Evaluation of a solar concentrating photovoltaic thermal collector (CPVT) in a dairy and swine farm in Europe

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Abstract

The use of CPVT collectors in combination with other renewable energy sources (RES) has been evaluated to develop market integrated, cost-effective and case sensitive RES solutions dairy and swine farms in view of fossil-free livestock farming practices. Electrical and thermal energy demands have been analyzed for the LVAT-ATB dairy farm in Germany, and for the ILVO swine farm in Belgium. The swine farm consumes more heat than electricity for pig raising while the dairy farm consumes more heat than electricity for milk production. A CPVT collector produced and tested by Solarus has been used to model the thermal and electrical performance output for each of the farms. Taking into consideration the demands of the farms, the use of the CPVT in a fossil-free energy system for the farm has been evaluated. For the swine farm it was suggested to make use of the higher efficiencies of the CPVT when operating at low temperatures at a mean temperature (Tm) of 20°C, to preheat grid water by 10-20°C and using to obtain the required temperatures for hot water and space heating. The specific annual thermal output of the CPVT at ILVO is 436.1 kWh/m^2. At the LVAT dairy farm, it is suggested to use the CPVT collectors to lift the temperature of the pre-heated water recovered from the milk coolers (40°C) by 10-15°C, running at a mean temperature (Tm) of 45°C. The specific annual thermal output of the CPVT at this Tm LVAT is 375.5 kWh/m^2. The remaining temperature difference can be supplied by an e-boiler. Running at the lowest mean temperature possible maximizes the thermal efficiency of the solar system.

Keywords: RES4Live project, CPVT Systems, Concentrating Photovoltaic-Thermal, Livestock Farms, Fossil-free Farming, Energy use of livestock farms

1. Introduction

Fossil fuel use in the agricultural domain 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 (Dubois et al., 2017). The proportion of direct energy used from the total primary energy consumption in agriculture in the EU is estimated at 61% and largely varies for the specific activity (Blázquez et al., 2021). One of the most energy consuming sub-sectors of agriculture is intensive livestock that is mainly based on fossil fuels use representing about 45% of the total energy demand in the agricultural sector (Dumont et al., 2017). Both electricity and thermal energy is required to cover strongly diversified energy demand, such as cooling-heating of the indoor livestock buildings environment, running of equipment and tractors, lighting, and ventilation systems.

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 are required for sterilization, ultra-high temperature processing, drying, etc. (Ramos et al., 2017).

(Wallerand et al., 2018) 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

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demonstrated that the integration of solar technologies, in combination with heat recovery and heat pumping, can reduce the CO2-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.

In the context of pig farming productivity, the conditions of the inside room are essential and highly influence the correct animal's growth. Nursery pigs are susceptible to low temperatures and hence, a significant proportion of the global costs associated with pig farming is for heating to achieve a comfortable temperature. In intensive breeding farms, for maintaining an adequate thermal environment, fossil fuels and electricity are the principal energy sources usually adopted. In this way, interventions on animal housing are required with the aim of reducing the energy demand and increasing the efficiency of the climatization systems. Strategies are then focused on the use of alternative energy sources as the renewable ones. In this regard, geothermal heat pump or PVT systems represent a potential improvement both in energy consumption and indoor air quality (Blázquez et al., 2021). Furthermore, the economic sustainability of agricultural production is a crucial concern for most farmers, especially for pig producers who face dynamic changes in the market (Malak-Rawlikowska et al., 2021).

A study by (Menardo et al., 2013) shows the importance of heating usage in northern parts of Europe such as Germany and Belgium where solar applications can bring a useful contribution to the large heating needs in the north. The study specifies that the annual energy demand of 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 3,600 MJ/m^2 in North European countries (Poland, Germany, and Netherlands).

A photovoltaic thermal (PVT) collector is able to generate electricity and heat from the same area and is a single unit formed by a combination of photovoltaic (PV) and solar thermal technologies (Zhang et al., 2012). 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) (Ramos et al., 2017; Zenhäusern et al., 2017). Concentrating hybrid photovoltaic thermal collectors (CPVT) provide a promising option to effectively contribute to the high intensity energy use of livestock farms. With declining costs and improvement of reliability and performance of key renewable energy sources (RES) technologies, the opportunities for farmers and specifically for livestock producers to engage in RES production are increasing. However, this large portfolio of options also creates complex questions, because the potential, performance and impacts of RES technologies depend on the local climate and desirable indoor conditions, size and type of farm, management techniques, degree of mechanisation, and socio-economic factors. Furthermore, very few case studies have been conducted to evaluate PVT systems in agriculture sector (Gorjian et al., 2020; Singh et al., 2018; Tiwari and Tiwari, 2016).

The integration of a concentrating PVT with a greenhouse was evaluated by (Hussain et al., 2016) 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 energy to the considered greenhouse. Results indicated better efficiency for the glass reinforced CPVT with reduced heat loss compared to the other. 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 and Life Cycle Saving.

In this paper, one dairy farm (LVAT-ATB) and one swine farm (ILVO) have been selected as case studies to evaluate the use and integration of solar CPVTs in the energy usage of the farms. Special attention has been taken in the thermal part of the energy usage and production, as in both farms the consumption is high. The heating and electricity demands have been analyzed for both cases. Then, the performance of a CPVT solar collector has been calculated for both locations. An evaluation on the integration of the CPVT into the heating processes of the farm was done, also considering its integration with other renewable energy sources (RES). Finally, an integration point of the solar thermal energy is proposed, as well as the operating conditions of the solar system. Both farms are chosen to be from a similar climate to minimize the variation in solar collector performance due to different solar radiation values. The average solar radiation over a year measured at the ILVO farm in Melle, Belgium is 83.9 kWh/m^2, while at LVAT in Potsdam, Germany it is 84.5kWh/m^2. It is important to understand that the electrical and thermal energy demand have been assessed for milk production (LVAT-ATB), and the raising of pigs (ILVO) as end products.

2. Swine farm at Vaarkenscampus EV ILVO (Belgium)

The Swine farm (Figure 1) is managed by EV ILVO, UGENT and HoGent for research and educational purposes alongside normal commercial production. It is a farrow-to-finish pig farm with place at any moment for 105 sows, 600 piglets and 750 fattening pigs. The total building area is 2,500 m^2 and contains mainly concrete and insulation with polypropylene panels dividing the compartments and partially slatted concrete floors above the manure pits.

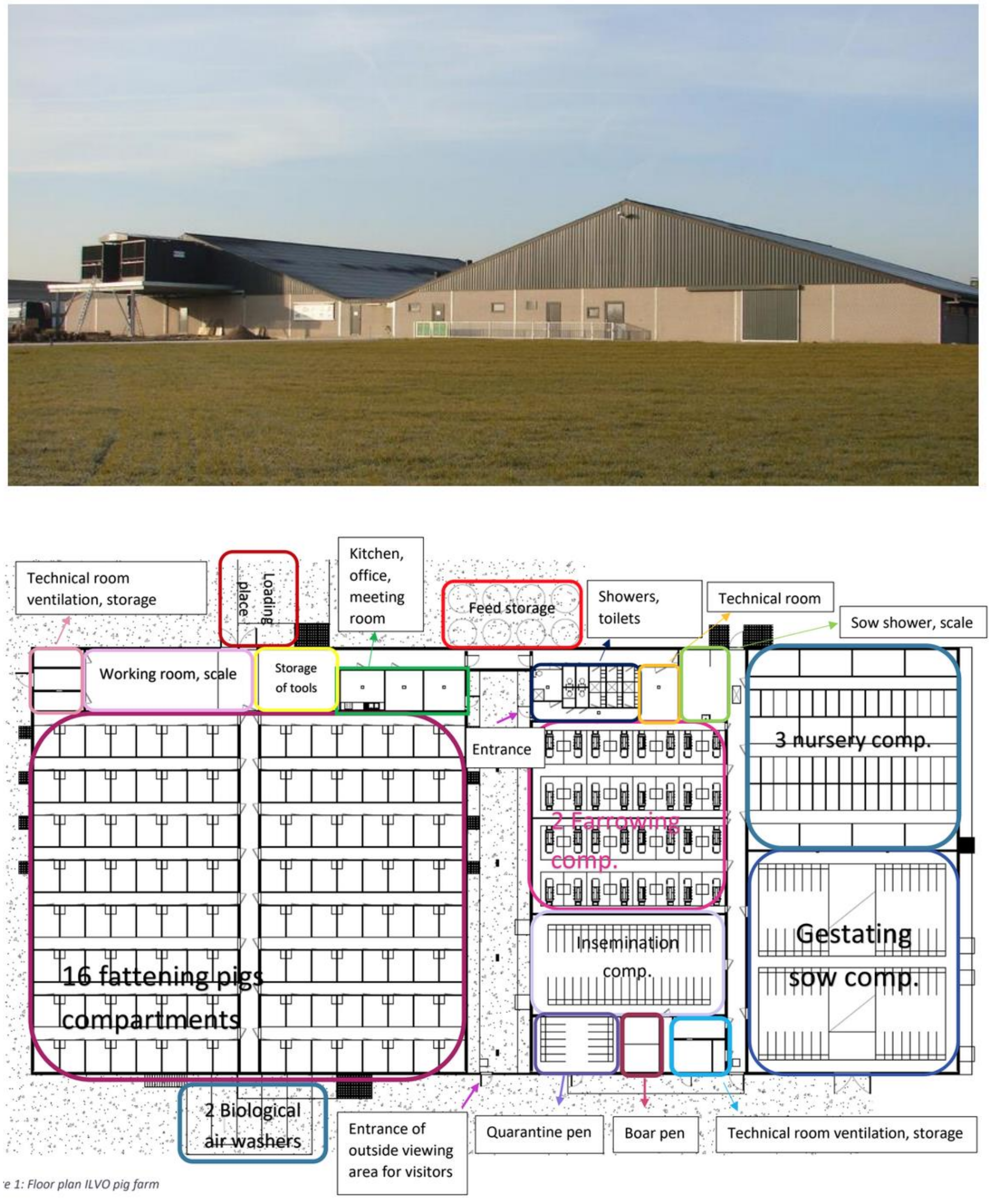


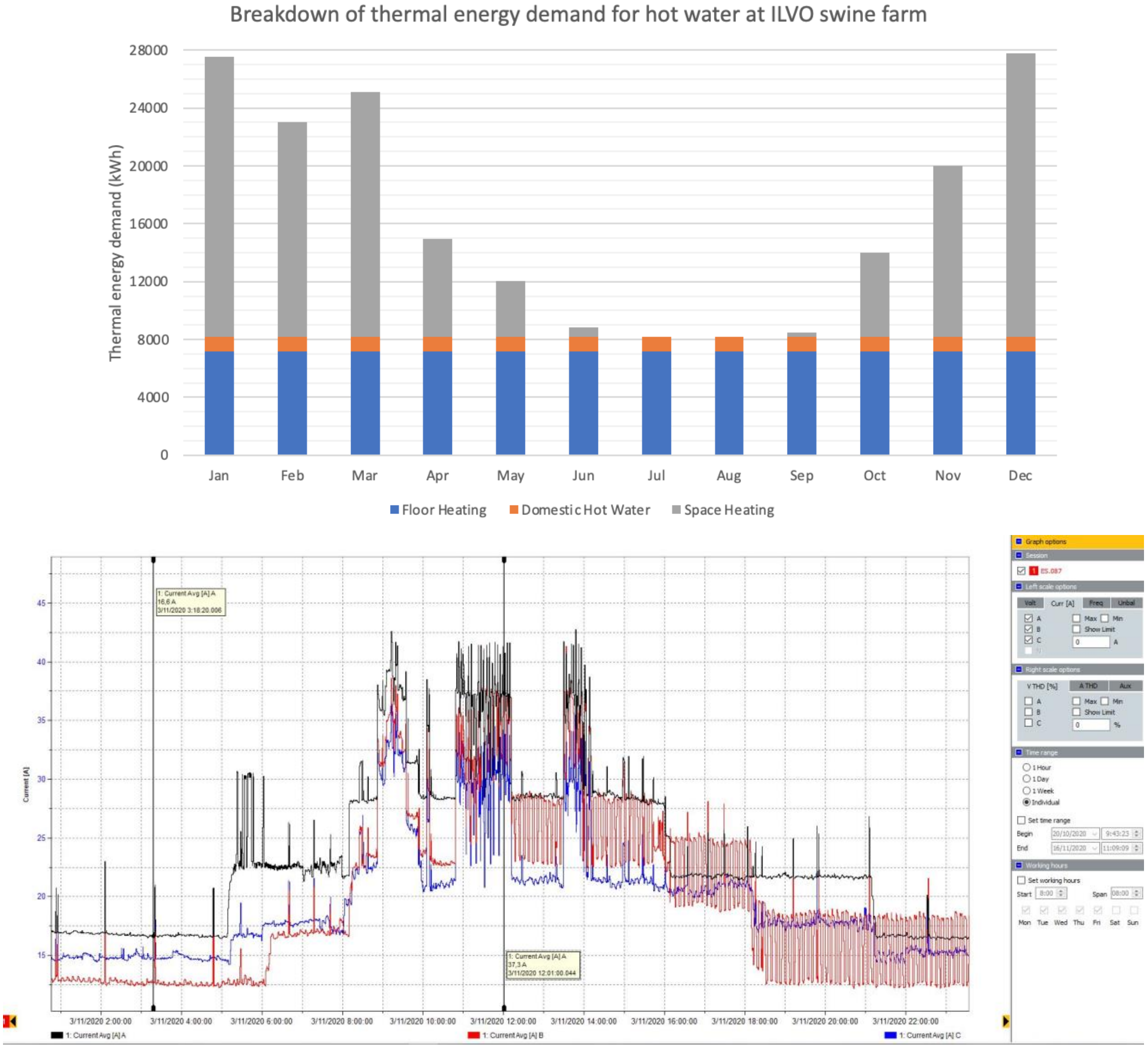
Fig. 1. ILVO swine farm in Belgium (top), and its floor plan (bottom)

Heating at the ILVO swine farm is currently provided year-round by a 60 kW gas boiler with a LPG energy consumption of 220 MWh/year. On top of this, thermal lamps are used to heat new-born piglets specifically. This is a characteristic of a swine farm as new-born piglets must remain at a temperature of 35-37°C, while the sow should remain at room temperature. Currently at the ILVO farm, the LPG gas boiler supplies hot water at 70°C. This is delivered to the air heating channels for the weaned and fattening pigs' compartments, as well as for domestic hot water. This hot water is reduced to 40°C for the floor heating system used for the new-born piglets and weaned piglets compartments. The multitude of delivery systems of heat depending on the stage of production is summarized in Table 1.

Tab. 1: Summary of heating requirements of the ILVO Farm

Stage of production	Heating required	Heating delivery
New-born piglets	35-37 °C first days after birth	Floor heating (water at 40°C) and thermal lamps
Weaned piglets	28°C gradually decreasing to 25°C during 4 weeks	Floor heating (water at 40°C) and air heating (from water at 70°C)
Fattening Pigs	20-25°C	Air heating and use of gas cannon at start-up
Sows	No need for extra heating (18-23°C)	

As the thermal lamps deliver location specific heating, it will be difficult to replace this using solar heating for the case of this specific farm. Thus, only the heating requirements from the LPG boiler will be considered. Using the heating schedules of the farm, and energy flow measurements recorded over a week in October 2020, the breakdown of thermal energy demand of the farm over a year was estimated as shown in Figure 2. Floor heating is constant at 7200 kWh/month. Domestic hot water is on average over the year constant at 992 kWh/month. Space heating fluctuates based on the outdoor temperature and between June and September, almost no energy is used for space heating additional to floor heating. However, space heating does take up the most energy overall during a year.



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Begin 20/10/2020 9:43:23
End 16/11/2020 11:09:09

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☑ Mon ☑ Tue ☑ Wed ☑ Thu ☑ Fri ☐ Sat ☐ Sun

Fig. 2. Estimated thermal energy demand for hot water at ILVO swine farm.

The overall average electricity demand of the farm is 110 MWh/year. The main electricity consumption comes from the 32 thermal lamps that are used to heat the newborn piglets. Otherwise, there are 200 LED lights, and several electric pumps for the feed and pressure cleaning. There are also 6 pressure fans and 8 DC fans for ventilation in the barn. The monthly electricity consumption over the year is constant as shown in Figure 3. The thermal lamps are needed all year round, however the ventilation is only needed during the summer which explains the slight increase in electricity usage over the summer months.

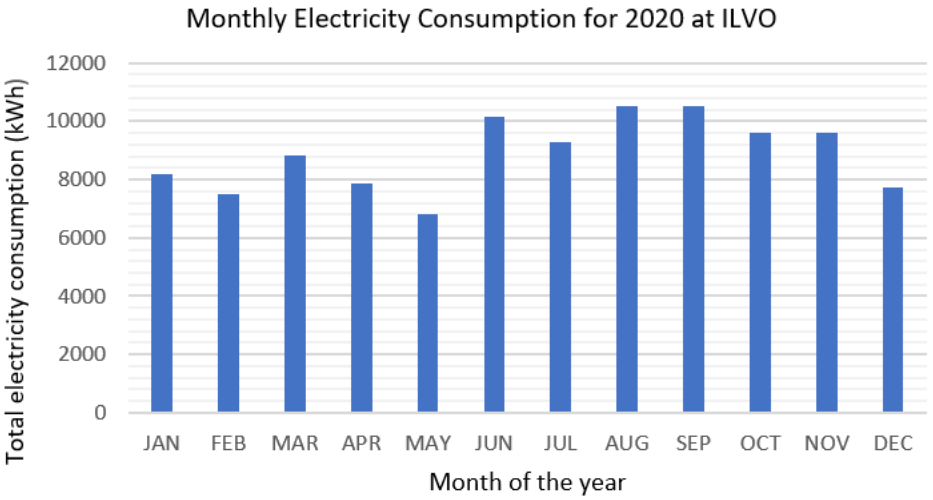

Fig. 3. Monthly distribution of electricity consumption during 2020 at the ILVO swine farm in Belgium

Figure 4 shows a daily fluke electricity analysis of the electricity demand over a day in November 2020. This shows that the electricity consumed in generally during the day between 5 am and 6 pm.

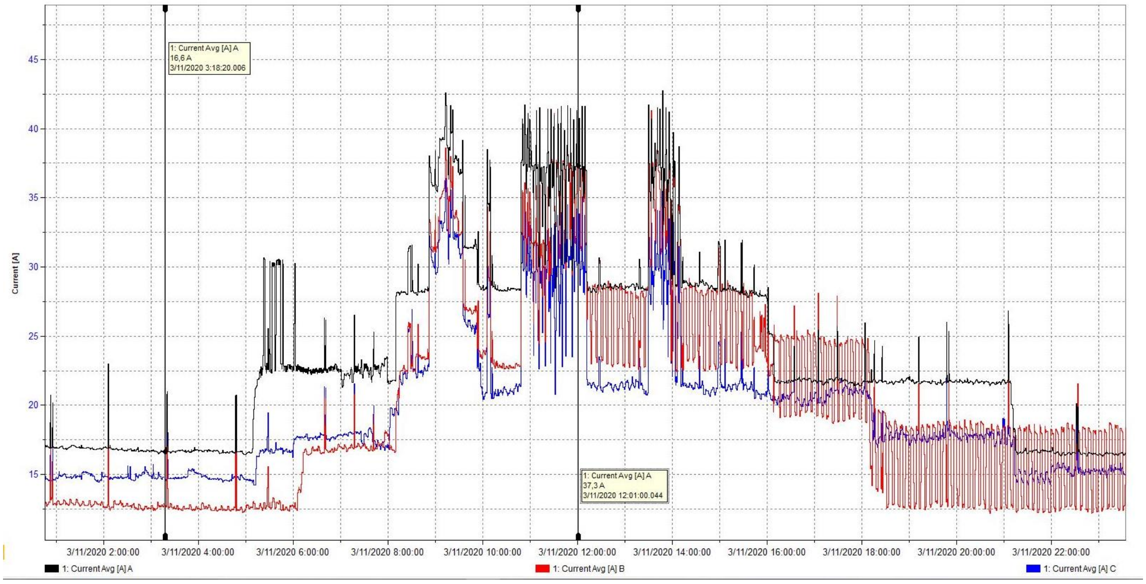

Fig. 4. Fluke Electricity analysis of the electricity demand over a day at the ILVO swine farm in Belgium

3. Energy Usage from the Dairy Farm at LVAT-ATB (Germany)

The LVAT-ATB dairy farm in Potsdam, Germany includes three barns for milk production with a total area of 3,950 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 (Figure 5). All barns are naturally ventilated, but there are ventilators with fans to provide fresh air and cooling in warmer days. An average energy consumption of the farm are presented next:

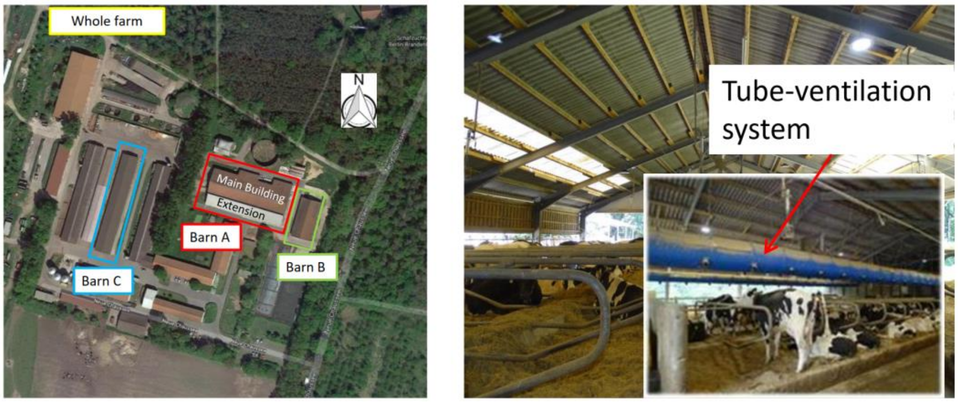

Fig. 5. Dairy farm at LVAT-ATB in Germany

For heating the working areas related to milk production (space heating), the farm has a LPG consumption on average of 30000 kWh/year. A unique feature in dairy farms in terms of energy is that they require a milk cooler to store the produced milk until it leaves the farm. In the described farm, there are two milk coolers which each recovers heat to supply to the heating processes of the farm. As seen in Figure 6, each milk cooler supplies heat to a different heat demand point. For the purposes of this paper, the two streams have been divided into cycle A and cycle B. Cycle A uses heat from the interior milk cooler to supply the automatic milking system (AMS) of the farm. The AMS uses any recovered heat and internally upgrades this heat electrically to 83°C. Cycle B uses heat from the exterior milk cooler to supply intermediary heat to the e-boiler which provides domestic hot water at 80°C for warm water taps and cleaning the milking parlors and tanks.

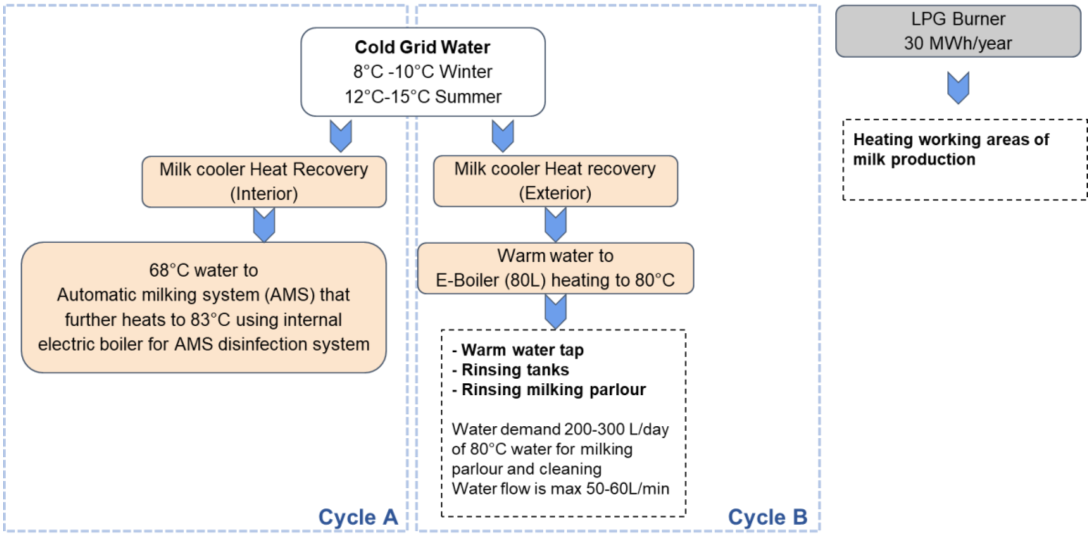

Fig. 6. Summary of the current situation of dairy farm at LVAT-ATB in Germany.

Figure 7 shows the estimated thermal energy demand at LVAT-ATB. In cycle A (Blue), cleaning and disinfection of the milking robot is performed 3 times a day (every 8 hours) by hot water. In addition, a general cleaning is also performed every day in 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 the inside and outside milk tanks (every two days between 7 and 8 pm), milking parlor (7am and 4.30 pm) and buckets. In addition, this cycle is also used for hot water taps. The total demand of hot water at 80°C in cycle B is 1500 L per day. The average monthly thermal energy demand of cycle A and cycle B in LVAT-ATB are 771 kWh and 3577 kWh respectively. The farm is operational all year round with a constant energy need. Thus, the average monthly contribution of annual heating for both cycles is 8.3%. The total estimated annual thermal energy demand for milk production (excluding space heating) at LVAT-ATB is 52197 kWh, where cycle A and cycle B require 9249 kWh and 42930 kWh respectively.

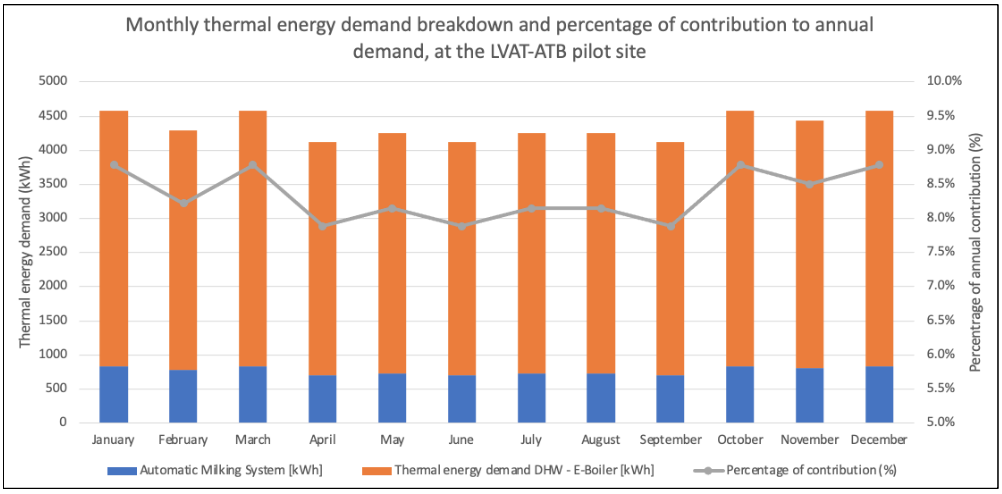

Fig. 7. Estimated thermal energy demand breakdown and percentage of contribution to annual demand for milk production at LVAT-ATB dairy farm.

Figure 8 shows an overview of 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. The electricity demand for the ventilation fans is 170 kWh/day in summer times. In winter times under frosty conditions, the troughs need heating with an electricity consumption of 118 kWh/day. The cows are milked with automatic milking systems, consuming electricity of 152 kWh/day. The milk needs to be cooled constantly over the year with an electric 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 LVAT-ATB farm has an electricity consumption of about 201000 kWh/year for milk production. For heating the working areas related to milk production, 30000 kWh/year is needed.

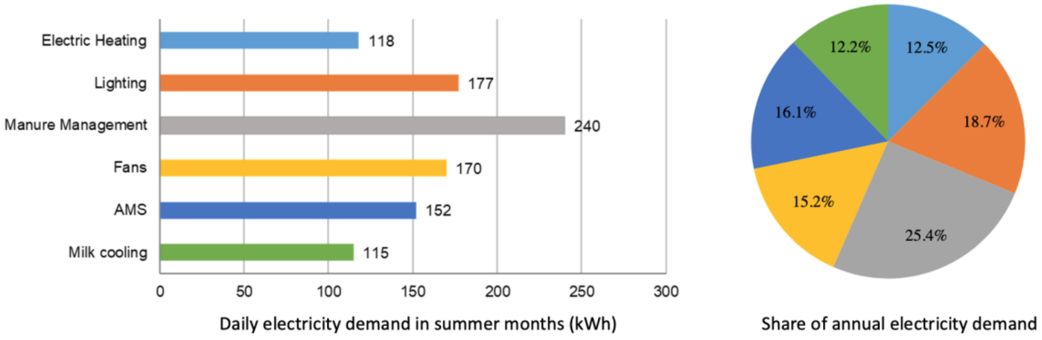

Fig. 8. Daily electricity demand breakdown in summer and share of annual electricity demand for each application at LVAT-ATB

4. The Solarus PowerCollector CPVT

CPVT is a concentrating, hybrid solar photovoltaic and solar thermal collector (CPVT), which generates both electricity (from PV) and heat (from the Thermal part) from the same gross area. The collector reflects and concentrates the incoming sunlight, from its reflective mirrors to the bottom side of a (horizontally placed) PVT receiver. When applied in the right system design, PVT provides energy yields per m^2 about 30% higher than having separate PV and solar thermal collectors with the same total surface area (Ramos et al., 2017).

The Solarus bi-facial CPVT collector has been selected for this study as a model CPVT to determine energy production values at the two different farms. The electrical performance of the Solarus CPVT collector was characterized according to IEC 62108 (2007) while the thermal performance was characterized according to ISO 9806:2017 (by Steady-state (SS) test methods). Results from performance assessment in the Solar Laboratory of University of Gävle showed that the electrical peak efficiency of 11.5% and 11.2% ($R^2 = 0.999$) has been achieved for the bottom and top trough (respectively) for a module temperature of 25 ºC. The steady electrical peak efficiency for higher temperatures, gives a temperature dependence coefficient of around 0.49 %/ºC. Regarding the optical efficiency η_0, a value of 58.2 % (divided in 47.0 $\%_{th}$ and 11.2 $\%_{elect}$, $R^2 = 0.997$) has been obtained per aperture area. The technical specifications of this collectors is presented in Table 2.

Tab. 2. Solar PowerCollector CPVT characteristics.

Company	Technology	Size [m^2]		PV 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	2.57	2.31	Mono	260	11	0.47	4.05	0.003

The efficiencies presented in the following sections for each farm at the corresponding mean temperature (T_m) were obtained using the formula presented in Eq.1. Subsequently, the specific yield was obtained accounting for the monthly direct normal irradiance values as in Eq.2.

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

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 heat loss coefficient [W/m^{2}K], a_2 is quadratic heat loss coefficient [W/m^{2}K^2], T_m is mean temperature [°C] and T_{amb} is ambient temperature [°C] (Eck et al., 2014; Janotte et al., 2014; Osório and Carvalho, 2014).

$$STP = DNI * \eta_{coll} \qquad \textbf{(Eq.2)}$$

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.

5. Use of CPVT collectors at a Swine Farm

The analysis of thermal requirements of the ILVO swine farm is used to better understand the effect of using solar technology in supplying the farm with heat and electricity. The specifications of the Solarus CPVT and the location of the farm have been used to estimate the energy production in using the Solarus CPVT as a model CPVT collector. In this analysis, the thermal production of the CPVT has been prioritized over the electrical production, which will be supplied as a by-product.

The total annual thermal demand of the swine farm (excluding thermal lamps) is estimated at 198 MWh, when assuming a gas boiler at 90% efficiency with a total annual LPG consumption of 220 MWh. To meet this annual demand only using the Solarus CPVT, it was calculated that at least 480 m^2 of collector aperture area is needed to fulfill this demand for an output temperature of 70°C. Furthermore, as seen in Figure 9, most of the solar thermal production is made during the summer months, while most of the thermal demand is during the winter months.

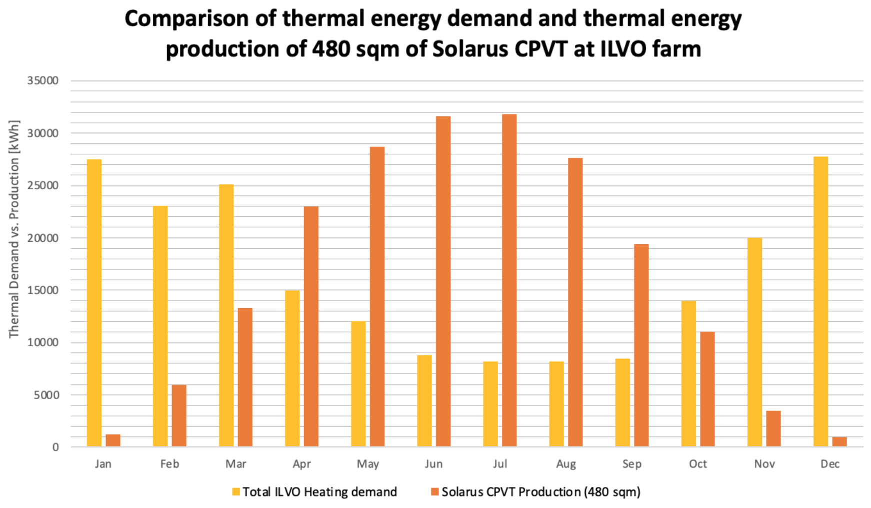

Fig. 9. Thermal energy demand (yellow) and thermal energy production of 480 sqm Solarus CPVT (orange) at the ILVO swine farm

To use the excess heat produced during the summer for use during the winter, a large seasonal storage is required. This scenario is not practical as this would incur very high costs. Furthermore, even though space is available at the farm, the large solar field will also incur a very high cost. From a technical point of view, running a solar thermal system at high temperatures, in this case from ca. 9°C (average grid water temperature) to 70°C will result in high thermal losses and drastically reduce efficiency during the winter. Figure 10 shows the difference in efficiency and specific thermal production of the collector running at mean temperature Tm=40°C and Tm=20°C. The efficiency at lower running temperature is much greater and will allow for more thermal output, thus decreasing the cost per thermal energy produced. Overproduction, which is the case here during the summer is also not recommended unless a suitable thermal storage is available. If there is excess thermal production in the solar system, there is a risk of the collectors shutting down as it reaches its maximum operating temperature. If there are no safety measures in place, this could lead to the breakdown of the collectors and system. Thus, it is proposed to run the system at lower temperatures, only lifting the temperature by ca. 10-20°C above grid temperature. In this case the specific annual thermal output of the CPVT at ILVO is 436.1 kWh/m^2.

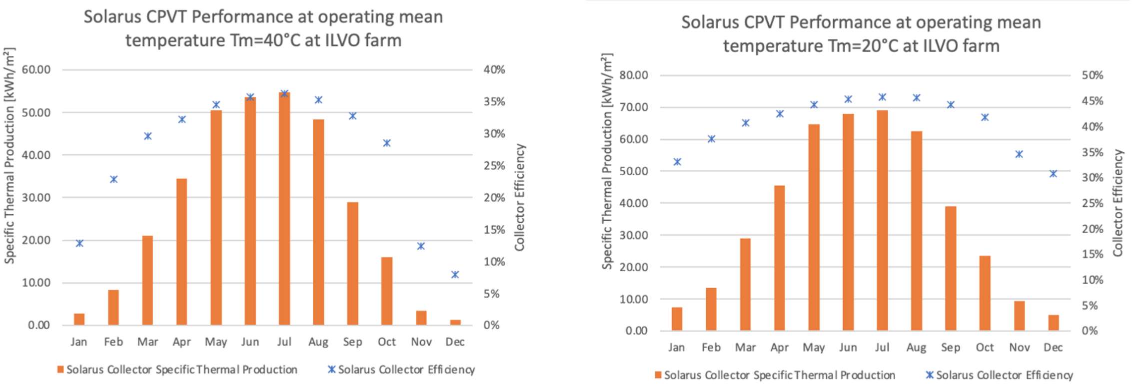

Fig. 10. Thermal performance of Solarus CPVT at Tm=40°C (left) and Tm=20°C (right) at ILVO farm

For the above reasons, the system proposed for the ILVO swine farm when using solar PVT collectors or CPVTs, is to use the collectors at lower temperatures at Tm=20°C to maximize efficiency and integrate the collectors with heat pumps that will deliver the final temperature requirements. In this case the solar collectors will produce heat to lift the COP of the heat pumps, increasing their efficiency, and decreasing their electricity load. One heat pump will supply heat for the floor heating system which runs constantly at 40°C. The other high pump will run at higher temperature to supply heat at 70°C for domestic hot water and the air heating channels. Figure 11 shows an overview of the proposed integrated system. The sizing of the solar collector system will then depend on the specifications of the heat pump.

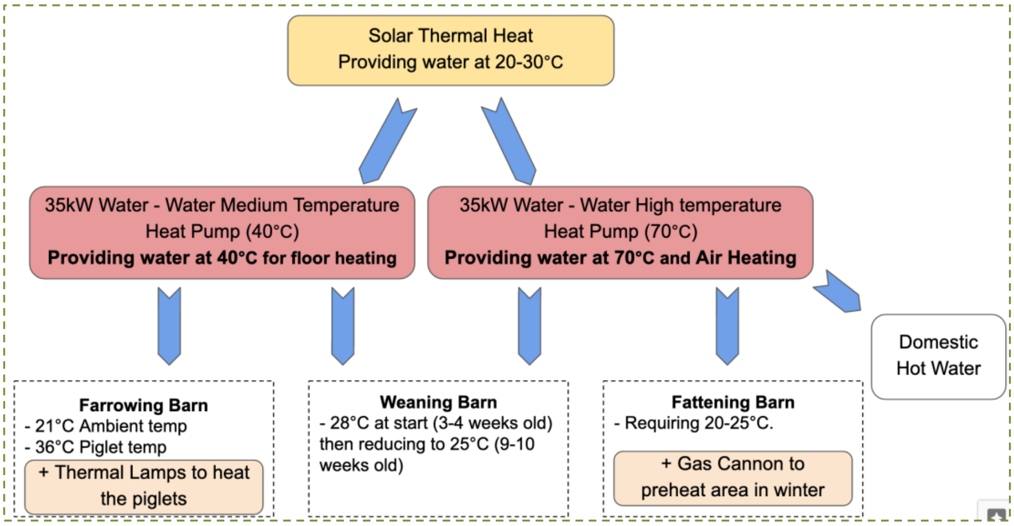

Fig. 11. Overview of proposed system integrating CPVT collectors at the ILVO swine farm in Belgium

The specific annual electrical production of the Solarus CPVT at the ILVO farm is 111 kWh/m^2. To meet the annual electrical demand of 110 MWh, 994 m^2 of aperture area is required. However, as the case of most PVT designs, the remaining electrical demand must be met from other sources such as PV or from the electricity grid.

6. Use of CPVT collectors at a Diary Farm

In this analysis, as with the case with the swine farm, the thermal production of the CPVT has been prioritized over the electrical production, which will be supplied as a by-product. As mentioned in previous sections, the dairy farm has the advantage of a milk cooler, where heat can be recovered from. 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. Thus, a system is proposed to use the thermal heat from the solar system to lift the temperature at the outlet of the buffer tank from 40°C to 50-55°C and use the milk cooler heat recovery as a quasi-heat pump. The last increase in needed temperature (from 50-55°C to 80°C) at cycle B of LVAT-ATB will be supplied by e-boiler (trough grid electricity). The proposed system is shown in Figure 12.

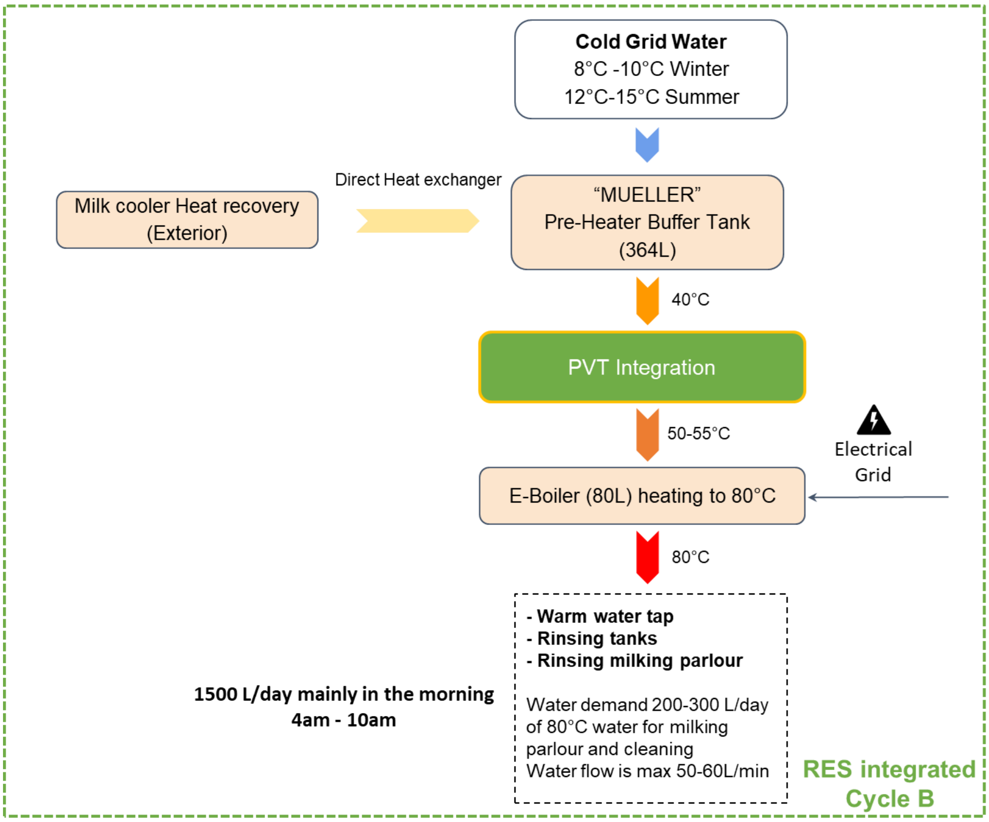

Fig. 12. Overview of the proposed system with (C)PVT collectors at the LVAT-ATB dairy farm in Germany.

With use of the PVT system in cycle B, the temperature available to the E-Boiler would be increased to 55°C and 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 by the help the electricity from the grid. Additional PV panels would be needed to meet all the electrical needs of the farm.

The total estimated annual thermal energy demand for milk production (excluding space heating) at LVAT-ATB is 52 197 kWh, where cycle A and cycle B (c.f. figure 6) require 9 249 kWh and 42 930 kWh respectively. To meet the heating demand (42 930 kWh) after the heat recovery system in cycle B, the CPVT collectors would need to supply the required amount of hot water at 80°C, effectively replacing the e-boiler. To do this, the total aperture area of the Solarus CPVT needed would be 140 m^2. This is a possible option considering the available roof space of the farm. However, as with the case at the ILVO farm, running at high temperatures would not be an efficient option, and in the case of low solar radiation, a backup heater is suggested. The safest option would be to run the solar system at the lowest possible temperature for highest efficiency, lifting the temperature from 40°C to 50-55°C, and use the e-boiler to heat up to the required temperature. Using the Solarus PVT at a mean temperature (Tm) of 45°C, the specific annual thermal output at LVAT is 375.5 kWh/m^2. The monthly thermal production over a year and the change in efficiency of the collector across the year is shown in Figure 13.

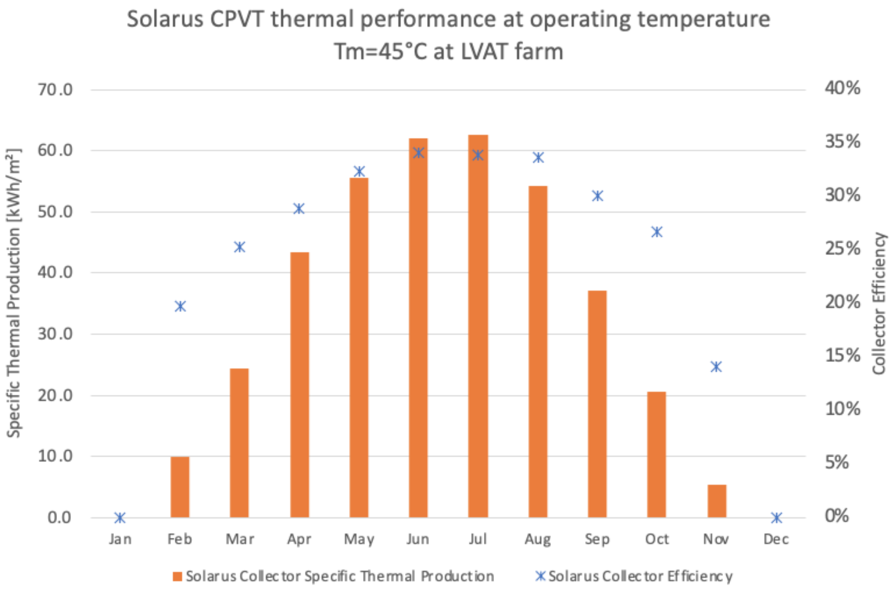

Fig. 13. Thermal performance of Solarus CPVT at Tm=45°C at the LVAT farm in Germany

The specific annual electrical production of the Solarus CPVT at the LVAT farm is 142 kWh/m^2. To meet the annual electrical demand of 201 MWh, 1416 m^2 of aperture area is required. Again, as the case of most PVT designs, the remaining electrical demand must be met from other sources such as PV or from the electricity grid.

7. Conclusion

The case study analysis of the energy usage of the swine farm at ILVO, Belgium, and the dairy farm at LVAT-ATB, Germany, shows the difference in heating and electrical demand of the two types of farms. The swine farm consumes more heat than electricity for pig raising while the dairy farm consumes more heat than electricity for milk production. This is partly due to the high electricity consumers of the automatic milking system in the diary farm and the year-round heating needs for raising piglets in the swine farm. For the swine farm it is suggested to make use of the higher efficiencies of the CPVT when operating at low temperatures at a mean temperature (Tm) of 20°C, to preheat grid water by 10-20°C and using two types of heat pumps to obtain the required temperatures for hot water and space heating. This is suggested to be a more economical scenario than installing CPVT collectors to cover the entire demand where most of the heat generated in the summer will not be used. The specific annual thermal output of the CPVT at ILVO is 436.1 kWh/m^2. The dairy farm has the advantage of possessing a milk cooler where heat can be recovered from. This is the case at the LVAT farm. It is suggested to use the CPVT collectors to lift the temperature of the pre-heated water (40°C) by 10-15°C, running at a mean temperature (Tm) of 45°C. The specific annual thermal output of the CPVT at this Tm LVAT is 375.5 kWh/m^2.The remaining temperature difference can be supplied by an e-boiler. Running at the lowest mean temperature possible maximizes the thermal efficiency of the solar system. Further modelling and simulations need to be done to determine the optimal integration temperatures of both systems coupled with the heat recovery storage and heat pumps, both technically and economically. Further study should also be made in the cost benefit of the size of such a solar system in comparison with heating with electricity. In the future the levelized cost of heat for solar thermal and (C)PVT applications is likely to decline as electricity and fossil-fuel prices rise.

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