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Evaluation of a solar photovoltaic thermal (PVT) system in a dairy farm in Germany

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A R T I C L E I N F O

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A B S T R A C T

Livestock farms are a major contributor to CO_2 emissions. The use of renewable energy sources (RES) is an important step to mitigate emissions from farms. This paper develops and evaluates a market-integrated, cost-effective, and case-sensitive RES solution for livestock farms. For this purpose, the dairy farm at LVAT-ATB in Germany; which includes three barns for milk production with a total area of 3950 m^2, was considered. A solar PVT system is designed to most effectively use the heat recovery of the milk coolers and to use the thermal heat from the PVT system to lift the inlet temperature of an electric boiler (E-boiler) and reduce grid electricity consumption. The performance and monthly thermal output of the designed PVT system are evaluated using two different PVT collectors; Solarus (concentrated) and Dual Sun (flat plate). A preliminary analysis was performed to determine the PVT collector most suitable for the livestock farm here studied. The DualSun collector generated a higher electricity output than the Solarus C-PVT, however, the C-PVT was able to reach higher temperatures. Since the LVAT-ATB farm site included an existing heat recovery system, the integration point was carefully defined and a semi-automated system was incorporated to (1) use the heat from the heat recovery system as the inlet heat for the PVT system and (2), to use the PVT buffer tank as additional storage to store excess heat from the heat recovery system. Using this approach, a maximum amount of thermal energy can be stored. The PVT system would further raise the temperature from the heat recovery system and thus minimize the electricity consumption of the E-boiler. Furthermore, a draft layout of all the components and outdoor enclosure was presented. 24 Solarus PVT collectors running at mean temperature of 45 °C meet 16% of the annual hot water demand of the dairy farm by direct solar heat and this number of PVTs can supply up to 38% of hot water demand in summer months. The payback period for this system is less than 6 years and annual electrical energy utilization ratio and highest solar thermal fraction are 9.7 and 51.9%, respectively. Furthermore, 24 PVTs on an annual basis, generate slightly more than 4,200 kWh of electricity that can be used to offset electricity consumed by electric boilers in the LVAT farm.

1. Introduction

Due to the accessibility of low-cost fossil fuels in agriculture over the past century, countries have been able to meet higher food demands and it will be extremely difficult to boost food production enough to meet projected food demand by 2050. Fossil fuel consumption in the agricultural sector has negative effects becoming a major source of greenhouse gas (GHG) emissions, with significant contributions to global climate change and the risk of food security [7,26]. Dairy farming is one of the most energy- and emission-intensive industrial sectors and offers noteworthy opportunities for displacing conventional fossil-fuel consumption both in terms of cost-saving and decarbonization. The main energy demands in dairy farms include electricity for pumps, refrigeration, storage, control, separation, lighting, etc., and thermal energy for pasteurization, evaporation, drying, cleaning, etc. The required temperature of thermal energy ranges from 20 °C to 200 °C, depending on the processes. Typically, low-temperature heat below 80 °C is used for thermalization, pasteurization, cleaning, preheating, concentration, etc., and higher-temperature heat at around 110 °C-180 °C is required for sterilization, ultra-high temperature processing, drying, etc. [27].

With declining costs and improvement in reliability and performance of key renewable energy sources (RES) technologies, the opportunities for farmers to engage in RES production are increasing. However, very limited studies have been conducted to expand RES in the livestock

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farms. In situations where the area is limited and particularly for both heat and electricity production Photovoltaic thermal (PVT) collectors provide an attractive option and can be installed on rooftops without occupying agricultural land.

In greenhouses, the desired microclimate is provided by heating, cooling, sufficient CO_2, humidity control, and in some cases, artificial lighting, which consumes considerable amounts of energy with nearly 65–85% allocation to heating and cooling applications. It has been specified that the annual energy demand for the greenhouse production is 220–320 MJ/m^2 of the cultivated area in Southern Europe (including Italy, Southern France, and Greece), while this value is up to 3600 MJ/m2 in North European countries (Poland, Germany, and Netherland) [21].

PVT collectors are power generation technologies that convert solar radiation into usable thermal and electrical energy. PVT collectors combine a solar thermal collector, which transfers the otherwise unused excess heat from the PV module to a heat transfer fluid, and photovoltaic solar cells, which convert sunlight into electricity. PVT collectors integrate photovoltaic and thermal solar energy conversion in a single device and thereby reach high yields per area (about 30% higher than having separate PV and solar thermal collectors with the same total surface area) [12,27,39].

Several studies regarding the technical and economical assessment of PVT systems in residential [23,25] and industrial [3,34] applications have been reported in the literature in the last decade. Some others have approached the optimization and design methodology of hybrid PVT systems for buildings [40]. Flat-plate PVT technologies have been the ones leading the reported evaluations in different regions of the world [2,5,13]. Nevertheless, concentrated PVT (CPVT) technologies have gained relevance in the last years due to their increased outlet temperature levels and efficiencies [6,16,17,37].

PVT systems have shown to outperform PV panels and solar thermal collectors working side by side and have presented an outstanding decarbonization potential in comparison with conventional solar technologies [1,13,20,30,32,34]. However, very few case studies have been conducted to evaluate the PVT system in the agriculture sector [15,28,29].

A.S. Wallerand et al. [31] performed an optimization of a solar-assisted energy supply system for a dairy farm, which integrated flat plate collectors, photovoltaic (PV) modules, high-concentration PV-thermal (PVT) collectors, and heat pumps into the existing natural gas and grid-electricity based system. The authors demonstrated that the integration of solar technologies, in combination with heat recovery and heat pumping, can reduce the CO_2-equivalent emissions by 65 to 75%. They also concluded that investment in solar energy for such applications can be economically and environmentally attractive for dairy farms if solar energy is optimally integrated and utilized.

(A.Maturo et al., 2021) by considering weather conditions and energy prices in a case study based in North Italy, several technologies were modeled and simulated in TRNSYS environment to determine the best scenario. General outcomes showed that economically all solutions propel to very good discounted payback (DPB); between 3.7 to 8.6 years. The best scenario prevented 2300 tCO_2/y;935 tCO_2/y regarding the electricity produced on-site and 1296 tCO_2/y because of biogas displacement. The integration of a Concentrating PVT (CPVT) with a greenhouse was evaluated by [18] from technical and economic points of view. In their study, two CPVT modules, one with and the other without a glass-reinforced plastic envelope, were used to supply the energy demand of the considered greenhouse. Results indicated better efficiency for the glass reinforced CPVT with reduced heat loss than the reference one. It was also found that the integration of a CPVT module with a greenhouse to meet the heat demand of the greenhouse causes a remarkable Discounted Payback Period (DPP) and Life Cycle Saving (LCS). [33] studied the thermos-economic potential of a solar-combined heat and power (SCHP) system based on concentrating, spectral-splitting hybrid photovoltaic-thermal (PVT) collectors for the provision of electricity, steam and hot water for processing milk products in dairy applications. In this study, transient simulations are managed by utilizing a system model accompanying real-time demand and weather info as inputs, evaluation of the spectrum-selective features of the PV cells in addition to key heat transfer methods that regulate the electrical and thermal efficiency of the PVT collector. Economic and environmental estimates show that the system has a superior decarbonisation potential and is economically reasonable if the expense of the spectrum splitter is lower than 0.85 of the cost of the parabolic concentrator.

Xu et al., [36] studied on a water-circulating solar heat collection and release system with a household collector built of hollow polycarbonate sheets. To save capital investment and simplifying system structure, they propose using collector also as a heating radiator during nighttime as well. The study shows that, the routine average heat collection rate was 72.1%, which surpasses that of similar systems, aiding from the novel technology solution. The proposed that, the rate could still be further boosted by expanding the convective heat incorporation from the indoor air. [11] proposed an experimental test result on a mixed-mode forced convection solar dryer equipped with a PVT air collector at the Laboratory of Electromechanical Systems in the National Engineering School of Sfax in Tunisia. This study supplies a commercial gain for farmers that earlier used natural drying methods. Results showed that using the performed model, produce dampness content discontinued from 91.94% to 22.32% within 44 h by against it dropped only to 30.15% for open sun dryer in 44 h. [9] presented an experimental study of a new solar greenhouse dryer. The solar greenhouse forced convection drying method was formed, built and proved for drying red pepper and sultana grape and a financial assessment was determined utilizing the proof of payback cycle that is found 1.6 years less in comparison to the life of the dryer 20 years.

As mentioned earlier, limited studies have been conducted to expand the application of PVT collectors in livestock farms. The adaptation of PVT collectors and in general RES technologies at a large-scale on farm level still needs more practical studies. This study aims to fill these gaps ensuring a wider adoption of RES (specifically PVT technology) and energy efficiency technologies in livestock farms towards a zero-fossil fuel consumption. A solar PVT system is designed to recover heat of the milk coolers most effectively and to use the thermal energy from the PVT system based on a monthly assessment for the proposed collectors (Solarus C-PVT-Glazed and DualSun PVT-Unglazed). This study provides useful information on a preliminary study of LVAT-ATB site and suitable technologies (C-PVT or PVT) for low-temperature application. One aim was to understand if concentrating PVT technology which is still in the early stages of market penetration can match the performance of a market advanced flat plate unglazed PVT for a given case study. Another aim was to understand the performance of 2 types of PVT collectors for a given case. The integration of the C-PVT collector with the existing systems of the case farm site was evaluated and an optimal design proposed to maximize heat recovery and energy efficiency. Finally, the physical integration of the components of the PVT system was designed for easy and plug and play installation, and in view of a standardized design of PVT integration for livestock farms. To summarize, the system operating temperature is the primary determinant for selecting the PVT collector technology to be deployed on any given site. In this case, given the nature of the pilot site, i.e., the LVAT-ATB site with a heat recovery system in place, the Solarus PVT collector fits better the needs of the farm guaranteeing increased contribution of renewable energy to the farm needs and cost-effectiveness of the overall deployed solution.

2. Current process description

The LVAT-ATB dairy farm is located in Germany. It consists of three barns for milk production with a total area of 3950 m^2, with an overall number of 445 cows and calves. Barn A houses 150 cows on an area of 2240 m^2, Barn B houses 70 cows on an area of 630 m^2, and barn C houses 140 cows on an area of 1080 m^2 (see Fig. 1). All barns are naturally ventilated, but there are ventilators with fans to provide fresh air

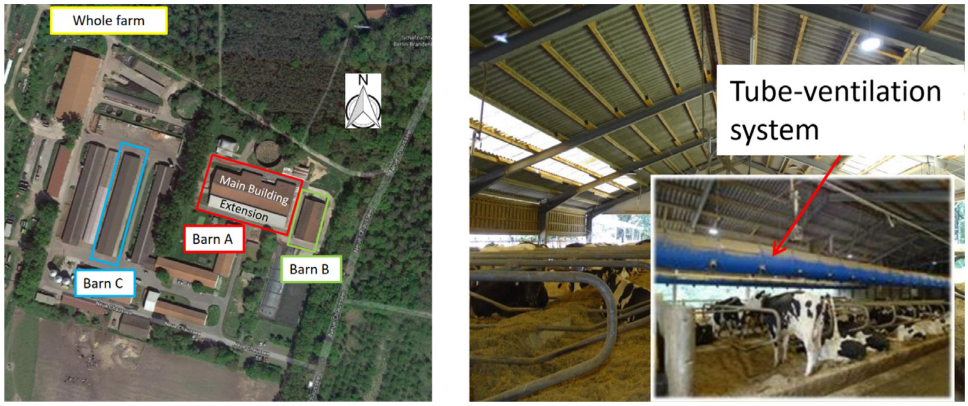

Fig. 1. Dairy farm at LVAT-ATB in Germany.

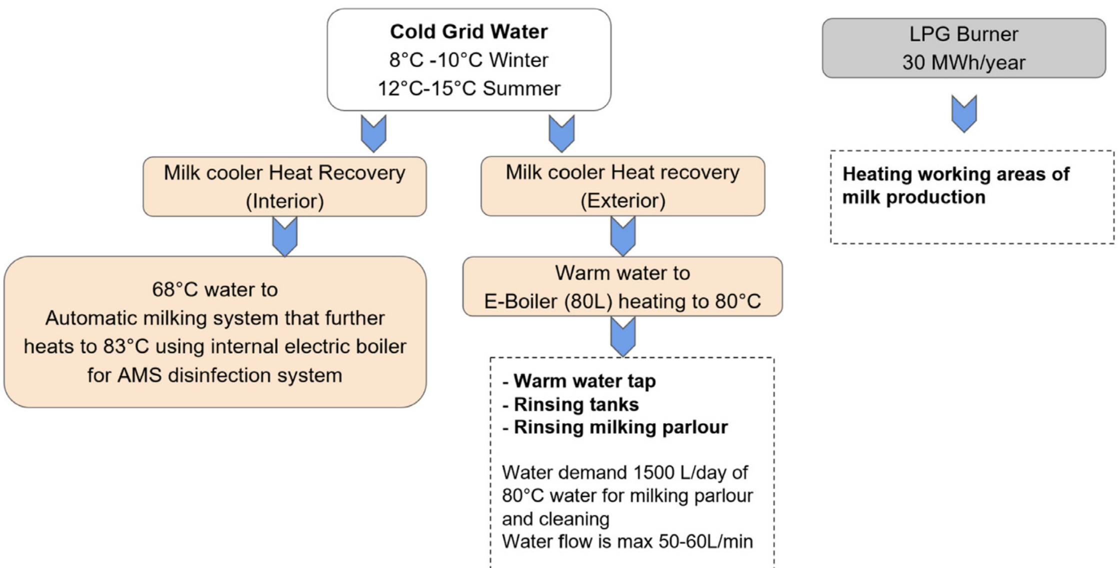

Fig. 2. Summary of the current situation of LVAT-ATB dairy farm.

and cooling on warmer days. The average electricity demand for these fans is 170 kWh/day in summer times. In winter times under frosty conditions, the troughs need heating which represents electricity consumption of 118 kWh/day. The cows are milked with automatic milking systems (AMS), consuming 152 kWh/day of electricity. The milk needs to be cooled constantly over the year with an electrical demand of about 115 kWh/day. The lighting of the barns demands around 177 kWh/day constantly over the year. For manure management, electricity needs are 240 kWh/day. Overall, the farm has an average electricity consumption of 201 000 kWh/year for milk production.

For heating the working areas related to milk production, the farm has a liquefied petroleum gas (LPG) consumption on average of 30,000 kWh/year. Apart from space heating, the farm requires heat for the AMS and for domestic hot water. A unique feature of dairy farms in terms of energy consumption is that they require a milk cooler. In the LVAT-ATB farm, the milk cooler acts as a heat recovery point to supply heat for AMS (Cycle A) and domestic hot water (Cycle B). This heat recovery system (HRS) will allow for most heating needs of the AMS and domestic hot water to be met, and can easily be supplemented by electric heating to reach desired temperatures. In Cycle A, the AMS further heats up the heat recovered to 83 °C through an internal electric heater. In Cycle B, the heat recovered is passed to an electric boiler where the water is heated up to 80 °C, used for domestic hot water in the farm. The consumption data presented until now have been supplied directly by the farm. These are calculated estimates taking into consideration the electrical demand of each appliance and the time of operation over a year. Fig. 2 shows a summary of the current situation of the dairy farm at LVAT-ATB depicting the energy flows and temperature requirements.

Fig. 3 shows the estimated thermal energy demand at LVAT-ATB. In cycle A, cleaning and disinfection of the milking robot is performed 3 times a day (every 8 h) with hot water. In addition, general cleaning is also performed every day by this cycle. Therefore, the total demand of hot water at 68 °C in cycle A is 400 L per day. In cycle B, hot water is used for rinsing inside and outside the tanks (every 2 days between 7 and 8 pm), milking parlours (7 a.m. and 4.30 p.m.), and buckets. In addition, this cycle is also used for tap hot water. Therefore, the total demand for hot water at 80 °C in cycle B is 1500 L per day. The average estimated thermal energy demand of cycle A and cycle B in LVAT-ATB are 771 kWh and 3577 kWh, respectively, and comparing the monthly contribution of the annual demand, we can see it is between 8% - 10% every month of the total annual demand, showing that the total demand is constant throughout the year. The total estimated annual thermal energy demand at LVAT-ATB is 52,197 kWh; 9249 kWh and 42,930 kWh for cycle A and cycle B, respectively.

Fig. 4 shows the estimated daily electricity demand at LVAT-ATB. The pie chart illustrates the share of annual electricity demand, giving the percentages for each application in LVAT-ATB. Manure management accounts for nearly 25% of annual electricity demand with average daily electricity demand of 240 kWh. The total estimated annual electricity demand at LVAT-ATB is 322,330 kWh. About half of the estimated an-

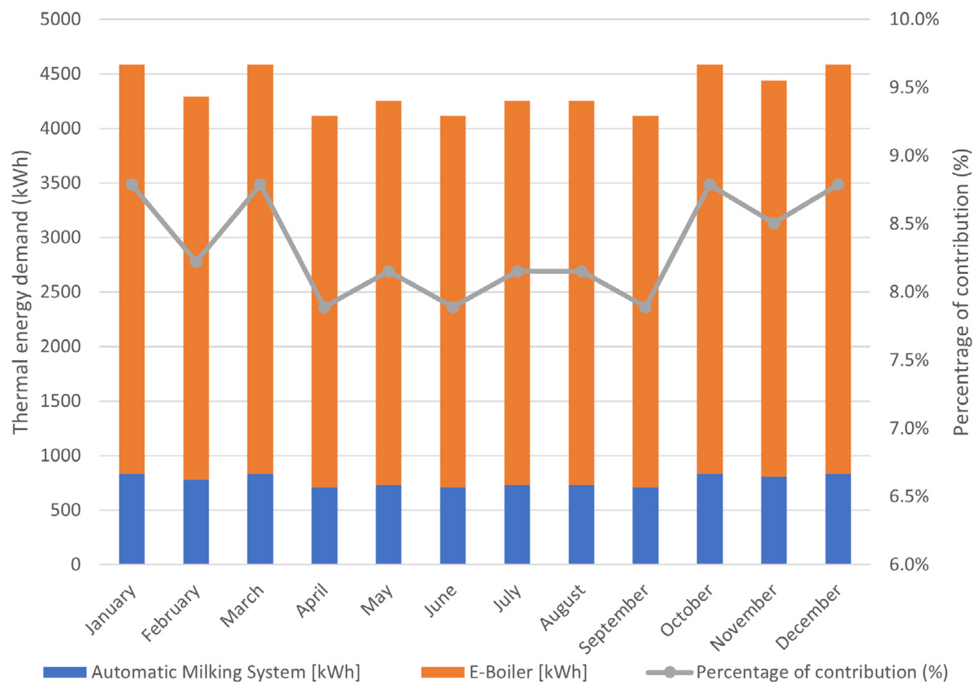

Fig. 3. Estimated thermal energy demand breakdown and percentage of contribution to annual demand at LVAT-ATB in Germany.

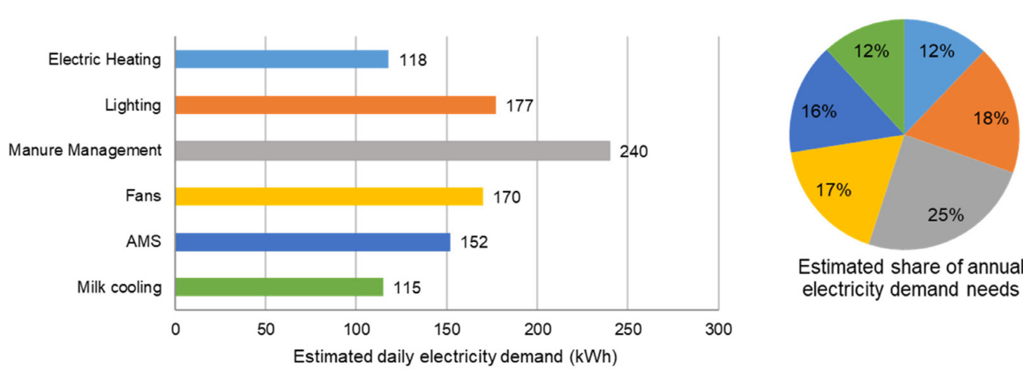

Fig. 4. Estimated daily electricity demand breakdown (left) and percentage of annual electricity demand (right) at LVAT-ATB in Germany.

nual electricity demand (51%) accounted for fans, AMS and lightning. The other annual estimated electricity demands are related to milk cooling and electric heating applications by almost equal 12% of total annual electricity demand. The electric heating system works 170 days per year and electrical demand of fans in average are 170 kWh/day in summer and 118 kWh/day in winter. The other annual demands related to lightning, manure management, AMS and milk cooling system are estimated based on 365 days of operation per year.

3. PVT system

In this analysis, the thermal production of the PVT has been prioritized over the electrical production, which will be supplied as a by-product. Since the energy demand of cycle B is greater than cycle A, it was suggested to intervene in the cycle B process. To use the heat recovery of the milk coolers and reduce the electricity consumption of the e-boiler, it was decided to keep this system as an integral part of the energy source of the farm and integrate the solar system in cycle B between the heat recovery tank and the e-boiler. In the proposed PVT integrated system, the main design criteria is to intervene as little as possible in the heating system currently employed on the farm. This is done to minimize additional costs and to take advantage of the existing infrastructure in the farm. Thus, it was decided to keep the e-boiler in the system which also acts as a buffer heater in case the PVT system is unable to produce enough heat. A system is proposed to use the thermal heat from the solar system to lift the temperature at the outlet of the HRS tank from 40 °C to 50–55 °C, recovering the heat from the milk cooler. The last increase in required temperature level (from 50 to 55 °C to 80 °C) at cycle B will be supplied by e-boiler (through grid electricity). The proposed system is shown in Fig. 5.

Currently, in cycle A, the milk cooler was recorded to consume 118 kWh/day, raising the water temperature in both tanks to 68 °C. In cycle B, the milk cooler heat recovery unit is raising the water temperature inside the buffer tank to 40 °C. By incorporating the PVT system in cycle B, the temperature available at the inlet of the E-Boiler would be increased to 55 °C, hence it would require less energy to meet the required temperature of this cycle. In this design, electric boilers would ensure any additional heating demand in the case of minimal solar radiation using electricity from the grid. The electricity generated from the PVT panels would be used to supply all the electricity required to run the PVT system and offset the electricity used by the e-boiler/farm. The PVT will still be connected to the grid in case any additional electricity can be fed out to the grid, however this is unlikely due to the high electricity demand of the farm. Additional PV panels would be needed to meet all the electrical needs of the farm. With these specifications and system design, two different PVT technologies have been evaluated.

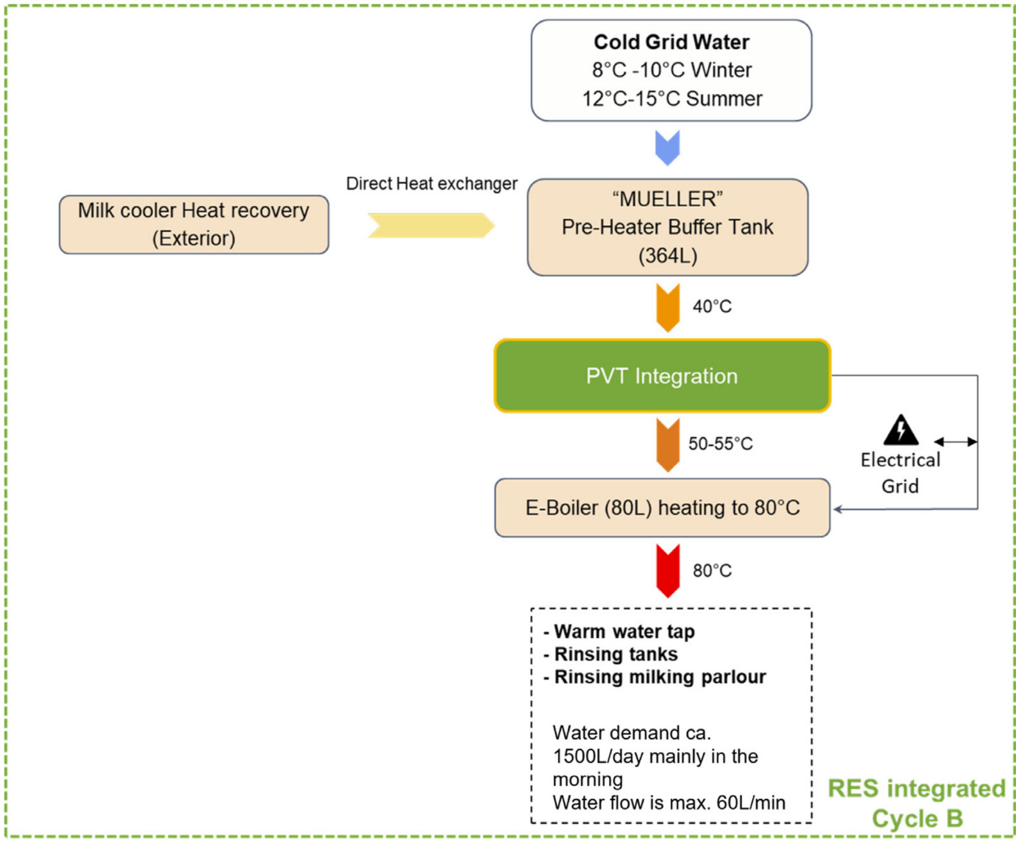

Fig. 5. Overview of the proposed system with PVT collectors at the LVAT-ATB dairy farm in Germany.

Table 1
PVT collectors and their characteristics.

Company	Technology	Size [m^2]		Electrical Specifications			Thermal Specifications		
		Gross	Aperture	Cell Type	Power Peak [W]	Eff. [%]	η_0	a_1 [W/m^2.k]	a_2 [W/m^2.k^2]
Solarus	C-PVT-Glazed	2.57	2.31	Mono	260	10	0.47	4.05	0.003
Dual Sun	PVT-Unglazed	1.66	1.58	Mono	280	17.2	0.472	9.1	0

4. Selection criteria of PVT panel and proposed system design

The performance and monthly thermal and electrical outputs of the designed PVT system in LVAT-ATB farm is evaluated using two different collectors: a CPVT collector developed by Solarus (PowerCollector PC2S) and an unglazed PVT collector developed by Dual Sun (Spring 300 black). As shown in Fig. 5 the system has been designed to be working at an operating temperature of T_m= 45 °C. Table 1 presents the chosen collectors along with the considered technology, size, cost, and characteristics. The main difference between the two of them is that the Solarus collector is a low concentrating collector (a concentration factor of 2), and the Dualsun is a conventional flat plate collector, this allows the former to achieve higher temperature levels and to have fewer heat losses due to the reduced reception area (see Fig. 6). The PVT Absorber material of Solarus collector is Aluminum and silicon encapsulated PV cells and the absorber of Dual Sun is made of PolyPropylene (more precisely Block-Copolymer). The receiver of the Solarus collector has 152 PV cells (52 × 156 × 0.2 mm) attached to the upper (112 W) and lower (157 W) sides, allowing the latter to receive concentrated DNI. As the output voltage of the array is not affected by concentration (40 V) the maximum power current is the one that is different on each array, 2.80 A for the upper array and 3.93 A for the lower one. Given that the Solar collector has a particular configuration, Fig. 7 presents the exploited render of the receiver and the operation principle.

Fig. 8 presents the obtained monthly collector efficiencies and specific thermal production for the two PVT technologies. The efficiencies were obtained using the formula presented in (Eq. (1)). Subsequently, the specific yield was obtained by accounting for the monthly direct normal irradiance values as in (Eq. (2)).

$$\eta_{coll} = \eta_0 - a_1 \frac{T_m - T_{amb}}{DNI} - a_2 \frac{(T_m - T_{amb})^2}{DNI} \tag{1}$$

where η_{coll} is the collector efficiency, DNI is direct normal irradiance [W/m^2], η_0 is peak optical efficiency, a_1 is linear loss coefficient [W/m^{2}K], a_2 is quadratic loss coefficient [W/m^{2}K^2], T_m is average temperature [°C] and T_{amb} is ambient temperature [°C] [8,19,24].

$$STP = DNI \cdot \eta_{coll} \tag{2}$$

where STP the specific thermal production in [kWh/m^2], DNI in [kWh/m^2] and collector efficiency η_{coll} as calculated in (Eq. (1)).

The cell (PV module) electrical efficiency can be described in a linear relation in the form of (Eq. (3)).

$$\eta_c = \eta_{T_{Ref}} \left[1 - \beta_{Ref} \left(T_c - T_{Ref}\right) + \gamma G_T\right] \tag{3}$$

where T_{Ref} is the reference temperature, β_{Ref} is the temperature coefficient, γ is solar radiation coefficient, η_{TRef} is the module's electrical efficiency at T_{Ref} and solar radiation of 1000 W/m^2 [10]. For crystalline silicon modules, β_{Ref} and γ are 0.004 K^{-1} and 0.12, respectively [22].

Fig. 6. Solarus PC2S (Left) (Solarus, 2015) and Dualsun Spring 300 (Right) (Dualsun, 2019).

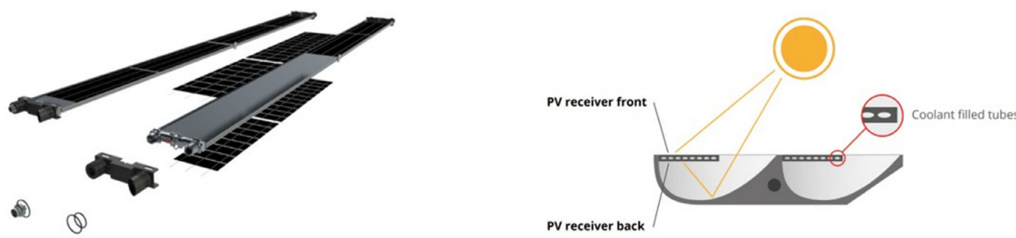

Fig. 7. Solarus PC2S exploited render (left) and working principle (right) (Solarus, 2015).

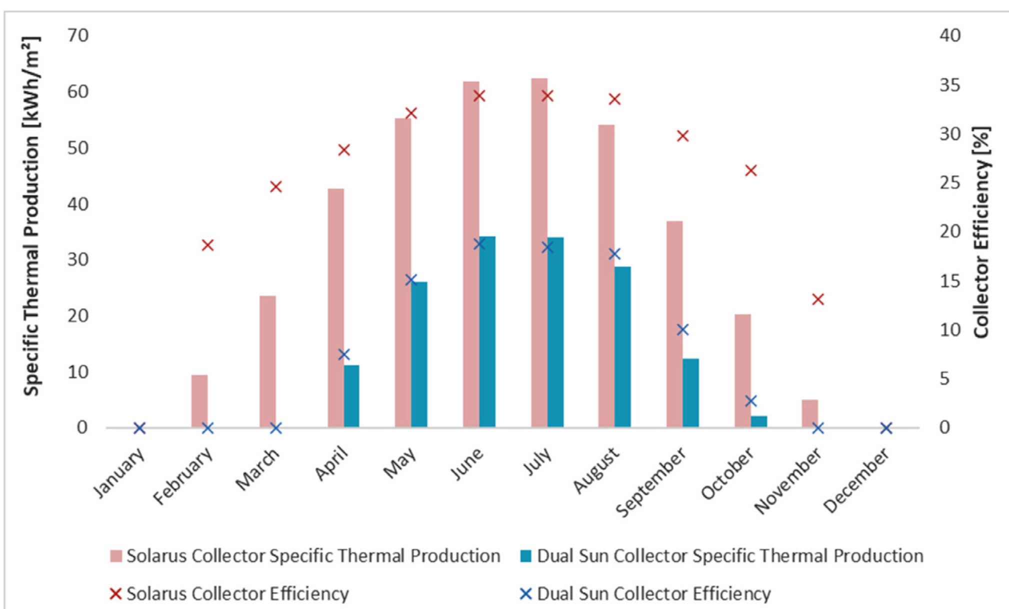

Fig. 8. Collector efficiency and specific thermal production at the LVAT-ATB dairy farm in Germany.

The second term is usually taken as zero and (Eq. (3)) reduces to (Eq. (4)) [10].

$$\eta_c = \eta_{T_{Ref}} \left[1 - \beta_{Ref} \left(T_c - T_{Ref}\right)\right] \tag{4}$$

Fig. 9 presents the monthly electrical energy yield[1] for the two PVT technologies considered in this analysis. The values were obtained using the formula presented in (Eq. (5)).

$$EEY = \eta_c \cdot G \tag{5}$$

where *EEY* is the electrical energy yield in [kWh/m^2], η_c is the cell (PV module) electrical efficiency (%) and *G* is the solar insolation hitting on the PVT collector [kWh/m^2].

[1] Temperature corrected values.

The integration of the PVT into the farm has been done in order to reduce the use of conventional solutions based on fossil fuels and increase the amount of thermal energy output that the deployed system can provide. Thus, the thermal generation was considered as a prioritized criterion for selecting the PVT collector to be deployed on-site, rather than the electrical component. Since the Solarus C-PVT was better suited to deliver high temperature heat output to lift the heat from the existing heat recovery milk cooling system (HRS), the Solarus C-PVT was chosen as the more suitable type of collector for this particular case.

As mentioned earlier, the evaluation of a PVT system based on hourly data is more accurate. However, this study is based on a monthly assessment for the proposed collectors (Solarus C-PVT-Glazed and DualSun PVT-Unglazed). Since the system operating temperature is the primary determinant for selecting the PVT collector technology for LVAT-ATB

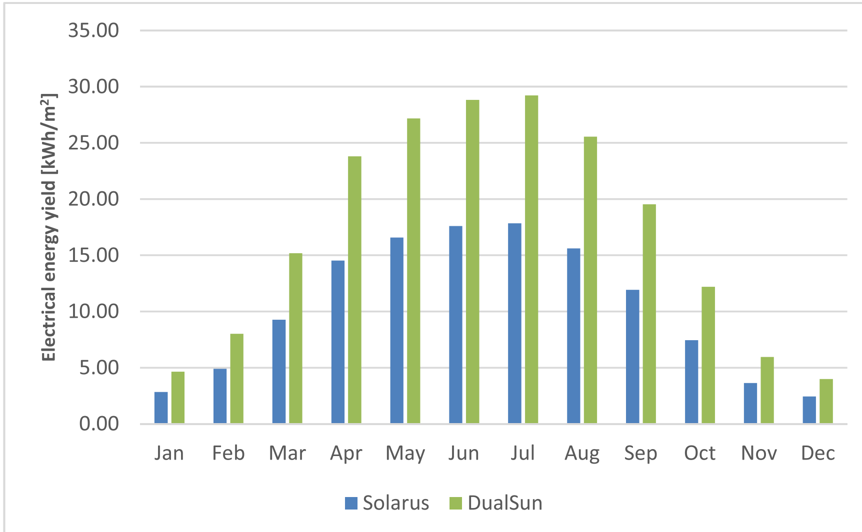

Fig. 9. Monthly electrical energy yield at the LVAT-ATB dairy farm in Germany.

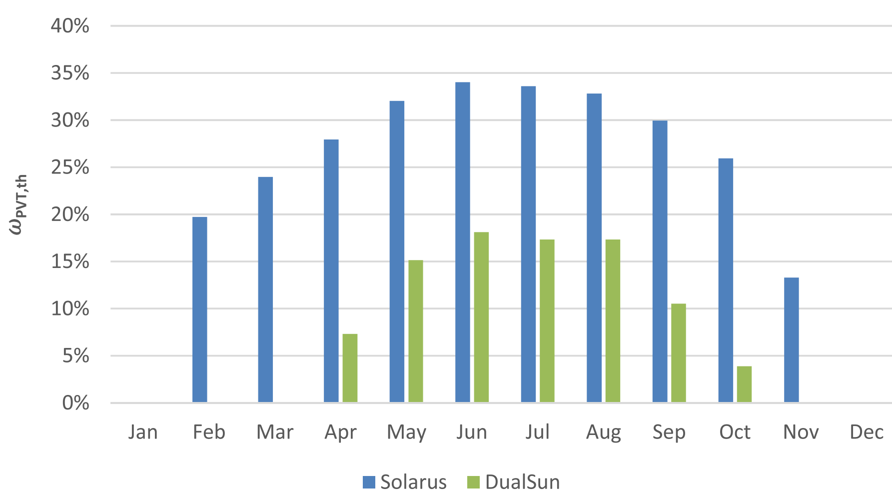

Fig. 10. Monthly thermal energy utilization ratio for Solarus and DualSun PVT collectors at the LVAT-ATB.

site with a heat recovery system in place, the Solarus PVT collector fits better the needs of the farm guaranteeing increased contribution of renewable energy to the farm needs and cost-effectiveness of the overall deployed solution.

Key Performance Indicators (KPIs) are required to evaluate the performance of PVT systems in field operation or simulated systems. Such indicators are used, for example, to quantitatively compare different components or systems, or to quantify the impact of optimization actions on a component or system [38].

Fig. 10 shows comparison of thermal energy utilization ratio for the proposed collectors (Solarus C-PVT-Glazed and DualSun PVT-Unglazed). The thermal and electrical utilization ratios can be used to quantify the performance of a collector (field) over a given time period. Thermal energy utilization ratio ($\omega^{gross}_{PVT,th}$) corresponds to how effectively the thermal energy is absorbed by the collector from the source and can be described by (Eq. (6)). Electrical Energy utilization ratio ($\omega^{DC,gross}_{PVT,el}$) corresponds to how effectively the electrical energy is produced by the collector from the source and can be described by (Eq. (7)). Annual electrical energy utilization ratio for Solarus and DualSun collector are 9.7 and 15.8%, respectively (see Fig. 10).

$$\omega^{gross}_{PVT,th} = \frac{Q_{PVT}}{A^{gross}_{PVT} \int G_{col}\, dt} \tag{6}$$

$$\omega^{DC,gross}_{PVT,el} = \frac{E^{DC}_{PVT}}{A^{gross}_{PVT} \int G_{col}\, dt} \tag{7}$$

where, Q_{PVT} is the heat from PVT in [kWh/year], E^{DC}_{PVT} is the solar DC electricity produced in [kWh/year], A^{gross}_{PVT} is the gross collector area in [m^2] and $G_{col}dt$ is the solar irradiation on collector plane in [$W/m^2 * year$].

The percentage of heat input into the system that comes from sun thermal energy called solar thermal fraction ($f_{sol,th}$) and can be described by (Eq. (8)).

$$f_{sol,th} = \frac{Q_{PVT,WS}}{Q_{PVT,WS} + Q_{HRS,*}} \tag{8}$$

where, $Q_{PVT,WS}$ is the heat from PVT to warm Storage in [kWh/year] and $Q_{HRS,*}$ is the heat from the heat recovery system to other components (warm storage) in [kWh/year]. Fig. 11 shows comparison of solar thermal fraction values for the proposed collectors (Solarus C-PVT-Glazed and DualSun PVT-Unglazed) at the LVAT-ATB.

Simulation results revealed that 24 Solarus PVT collectors running at mean temperature of 45 °C (total aperture area for 24 collectors is 55.44 m^2) meet 16% of the annual hot water demand of the dairy farm by direct solar heat and this number of PVTs can supply up to 38% of hot water demand in summer months. Furthermore, 24 PVTs on an annual

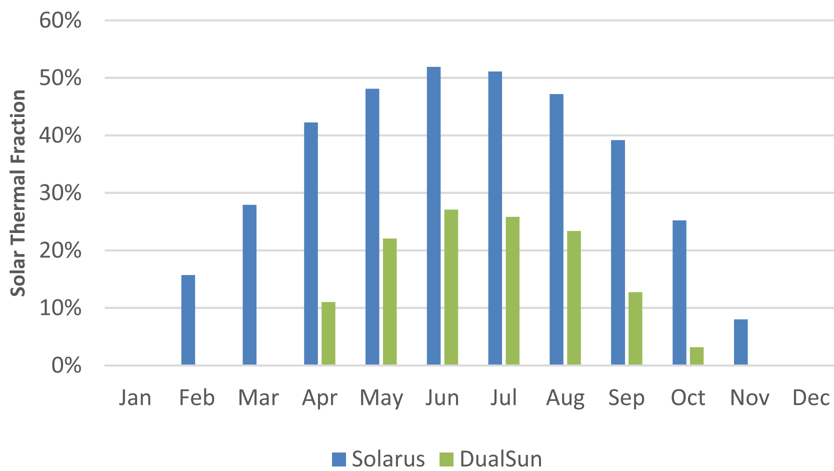

Fig. 11. Monthly solar fraction values for Solarus and DualSun PVT collectors at the LVAT-ATB.

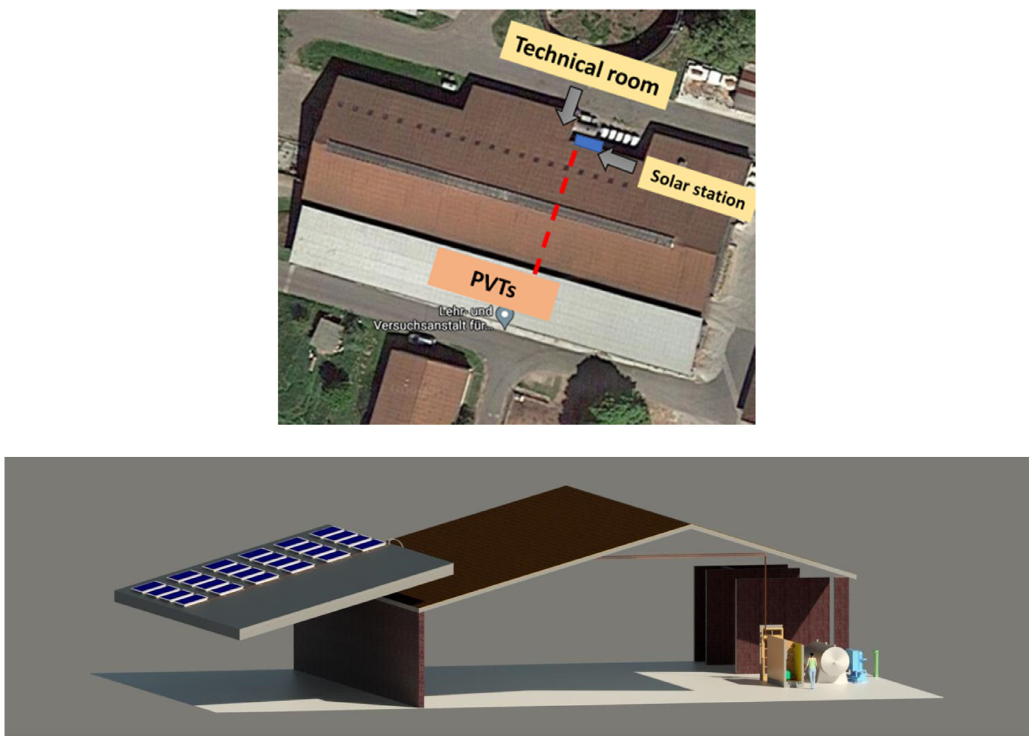

Fig. 12. Locations of PVTs, solar station, and technical room in LVAT-ATB dairy farm.

basis, generate slightly more than 4200 kWh of electricity that can be used to offset electricity consumed by electric boilers in the LVAT farm.

Fig. 12 shows the location of the PVT collectors on the roof and where the solar station will be installed. For roof installation, long steel bars will go from top to bottom of the roof to support the collectors and there will be 3 mounting points per collector. The piping and electrical cables will pass in between the roofs of B1 and B29 and along the trusses of the roof structure of B1 to the solar station (see Fig. 15).

5. Cost assessment of PVT design at LVAT-ATB

As an important factor in the market uptake of novel renewable energy technology, a simple cost assessment was done on the design option 2 (the design options are described in detail later in Section 6), integrating the solar system with two heat stores and using the heat stores as an additional storage for the recovered heat from the HRS/milk chillers. Both the Solarus collector and the Dual Sun collector have been analysed with 24 collectors to be installed.

In determining the total cost of the retrofit system, the price of the collectors, solar station and piping, electrical equipment for the PV modules, control system, and thermal integration piping and instrumentation, two heat storage tanks, and an outdoor enclosure were considered as material costs. Further to this comes estimated installation and shipping costs. It is important to note that the overall cost is much higher than a market-available system, as the entire system included in the solar station house (outdoor enclosure) is made as a custom order and can not benefit from economies of scale at this stage. The total investment for a system with 24 Solarus collectors is 34 000 Euros, and with 24 Dual Sun collectors, 32 000 Euros. The difference is only due to the minor difference in collector price. The total costs have been calculated with pricing information directly from the manufacturer (collectors, electrical cabinet, piping and solar station), suppliers (individual components) and local installers.

Table 2
Net profit due to saved electricity and cash flow considering an investment in 24 collectors of the Solarus CPVT.

Solarus CPVT (24 collectors)	Year										
	0	1	2	3	4	5	6	7	8	9	10
Savings electricity (kWh)		17,000	17,000	17,000	17,000	17,000	17,000	17,000	17,000	17,000	17,000
Electricity price [€]		0.35	0.36	0.37	0.38	0.39	0.41	0.42	0.43	0.44	0.46
Savings electricity [€]		5950	6128	6312	6502	6697	6898	7105	7318	7537	7763
Maintenance costs [€]		680	694	707	722	736	751	766	781	797	813
Net Profit [€]		5270	5435	5605	5780	5961	6147	6339	6537	6741	6951
Cash Flow [€]	- 34,000	- 28,730	- 23,295	- 17,690	- 11,910	- 5950	197	6536	13,073	19,813	26,764

Table 3
Net profit due to saved electricity and cash flow considering an investment in 24 collectors of the Dual Sun Spring 300.

DualSun PVT (24 collectors)	Year										
	0	1	2	3	4	5	6	7	8	9	10
Savings electricity (kWh)		13,341	13,341	13,341	13,341	13,341	13,341	13,341	13,341	13,341	13,341
Electricity price [€]		0.35	0.36	0.37	0.38	0.39	0.41	0.42	0.43	0.44	0.46
Savings electricity [€]		4669	4809	4954	5102	5255	5413	5575	5743	5915	6092
Maintenance costs [€]		640	653	666	679	693	707	721	735	750	765
Net Profit [€]		4029	4157	4288	4423	4563	4706	4855	5008	5165	5328
Cash Flow [€]	- 32,000	- 27,971	- 23,814	- 19,526	- 15,103	- 10,540	- 5834	- 979	4029	9194	14,521

With the total system price known and the amount saved, it is possible to make a simple cost assessment including cost savings over each year and payback period of the system. In this case at the LVAT-ATB farm, the total thermal energy produced by the PVT collectors will offset the electricity consumption of the e-boiler. The total electrical production of the PVT collectors will be first self-consumed on the farm and offset any electricity bought from the grid. Thus, the energy produced by the PVT collectors can be translated to the electrical energy saved by the farm. With certain assumptions, cost savings of the reduced electricity bought from the grid can be calculated. With the known cost of the complete solar system retrofit, a cash flow and payback period can be obtained. The following assumptions were taken into account:

- No loan taken out for initial investment, hence no interest rate
- Depreciation of investment is not taken into consideration
- Average annual rate of inflation: 3% [35]
- Average annual increase in electricity prices: 4%
- Maintenance costs of the system: 2% of the total initial CAPEX cost
- Residential electricity price in Germany (2021): €0.35/kWh [14]
- Boiler efficiency: 90% → Electrical energy = 0.9 * thermal energy production of collector

The annual thermal and electrical production for the Solarus and Dual Sun collectors were calculated using the equations from Section 4. The annual thermal production for 24 Solarus and Dual Sun collectors running at a mean design temperature of 45 °C are 14,151 kWh and 5798 kWh respectively. The annual electrical output is 4264 kWh for the Solarus system and 8131 for the Dual Sun system. The total amount of energy produced is multiplied by the electricity price (including annual increase of electricity prices) to give the electricity costs saved by the farm. Maintenance costs of the solar system are then subtracted to give the final cost savings of the farm, i.e. net profit or cash inflow. The annual cash inflow was calculated using Eq. (9).

$$Annual\ cash\ Inflow = electricity\ energy\ savings * electricity\ price - maintenance\ costs \quad (9)$$

This has been done for both the Solarus CPVT and Dual Sun collector scenarios. The results are presented in Table 2 and Table 3 below with the cash flow visually represented in Figs. 13 and 14 for the Solarus CPVT and Dual Sun PVT respectively. The payback period for both systems occurs when (Eq. (10)) is satisfied [4].

$$\sum_{t=1}^{T} C_t = C_0 \quad (10)$$

where t is the number of time periods, C_t is the net cash inflow in period time t, and C_0 is the initial investment cost. It can be seen from Tables Tables 2 and 3 that the payback period for the Solarus collector is less than 6 years, and for the Dual Sun collector, less than 8 years. This is due to the Solarus collector being able to produce more heat at the higher temperature requirement of the farm. Even with the higher investment and maintenance cost of the Solarus collector, it is still more cost effective.

It is worth noting that the cost of both systems are tailor made to the current energy systems in place at the farm such as the HRS and e-boiler. For this reason the solar pumping system and controller are being manufactured as a one off piece which raises the total system investment price compared to market available systems. In determining the costs of investment it was also assumed that no loan was taken out for the initial investment, which would add interest rate costs to the investment. Furthermore depreciation was also not taken into account. However, local and national subsidy schemes are also not taken into account which would be a positive cash flow into the investment.

6. PVT plant design

The PVT system generally consists of the field of PVT collectors, the solar station and the technical room. The solar station is a dedicated mechatronic system that allows effective and efficient control of the mechanical (i.e. pumps, valves, tanks), PV Balance-of-System (BoS), and instrumentation (i.e. sensors, actuators, data acquisition, controllers) components. All the equipment and components of the PVT system; other than the PVT collectors will be located in the solar station house.

Fig. 15, shows plan of farm (A) and roof layout of building B29 (B). In first phase of the design process, dairy barn (B1, south-facing) and welfare barn (B2, east-west facing) have been proposed for the collector integration, since B2 already has been used for scientific purposes and it has a separate AMS. However, in second phase building B29 has been proposed and selected for installation due to the partial shading on roof of B1 in summer and winter. It has been decided that the ideal installation location of the PVTs is on B29 in the center so that it can be visible from the road entering LVAT and in line with the location of the solar station on the other side of the building.

In PVT thermal system design two options are examined for integration points in the existing system in the farm. The two options have been designed to keep any changes to the existing components already installed in the farm to a minimum. This is to avoid any major instal-

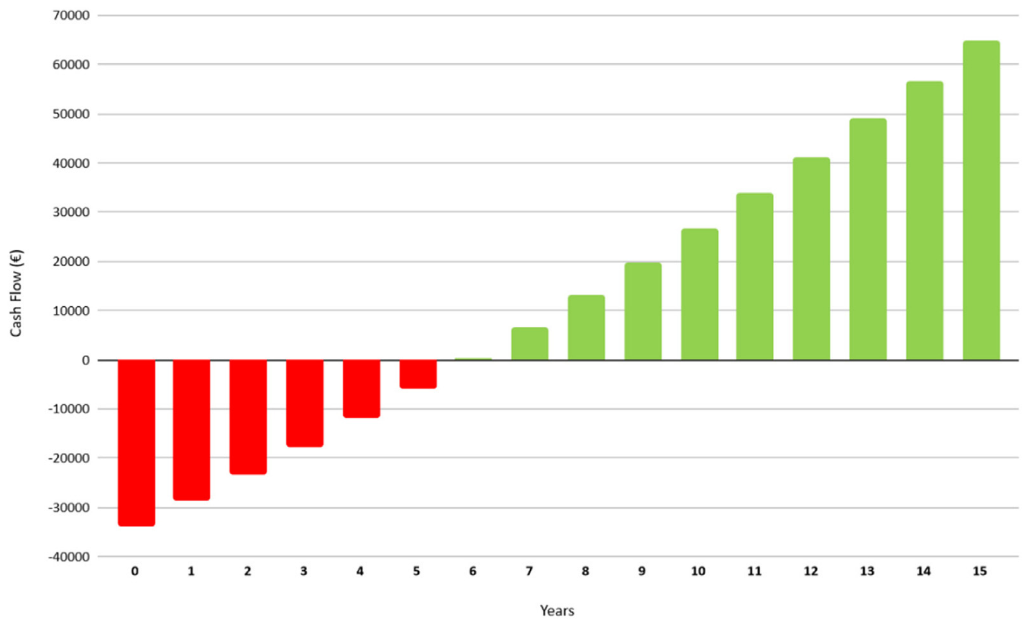

Fig. 13. Cash flow of investment in 24 Solarus CPVTs at the LVAT-ATB farm.

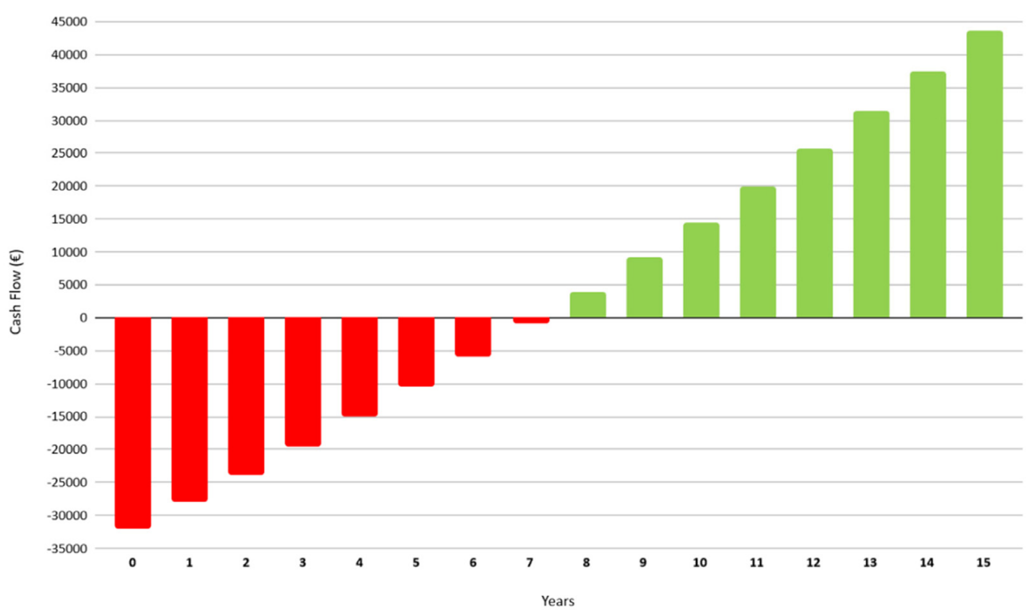

Fig. 14. Cash flow of investment in 24 Dual Sun unglazed PVTs at the LVAT-ATB farm.

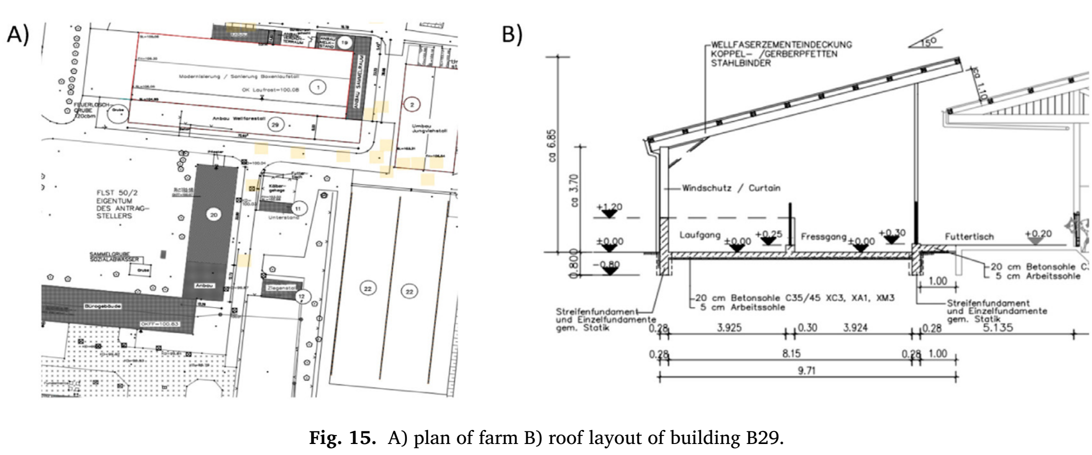

Fig. 15. A) plan of farm B) roof layout of building B29.

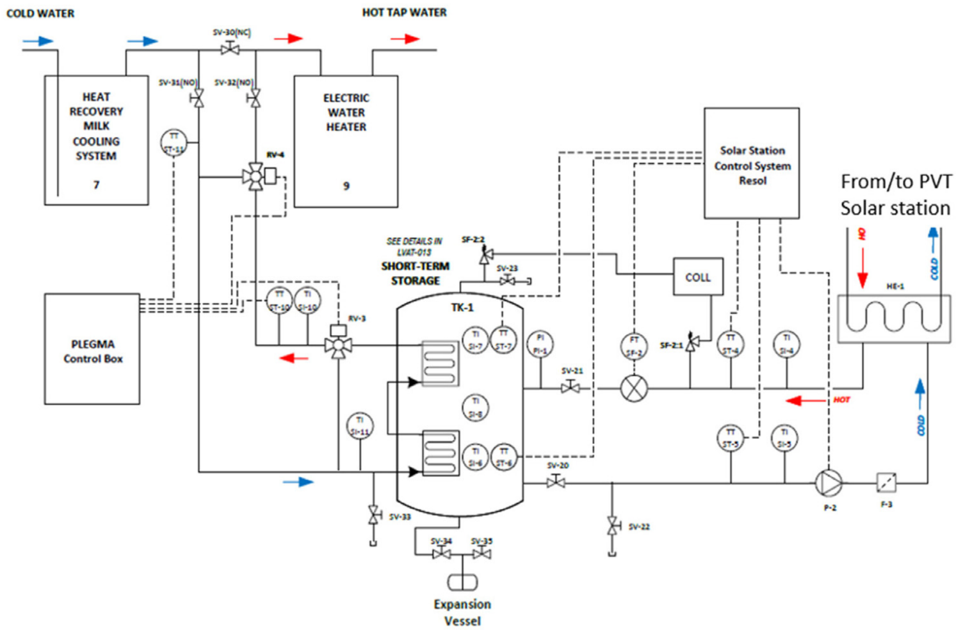

Fig. 16. First P&ID design of PVT system at LVAT-ATB dairy farm in Germany.

lations works and provide a simple and low cost retrofit solution for introducing renewable heating into the farm and improving its energy efficiency. Also, usually, facilities owners are more reluctant to changes in the processes and equipment. Hence the installations should be as discreet as possible.

In the first design option (see Fig. 16), the PVTs will take the heat from the milk cooling HRS and lift its temperature before the e-boiler. This ensures a series connection where the control algorithm will allow heat from the solar buffer tank to lift the heat coming from the HRS if the solar buffer tank is of higher temperature than that of the HRS. If not, water coming from the HRS will pass directly to the e-boiler. This is done through the automatic 3-way valve (RV-4) to regulate the direction of flow of the heat transfer fluid and in this case if the temperature in the heat storage is lower than water temperature from HRS the flow takes short circuit. Second 3-way valve (RV-3) is a mixing valve and used to control the hot water temperature. Overheating protection of the e-boiler is set at 95 °C and RV-3 is used to make sure that the boiler does not go into overheating protection mode by mixing colder temperature water based on temperature sensor (TT-ST10).

In the second design option (see Fig. 17), the PVT buffer tanks can be used as an additional heat storage tank to store heat coming from the HRS. This integration will allow a larger volume of heat storage to storeheat coming from the HRS; however at lower temperature levels. Lower operational temperatures will allow running the PVTs at higher efficiency levels, both electrically and thermally. In this design, the controller will allow heat from the HRS to be stored in the PVT storage tank if its temperature is higher than that of the HRS storage tank (Pump P-3 is on). In this “loading” operation mode, if heat is required by the e-boiler the flow will directly pass to the e-boiler, otherwise, it will pass to the PVT buffer tank. If the buffer tank has a higher temperature than the HRS, the “unloading” operation mode will occur (Pump P-3 Off, Valve RV-4 Open), and heat will be taken from the buffer tank to the e-boiler. Identical to both designs, if the temperature from the PVT system is higher than the buffer tank, P-2 will be switched on and heat will be transferred to the buffer tank from the PVT system.

The second design option (Fig. 17) was considered more suitable and more energy effective as it was found that a significant amount of heat was lost in the HRS. The heat demand was not consistent enough to make use of all the heat from the HRS. Increasing the storage capacity of the HRS heat will allow for enough heat to be stored at ca. 35 °C - 45 °C. The PVT system will be able to lift this temperature to ca. 55 °C – 65 °C before passing to the e-boiler. The ability to supply higher temperatures is the main reason why concentrating PVTs were chosen as the most suitable technology from a technical perspective.

With regards to the placement of all these components, the novel assembly of all components was designed and called the “solar station”. The goal is to design a plug and play integration system for PVT collectors within dairy farm application, in view of standardization. This will enable a more cost-effective and market-available integration solution for PVTs in agriculture that could be further replicated in other applications. It was designed specifically for this farm case at LVAT-ATB dairy farm, and can be used in farms containing a heat recovery system. The complete solar station will be placed outdoors as there is not enough space indoors for this particular farm. It is a simple house structure that will include a solar wall and two heat stores, each of 0.75 m^3 in volume.

The solar house is a novel design layout of all components needed to run the PVT system. It includes the solar thermal pumping unit, solar controller, electrical equipment (inverter, protection devices), and integration components (i.e. most components in Fig. 13). The solar station house is designed to be assembled and transported as easily as possible, and from the best of the authors’ knowledge, is the first attempt to standardize a design of a PVT system integration. Once brought to the installation site, the installation can be performed in the easiest way with only five piping connections and the electrical connection to the main switchboard of the farm. It is dimensioned to fit on four Euro-palettes (1200 mm x 800 mm). This is why two heat stores have been opted for instead of one bigger one. The heat stores will be placed next to all the components needed to run the solar thermal system including the components seen in Fig. 17. A draft 3D model of the placement of the solar station house is shown in Fig. 18(A). The component placement inside the solar station house is shown in Fig. 18(B). In this figure, not all of the components are shown as it is still in development.

Regarding the control and instrumentation system, the design was based on the variables and actions that were needed to both control the system in a semi-automated manner, and to be able to quantify the energy flows of the entire energy generation system (PVTs, HRS, and E-boiler). The variables to be monitored are temperature; inlet, outlet and heat storage, volumetric flow, and pressure. The automated valves are activated based on the control strategy that was previously mentioned. The control system consists of two sub-systems; RESOL and PLEGMA

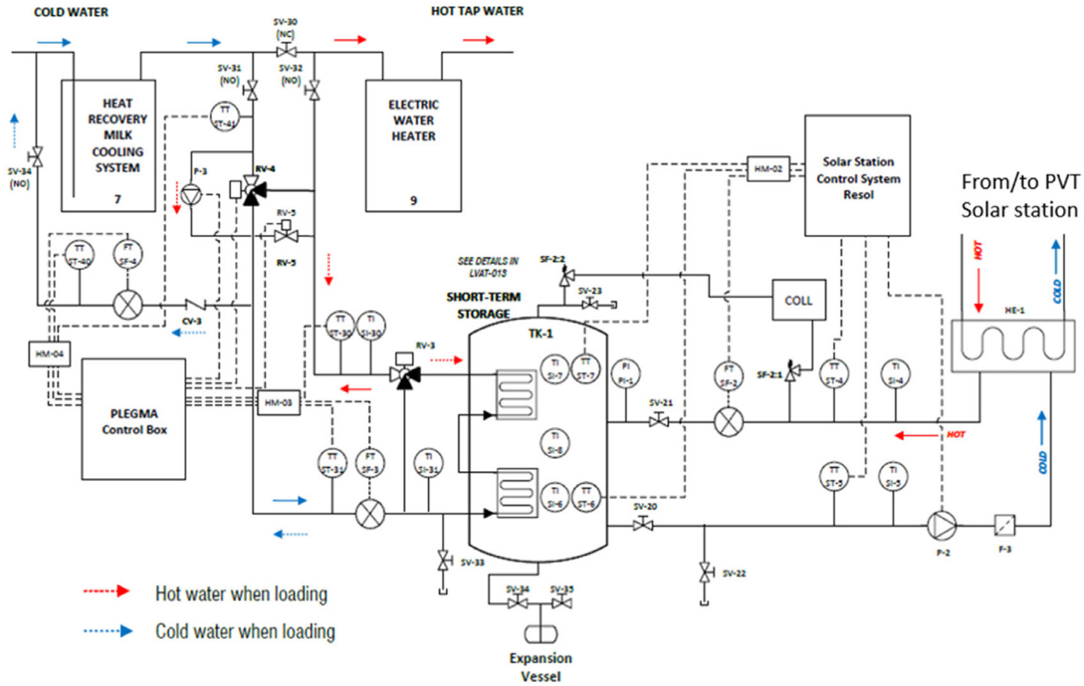

Fig. 17. Second P&ID design of PVT system at LVAT-ATB dairy farm in Germany.

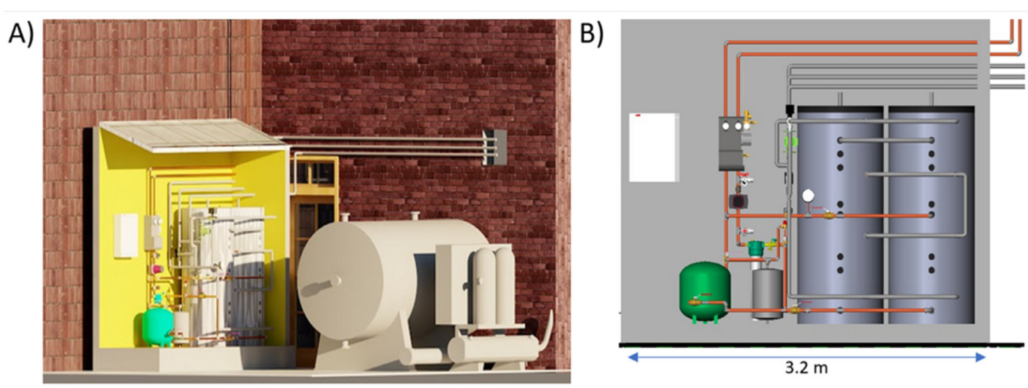

Fig. 18. Placement of the solar station house, B) Component placement inside the solar station house.

control box. The first one controls the operation of the PVT field based on the status of the heat storage, whilst the second controls the pumps and automated valves on the demand side based on the status of the HRS, and the heat storage. This design approach will guarantee that the system operates in an effective, efficient, and safe manner.

7. Conclusion

In this preliminary analysis of candidate collector for the LVAT case study, the Solarus C-PVT is recommended as the LVAT farm requires the high temperature heat and concentrating PVTs having higher efficiencies at higher operating temperatures than flat plate PVTs (such as Dual-Sun). The unglazed flat-plate collectors did have higher electrical output however the thermal production is a higher criterion for PVT selection in this case. Furthermore, the Solarus C-PVT is still in its early market stages and with improvements, the electrical output can be improved. Total annual thermal production of Solarus C-PVT is 15,058 kWh for 24 collectors and 55.44 m^2 aperture area. (at collector mean temperature of 45 °C and total aperture area of 40 m^2). With use of the PVT system in cycle B, the temperature available to the e-Boiler would be increased to 55 °C - 65 °C and would reduce the electricity consumption of the e-boiler to meet the required temperature of this cycle. In this design electric boilers would ensure any additional heating demand in the case of minimal solar radiation by the help the electricity from the grid. For an efficient integration with the current heat recovery system, a design was made to use the PVT buffer tank as an additional heat storage for heat coming from the HRS. This would enable more heat to be stored. The heat provided by the C-PVTs would lift the temperature of the heat from the HRS to supply the e-boiler with a maximum temperature. Additional PV panels would be a very good option to meet the additional electricity demands of the farm including the electrical needs for the milk cooling. As a next step, more accurate simulations based on hourly data will enable a system design including heat storage temperatures, detailed control system algorithms, detailed installation components. A more thorough energy analysis of the existing systems such as the HRS' temperatures and energy outputs would have helped in performing more concrete thermal simulations.

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.

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