWh (S1/2023)	20.5	29.1	

Figure 1 illustrates the yearly energy requirement and electrical usage for the Malaga base case, without solar energy (left). Notably, the most substantial energy usage involves heating water/wort before boiling. The right diagram depicts the hourly electricity demand for one sample week in May. It can be observed the amount of electric energy employed for process heat (for both heating water and boiling) in yellow bars. This causes peaks of electricity demand from the grid.

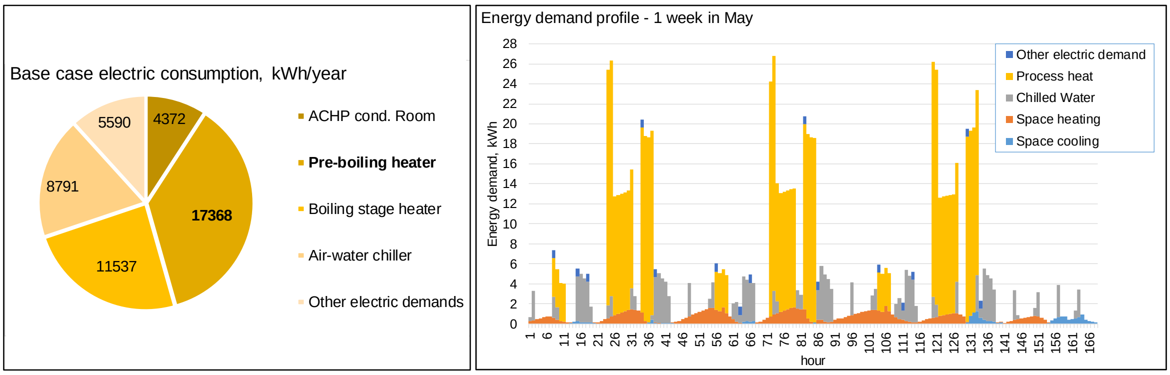

Fig. 1: Base case energy demand (left) and hourly electric consumption for a sample week in May disaggregated by component (right) for Malaga.

2.2. PV and PVT specifications

The proposed PV system aims to connect to the main network using an on-grid inverter to inject excess electricity into the grid. Similarly, the PVT system offers this grid surplus option via an inverter but also integrates a pump, hydronic elements, and a stainless steel thermal storage tank (1.5 m^3 volume, U-value: 0.3 W/m^2K). This tank supplies pre-heated water to the brewing process, a critical ingredient without a return stream. The mains supply the production water, treated to eliminate elements that might impact beer flavors. Figure 2 illustrates the PVT system's integration scheme, with the electric output (yellow) linked to an inverter and the thermal circuit connected to the storage tank (blue: cold water, orange: hot water). It also displays the temperature levels for heat (Qh) and cold (Qc) provided by the various components. The detailed components' specification and performance can be consulted in the simulation tool reference (Pino et al., 2023).

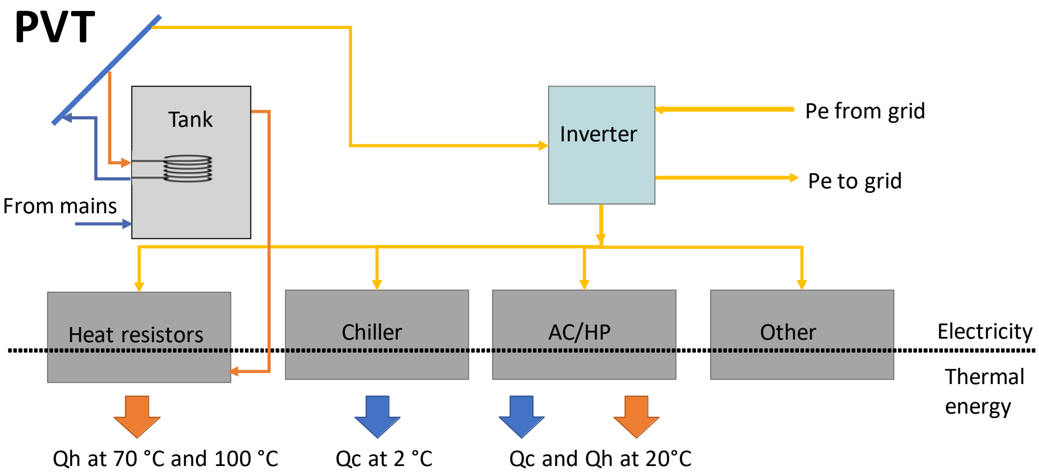

Fig. 2: Schematic diagram of electric and thermal integration of the PVT system in the brewery.

The PV and PVT systems' performance relies on mathematical models within TRNSYS's component library. Type 94a represents the PV module, specifically the Sunrise Solartech SR-M660260, while Type 50 models the PVT module selected for this study: PVT ENDEF390 W. Table 2 details specifications for both modules, with the PVT module having an electric datasheet (Endef Solar Solutions, 2023) and a Solar Keymark certificate for thermal performance (AENOR Internacional S.A.U., 2022). The grid-connected PV inverter is modeled using the Sandia Performance Model (King et al., 2007).

Tab. 2: Specifications for selected PV and PVT modules.

Parameter	**PV**	**PVT**	**Unit**
Nominal power (Pmax)	260	390	Wp
Nominal voltage (Vmp)	30.4	38.5	V
Maximum current (Imax)	8.6	10.13	A
Open-circuit voltage (Voc)	37.4	46.3	V
Short-circuit current (Isc)	9.2	10.87	A
Module efficiency	16.02	19.9	%
Power temperature coefficient	-0.495	-0.27	%/K
Gross area	1.623	1.96	m2
Flow rate for testing	-	0.023	Kg/(sm^2)
a0	-	0.36	-
a1	-	8.71	W/(m^{2}K)
a2	-	0.048	W/(m^{2}K^2)
IAM (50°)	-	0.84	-
Standard stagnation temperature	-	79	°C

2.3. Energy price and system costs

In Spain and Germany, the electricity that regulated users observe in their billing receipt is separated into a fixed term and a variable term. The fixed term represents mainly the cost for the contracted power, whilst the variable term represents the cost of the energy consumed. Since under the scope of this study the contracted power is not varied, only the variable term will vary with self-generated electricity. In addition, a net-billing scheme where the energy injected to the grid is payed as 40% of the energy purchased from the grid is assumed. The electricity rates employed in this study are 0.205 €/kWh for Spain (energigreen, 2023) and 0.291 €/kWh for Germany (Destatis, n.d.), based on the average electric price for regulated user in the small-scale industry (>15 kW contracted power and <50 MWh annual consumption) for the first semester.

Prices for the PV and PVT systems' components were gathered from benchmark sources [16] and direct supplier quotes in Spain. Table 3 presents the detailed costs utilized in this analysis. To facilitate comparison, the PV cost per unit capacity (€/Wp) is a common format, similarly applied to specify the PVT values. The Balance of the System (BoS) for the PVT setup encompasses the pump, pipes, expansion tank, and electric components.

Tab. 3: Specific cost of the PV and PVT components.

	Item	**Specific cost**	**Unit**
Photovoltaic (PV)	PV Module	0.4	€/W$_{DC}$
	Inverter	0.2	€/W$_{DC}$
	BoS equipment	0.2	€/W$_{DC}$
	Installation labor	0.3	€/W$_{DC}$
	Total PV system cost	**1.1**	**€/W$_{DC}$**
Photovoltaic-thermal (PVT)	PVT Module	0.82	€/W$_{DC}$
	Inverter	0.2	€/W$_{DC}$
	BoS equipment (elec. + hydraulic)	1.33	€/W$_{DC}$
	Installation labor	0.7	€/W$_{DC}$
	Total PVT system cost	**3.05**	**€/W$_{DC}$**
	Storage tank with HX	2000	€/m^3

Hence, the calculated total costs for the proposed systems stand between 5,500 € for the 5 kWp PV system and 16,500 € for the 15 kWp version. As for the complete PVT system, encompassing the 1.5 m^3 thermal storage, the total cost ranges between 18,259 € for the 5 kWp and 48,778 € for the 15 kWp size. The study assumes a 3% discount rate over a 25-year period.

3. Results and discussion

The simulation results show promising solar energy yields. As expected, due to the higher solar resource in Malaga, the energy yield for Malaga is higher than for Stuttgart, in all comparable configurations studied (e.g., 5 kW PV in Malaga vs 5 kW PV in Stuttgart). In addition, PVT systems provide added valuable heat, reducing initial brewing heat needs, when compared with a PV system of the same size at the same location. Table 4 details energy values (electricity and thermal) for both locations and the six systems studied (three PV, three PVT). Assessing total useful energy (electricity + heat), in Malaga a 5 kW PVT system outperforms a regular PV by 29%, while in Stuttgart, it is 31% higher. For a 15 kWp PVT system, Malaga yields 11% more than regular PV, and Stuttgart shows an 8% increase.

Tab. 4: Annual energy figures for the PV and PVT systems in both locations.

	Annual energy values, kWh								
	Pre-boiling heat	**Boiling heat**	**Total Heat**	**Total elect. consumption**	**PV generation**	**PV electricity self-consumed**	**PV elect. sold**	**Useful heat from tank**	**Total solar energy (elec. + heat)**
Malaga									
Base case	17368	11537	28905	47656	0	0	0	0	0
PV 5 kW					9381	7889	1492	0	9381
PV 10 kW					18761	11686	7075	0	18761
PV 15 kW					28142	13643	14499	0	28143
PVT 5 kW	14223		25760	44512	8839	7480	1359	3231	12069
PVT 10 kW	13431		24969	43725	17727	11072	6655	4042	21769
PVT 15 kW	12943		24481	43241	26640	12860	13779	4543	31183
Stuttgart									
Base case	20967	11555	32523	59596	0	0	0	0	0
PV 5 kW					5661	5068	593	0	5661
PV 10 kW					11323	8480	2843	0	11323
PV 15 kW					16984	10832	6152	0	16984
PVT 5 kW	18522		30077	57153	4920	4430	490	2512	7432
PVT 10 kW	17913		29468	56544	9865	7467	2398	3137	13002
PVT 15 kW	17557		29112	56187	14824	9587	5237	3502	18326

Considering the self-consumed electricity and not the net-billing valued, the PVT system covers between 17% and 30% of the total electric demand in Malaga, depending on the size. For Stuttgart this ranges vary from 8% to 17%. In the case of heat demand, 23% to 35% can be cover with the PVT in Malaga, and between 14% and 20% in Stuttgart. These results infer that the 15 kW PVT system is oversized for the demand. Stuttgart's lower PV generation is partially compensated the PVT system's enhanced yield due to lower mains water temperatures, boosting solar thermal efficiency. For instance, when comparing a 5 kW PVT system in Malaga and in Stuttgart (Table 5), the former yield 80% more electricity than the latter, but only a 29% more useful heat, regardless that the annual GHI is 68% higher in Malaga than in Stuttgart.

Tab. 5: Comparison of PVT electric and heat performance for a 5 kW system in Malaga and Stuttgart.

Annual GHI ratio	PV generation ratio	Useful heat from tank ratio
$\frac{GHI_{Malaga}}{GHI_{Stuttgart}} = \frac{1832}{1088} = 1.68$	$\frac{PVgen_{Malaga,5kW}}{PVgen_{Stuttgart,5kW}} = \frac{8839}{4920} = 1.80$	$\frac{Qu_{Malaga,5kW}}{Qu_{Stuttgart,5kW}} = \frac{3231}{2512} = 1.29$

When the economic figures are analyzed, the findings appear less favorable for PVT. The substantial investment in the PVT system, notably in the BoS, labor, and the thermal storage tank, renders it less cost-efficient than a regular PV system, under the economic parameters assumed in this assessment. Figure 3 illustrates the cumulated cash flow for both PV and PVT systems with capacities of 5 kWp, 10 kWp, and 15 kWp for Malaga (left) and Stuttgart (right). In all cases the PV systems prove profitable for both locations, with low payback periods (under 5 years). The similarity between the results of Malaga and Stuttgart is caused by the lower solar radiation in Stuttgart is nearly compensated by the higher electricity rates than in Malaga (0.291 vs 0.205 €/kWh, respectively). Moreover, the higher investment in PVT systems leads to higher payback periods, ranging from 12 to 20 years for the 5 kW and15 kW systems in Malaga, respectively. In Stuttgart the payback periods are slightly longer, 14 years for the 5 kW system and 22 years for the 15 kW system. Regarding net present value (NPV) for PV the largest system will lead to the higher profit in both location, whilst for PVT system the two smaller systems (5 and 10 kW) will lead to the higher profit. Nevertheless, when comparing same-sizes PV and PVT systems for each location, the PV system will always offer higher NPV than the PVT.

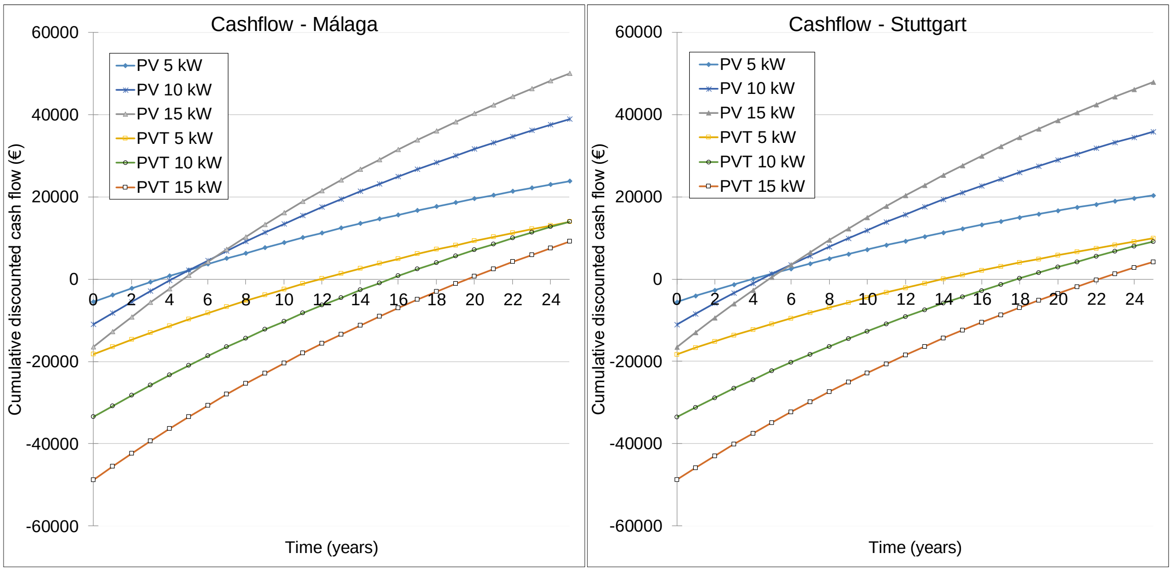

Fig. 3: Cumulated cash flows for the different PV and PVT systems in Malaga and Stuttgart.

4. Conclusions

The comprehensive yield of PVT systems, comprising heat and electricity, surpasses the electricity output of PV systems of comparable sizes. The 5 kWp PVT system yields 29% more in Malaga and 31% more in Stuttgart compared to PV. Similarly, the 10 kWp PVT system outperforms PV by 16% in Malaga and 15% in Stuttgart; while the 15 kWp PVT system outperforms PV by 11% in Malaga and 8% in Stuttgart. Therefore, it is recommended to avoid oversizing the PVT system, especially with a load profile highly variable as in batch processes, since the thermal energy benefits over regular PV are decreasing with larger systems due to lower utilization of the heat. Further sensitivity studies should be performed with different thermal storage sizes. When only electric generation is considered, the PVT model selected performs worse than the PV of same size due to the higher operation temperature, which impacts in the cell efficiency.

The drawback of PVT systems lies in their high investment and operation/maintenance costs. The initial investment for PVT, excluding thermal storage, is nearly three times that of a standard PV system. Normalizing by electric capacity reveals a cost of 1.1 €/kWp for PV versus 3.05 €/kWp for PVT. Operation and maintenance costs for PVT systems significantly impact economic analyses due to movable components (e.g., pumps) and hydronic elements.

Economic analysis shows PVT systems in Malaga and Stuttgart lead to lower long-term profit (NPV) and higher payback period that a regular PV of comparable size. A conclusion in this regard is that, although having energy storage behind-the-meter reduces the grid stress by clipping load peaks, under the current electric market conditions it adds no economic value for the user. Manufacturers and developers should focus on reducing additional balance of system costs to foster PVT system proliferation despite advanced technology and contained module costs.

Future research aims to explore alternative hydraulic integration schemes for PVT systems to cut costs in thermal storage and hydronics. In addition, collaboration with actual breweries is vital to understand their requirements due to material restrictions for food and beverage production. Finally, implementing active control of PV-generated energy, especially with electric or thermal storage, could optimize system economic performance by leveraging time-of-use electric rates.

5. Acknowledgements

The authors would like to thank ENDEF for providing economic and performance data of their PVT collectors.

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