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Requirements and Economic Implications of Integrating a PV-Plant-Based Energy System in the Dairy Production Process

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Abstract: To expand the potential of renewable energies, energy storage is required to level peaks in energy demand and supply. The aim of the present study was to examine and characterize the energy consumption of a milk production system to find possibilities and boundaries for a self-sufficient energy system. A detailed quantification of energy production of the test farm and the consumption of the milk production system showed, that the total energy production could cover the energy consumption of the production process. However, the temporal distribution of energy production and consumption requires energy storage in the production process. Though ice bank milk cooling and water heating have the potential to cover parts of this storage capacity, battery storage is mandatory to enable full autarky. The consideration of different seasons leads to different optimal dimensions of the energy system. The energy price is decisive for profitability, both in the purchase and in the sale. Smaller energy systems are generally at an advantage due to the higher self-consumption quota.

Keywords: renewable energy; self-sufficient energy supply; energy management; dairy farming; milk production

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1. Introduction

The combination of increased mechanization, automatization and rising energy prices has resulted in higher energy costs in dairy farming [1] (p. 160). As a result, there is a growing economic interest in energy-efficient and renewable energy technologies, improvements in energy independence and reduction of energy usage [2] (p. 2).

In German dairy farming, the majority of energy consumption occurs during milking and milk cooling, accounting for approximately 56 to 70% of the total energy consumption [3]. Additionally, automatic milking systems (AMSs) can contribute to increased electricity consumption on dairy farms [4] (p. 4171).

Upton et al. (2013) have shown that the milking machine alone consumes about 20%, and milk cooling 31%, of the total electricity consumption on Irish dairy farms [5] (pp. 6496–6497). The energy consumption of the milking machine consists of the vacuum pump, milk pump, milking robot, air compressor and warm water boiler (BWAC) [6]. The main electricity consumers for milk cooling are the compressors of the cooling units, the fans at the condenser and the agitators of the milk storage tanks [3] (p. 15).

Further, a seasonal effect on the electricity consumption that aligns with the milk production curve was found. Additionally, the daily profile of electrical energy consumption trends followed a sinusoidal pattern of significant consumption peaks from 7:00 a.m. to 12:00 a.m., as well as 4:30 p.m. to 7:30 p.m., corresponding to the morning and evening milkings [5] (p. 6494).

According to Behnisch et al. (2021), an initial assessment shows that there is enormous potential for building-integrated photovoltaics to make decisive contributions at the local level towards a future climate-neutral energy system [7]. In addition, there are already legal regulations in German regions that require a photovoltaic plant (PV plant) on agricultural buildings such as machine sheds and stables [8]. This also creates a potential for using this energy production in farms' own production processes. Neiber and Neser (2016) indicate the self-sufficient use of solar power as a possibility to reduce energy costs for agricultural enterprises [9]. However, renewable energies from wind power and PV plants are not generated as required but rather depend on the weather, location and the time of day and year [10] (p. 6), [11] (p. 270). Energy production and energy consumption in agriculture usually occur separately due to the current legal regulations [12]. According to Upton et al. (2013), more than 60% of milk cooling energy consumption currently occurs on more expensive day-rate tariffs [5] (pp. 6496–6497). Energy saving alone is not incentive enough to invest in solar technologies, but there are niches for which solar energy applications are feasible [13] (p. 53).

To expand the potential of renewable energy, energy storage is needed to balance peaks in energy demand and supply excess capacity during periods of low demand, as well as to balance congestion during periods of high demand [11] (p. 270), [14] (p. 1018), [15]. When the supply from renewable energy exceeds demand, the excess energy can be stored and released during times of high demand [16] (p. 9). Hence, batteries are required to store energy for use at night or to meet load requirements when PV modules cannot generate sufficient power [17] (p. 392). The storage of solar energy and wind energy, which is usually converted into electric energy, is challenging and expensive [15] (p. 5).

However, there are alternative approaches to shift loads and store energy. As an example, for milk cooling, either direct cooling or the indirect cooling process is used [18] (p. 448), [19] (p. 143). In contrast to direct expansion (DX) milk cooling, where the evaporator comes into direct contact with the milk, the indirect cooling principle uses ice water as a coolant between the evaporator (refrigerant) and the inner container wall [18] (p. 448), [19] (p. 143), [20] (p. 129). In this ice water cooling system (IB), the ice water is sprayed onto the wall of the inner container via a circulation pump and then directed to the refrigeration unit for regeneration [20] (p. 129). This ice water supply can be created independently from the milking times [20] (p. 129), allowing the ice water preparation of an ice water cooling system (IB) in times of low-cost electricity production [21] (pp. 19–20). Therefore, the ice storage systems are able to improve the imbalance of power load distribution [22] (p. 179).

Consequently, this creates opportunities for utilizing low-priced energy produced at night or during weekend periods when energy costs are often 50–70% cheaper than during the day [23]. Upton et al. (2013) characterized the energy consumption of different milk cooling systems [5]. Their findings revealed that IB systems ran on day tariff for 30% of their operating times, whereas the DX systems used 70% day tariff electricity [5] (p. 6493).

However, the authors did not consider automatic milking systems (AMSs) in their research. The use of AMS in modern dairy farms is becoming more and more popular [6,24]. In contrast to conventional milking systems, AMSs avoid high milk accumulation during the milking times, distributing milk evenly throughout the day [24] (p. 28). Energy use varies significantly among farms, ranging from 300 to 1500 kWh/cow annually. Larger modern free-stall dairies consume less electrical energy per cow due to higher-efficiency milk cooling systems, variable-speed vacuum pumps, heat recovery, and other more efficient technologies [25] (p. 5409). Implementing intelligent energy management increases energy independence and reduces energy costs at the farm level [26]. For battery storage, the charge controller regulates the flow of electricity from the PV modules to the battery and the load [17] (p. 392). In this context, energy management of agricultural activities can have a strategic role in the future of agriculture by reducing production costs and supporting the sustainability of rural development [27].

Since milking-related activities account for the major proportion of overall electric use on the farm, they offer substantial potential for electric energy savings and cost reduction [28] (p. 831). To achieve low operating costs, a detailed quantification of energy consumption is essential [29] (p. 4043). When modeling the electrical devices, the characteristics of the individual devices must be carefully observed [30] (p. 80).

Therefore, the objective of the present study was to investigate and characterize the energy consumption of a milk production system in different seasons and during the day under practical conditions. This provides information on the requirements for a self-sufficient energy system made of a PV plant and a battery storage unit. Subsequently, an energy system was modeled regarding the expected requirements for the corresponding season. Based on cost factors from the literature, the mean energy costs of these energy systems were compared to a simple external energy supply by public electricity suppliers.

The results were discussed, focussing on the optimization potential for energy storage opportunities within the production processes and the economic consequences of different degrees of self-sufficient energy supply by an energy system with a PV plant and a battery storage system.

2. Materials and Methods

2.1. Description of the Farm and the Investigated System Configurations

The research was conducted at a free-stall dairy barn located in southern Bavaria, Germany, with a rooftop photovoltaic plant (PV plant) that has a capacity of 205.2 kWp (Figure 1).

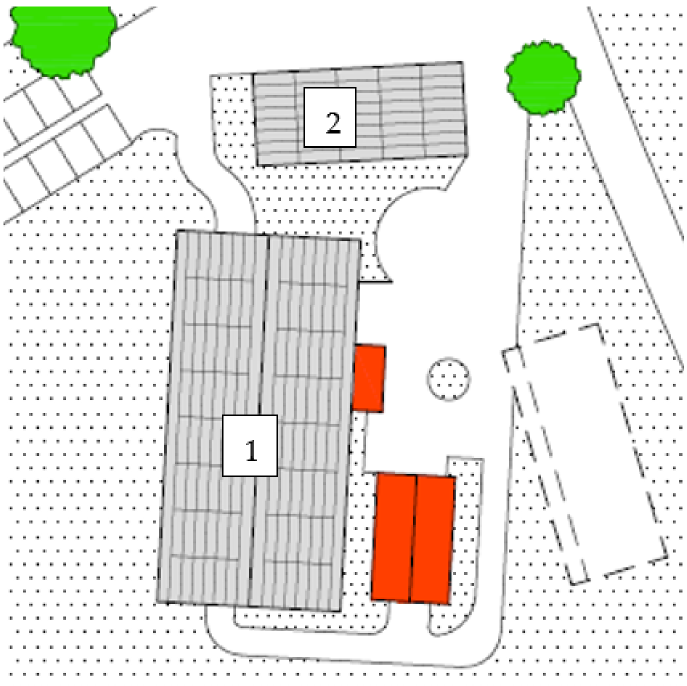

Figure 1. Overview of the model farm, with the dairy barn with the production system and the rooftop PV plant (1) and the position of the battery storage (2).

In order to achieve a better distribution of energy production throughout the day, the roof or PV system was oriented with an angle of inclination of 20° to the east and west.

The geographical coordinates of the farm are 47.941° N, and 12.125° E. Data on energy production and consumption of the individual components was collected between May 2020 and April 2021.

The components of the AMS that are directly connected to the milking process are the milking robot, the vacuum pump, the air compressor, the heating unit and the water reservoir for the boiling water cleaning system (BWAC) (Table 1). The energy consumption of the milking robot includes the electric drives that move the attachment arm.

Table 1. Technical and energetic characteristics of the considered energy consumers of the different milking systems.

Production System	Main Components
Automatic milking system	Fullwood M^{2}erlin System control: 0.5 kW Milk pump: 1.5 kW
Vacuum pump	Dry claw vacuum pump: 3.0 kW
Air compressor	Piston compressor: 3.0 kW
Hot water boiler	CitrinSolar GmbH Type ESH6DN40: 4.5 kW 230/400 V

The milking vacuum operated on a frequency-controlled dry claw vacuum pump with a maximum pressure of 400 hPa powered by a 3.0 kW motor. Compressed air for opening/closing the entrance of the milking robot as well as for removal of water and milk after milking and cleaning was provided by a 3.0 kW piston compressor (REKO 500/90, RENNER GmbH Kompressoren, Güglingen, Germany) combined with a 90 L pressure vessel. A pressure between 8 and 10 bar was applied. The BWAC cleaned the milking system three times every day. The 240 L boiler operates on a 4.5 kW heating unit. The required temperature was 90 °C. The starting temperature was 45 °C. Concentrate feed supply screws were not considered.

The milk cooling system was a Fullwood Packo RM IB 4400 cooling tank with an integrated heating unit for automatic cleaning. The maximum nominal electrical power consumption of the milk cooling tank was specified as 13.965 kW (Table 2). The milk was collected at 12:00 a.m. every second day, followed by an automatic cleaning process. The warm water required for cleaning was heated to a temperature of 45 °C during the cleaning process. The cooling unit operated separately from the milk tank and had a nominal electrical power consumption of 3.3 kW. A waste heat recovery system was used for warm water production during cooling.

Table 2. Technical and energetic characteristics of the IB milk cooling system.

Production System	Characteristic
Milk cooling tank volume	Fullwood Packo RM IB 4400/13.965 kW
Capacity ice bank storage	78 kWh
Cooling unit	3.3 kW

A precooling system that utilized a well water supply was incorporated into the cooling system. Energy consumption for pumping water through the precooler was not taken into account since the water was also used for drinking. Hence, a clear assignment of the energy consumption to the milking system was not possible.

2.2. Data Aquistition and Technical Equipment

Data on power and energy production from the PV plant were obtained from the SunnyPortal System (SMA Solar Technology AG, Niestetal, Germany) at 15-min intervals, providing the highest temporal resolution. The data regarding milk production was collected from the AMS management software Crystal (Version 2.7).

The data acquisition was carried out analogously to Höhendinger et al. 2021 [6]. The energy consumption of the milk cooling system is measured continuously with digital smart meters (certified 3-phase meters for measurement of active power of up to 460 V/65 A with three digital inputs and RS-485 interface). Monitoring and analytics of the data are performed using the Grafana dashboard tool. Active energy is selected for the analysis as the machinery does not use inductive fields and the energy provider accounts for active energy consumption. Effects of apparent energy and reactive energy are not considered for this research. [6]

2.3. Statistical Methods

Statistical analysis was performed with MATLAB R2020a (The MathWorks, Inc. Natick, MA, USA). For the seasonal analysis based on the calendar system, energy data at 15-min intervals were summarized for every system component daily by date. Days with incomplete recording or missing data from one or more components were not further considered.

The intraday analysis was performed with the energy data measured in kWh/15 min. The production interval of milk production for South German dairy farming is determined by milk collection every 2 days. To avoid smoothing the energy consumption for the subsequent cleaning of the milk tank viewed on a 24-h interval, the intraday analysis was conducted over a 48-h observation period.

Self-sufficiency was characterized by the balance of energy production and energy consumption in the milk production system. These represented the time periods of self-sufficient energy supply and periods with an energy production deficiency on the farm. These periods were then used to determine requirements for the required battery storage for the energy system of the farm.

The energy efficiency of individual energy consumers, partial systems and the overall milk production system were evaluated daily and relative to the production of kg of milk per day. Differences in the active energy consumption between different seasons were carried out with a one-factorial ANOVA analysis.

2.4. Modeling of the Energy System

The daily energy demand of the milking system was used to model an optimal system for a self-sufficient energy supply using a combination of a PV plant and battery storage. To account for seasonal influences, separate calculations were performed for each season.

The required power capacity of the PV plant (CapPV [kWp]) was calculated in Equation (1) based on the average energy yield per kWp installed capacity per day ($E_{ProdAvg}$ [kWh/kWp*d]) and the daily consumption for the respective season ($E_{ConsumTota}l$ [kWh/d]). The average daily energy yield for the site and the corresponding season was calculated from the PV plant data collected on the research farm.

$$\text{CapPV [kWp]} = E_{ConsumTota}l \text{ [kWh/d]}/E_{ProdAvg} \text{ [kWh/kWp*d]} \quad (1)$$

For comparison, the daily energy balance was calculated for the respective plant size in the other seasons and with the respective energy consumption.

The required storage capacity corresponded to the energy deficiency for the respective season. Since the energy consumption during deficiency periods remained uniform in the 48 h intraday analysis, the average energy deficiency for a 24 h observation interval was assumed to be the necessary storage capacity to bridge the nighttime periods for an energy-autonomous milking system.

To calculate the required storage capacity of the battery (CapBat [kWh]) in general, the average load during the deficiency period ($Load_{avg}$ [kW]) was calculated. Using the average duration of the night, the required capacity for the battery storage was calculated in Equation (2):

$$\text{CapBat [kWh]} = Load_{avg} \text{ [kW]} \times (24\text{ h} - \text{Day length [h]}) \quad (2)$$

2.5. Economic Evaluation of the Energy Supply System

The investment costs for the PV system were set at 1000 €/kWp installed capacity [31], and for the battery storage, it was 800 €/kWh storage capacity [32]. To calculate the annual costs of the system, a depreciation period of 20 years, a 4% interest rate and 1% of the investment amount for maintenance were applied.

The costs for the storage system can be determined by multiplying the annual costs per €/kWh storage capacity by the necessary storage capacity (CapBat). Similarly, the costs for the PV system were calculated and added to the storage costs, resulting in the total costs for the entire energy supply system.

For the surplus electricity fed to the public grid, a tariff of 0.07 €/kWh was applied [33]. For the energy deficiency, an electricity price of 0.30 €/kWh was assumed [34].

The total costs are a result of the energy purchase ($TotCosts_{EPurchase}$ [€/a]), the revenues for the feed-in ($TotalRevenue_{Eprod}$ [€/a]) and the annual costs for energy system ($TotCost_{ESystem}$ [€/a]). In Equation (3), these total costs are then divided by the average electricity consumption per year (Tot_{ECons} [kWh/a]) to calculate the mean costs per kWh (MeanEPrice) of consumed energy:

$$MeanEPrice\ [€/kWh] = (TotCost_{ESystem}\ [€/a] + TotCosts_{EPurchase}\ [€/a] - TotalRevenue_{Eprod}\ [€/a])/Tot_{ECons}\ [kWh/a] \quad (3)$$

For further economic evaluation, the amortization period of the plant was calculated in comparison to a purely public power supply. In order to evaluate the economic risk, a sensitivity analysis was carried out with different electricity purchase prices. Scenarios with a price increase of 5%, 10% and 15% were assumed.

3. Results

3.1. Analysis of Seasonal Impacts in the Production Processes

The mean milk production during the observation period was 1847.3 kg milk/day. Differences in the daily milk yield between the seasons were assumed to depend on the variation of livestock and milk yield per cow during the observation period. Hence, impacts of the seasonal circumstances regarding the milk yield were assumed negligible. This is supported by the system with year-round housing and silage feeding.

The mean energy production of the 205.2 kWp PV plant on the farm varied with the seasons from about 143.54 kWh/day in winter to 749.65 kWh/day in summer (spring 626.7 kWh/day, summer 749.6 kWh/day, autumn 356.5 kWh/day and winter 143.5 kWh/day).

Meanwhile, the mean energy consumption of the milk production system was between 77.50 kWh/day in summer and 56.62 kWh/day in winter (Table 3). The separate analysis of the milking system showed a variation of energy consumption between 39.14 kWh/day in summer and 41.85 kWh/day in winter (Table 3). In terms of milk production, energy consumption was highest in spring (23.41 Wh/kg milk) and lowest in summer (20.45 Wh/kg milk).

The mean energy consumption of the milking robot was 6.49 kWh/day, with a range from 5.06 kWh/day in spring to 6.85 kWh/day in winter. Compared to the energy consumption per kg of milk, the differences are smaller. The vacuum pump and air compressor showed similar differences in energy consumption between the seasons. However, for both consumers, no significant ($p < 0.01$) differences were observed in the mean daily energy consumption. According to this, the energy consumption of the milking robot, vacuum pump and air compressor are likely to depend mainly on the milk yield.

The energy consumption of the BWAC was highest in winter (17.05 kWh/day). Significant differences in daily energy consumption are found between winter, summer (14.35 kWh/day) and autumn (16.15 kWh/day). Spring (16.58 kWh/day) was between summer and winter but did not differ significantly from autumn and winter. The BWAC was applied regularly during fixed operational times independent of the milk production. Hence, the energy consumption in relation to milk production is immaterial for the BWAC.

The energy consumption of the milk cooling system consists of the consumer's milk cooling tank and cooling unit (Table 3). The main energy consumer was the cooling unit with a mean energy consumption of 20.43 kWh/day, respective to 11.03 Wh/kg milk.

Except for spring and autumn, significant differences ($p < 0.001$) were found between all seasons.

Table 3. Seasonal differences in the energy consumption of the ice bank cooling system; significantly different groups are indicated with letters ([a,b,c]).

	Unit	Year	Spring	SE	Summer	SE	Autumn	SE	Winter	SE	*p*-Value	F-Value
Milk production system	kWh/d	65.68	60.96 [ac]	1.67	77.50 [b]	1.23	67.84 [c]	1.14	56.63 [a]	1.08	<0.0001	58.18
	Wh/kg Milk	35.55	32.73 [a]	0.94	40.49 [b]	0.69	38.24 [b]	0.64	30.52 [a]	0.60	<0.0001	49.11
Milking system	kWh/d	40.85	39.98 [ab]	0.59	39.14 [b]	0.45	41.52 [a]	0.41	41.85 [a]	0.38	<0.001	8.83
	Wh/kg Milk	22.38	23.41	0.81	20.45	0.61	23.38	0.56	22.48	0.52	<0.0024	4.94
Milking robot	kWh/d	6.49	5.06 [a]	0.20	6.47 [b]	0.15	6.78 [b]	0.14	6.85 [b]	0.13	<0.0001	20.63
	Wh/kg Milk	3.55	2.96 [b]	0.15	3.41 [ab]	0.11	3.82 [a]	0.11	3.68 [a]	0.10	<0.0001	8.19
Vacuum	kWh/d	9.60	9.50	0.12	9.46	0.10	9.85	0.09	9.54	0.09	<0.0145	3.58
	Wh/kg Milk	5.24	5.41 [ab]	0.14	4.96 [a]	0.11	5.53 [b]	0.10	5.12 [ab]	0.10	<0.0004	6.19
Air compressor	kWh/d	8.63	8.53 [ab]	0.15	8.74 [ab]	0.12	8.822 [b]	0.11	8.42 [a]	0.10	<0.0347	2.92
	Wh/kg Milk	4.71	4.86 [ab]	0.14	4.59 [ab]	0.11	4.97 [b]	0.11	4.52 [a]	0.10	<0.0082	4.00
BWAC	kWh/d	16.04	16.58 [ac]	0.26	14.35 [b]	0.19	16.15 [c]	0.18	17.05 [a]	0.17	<0.0001	39.53
	Wh/kg Milk	8.78	9.60 [a]	0.30	7.52 [b]	0.22	9.08 [a]	0.21	9.15 [a]	0.20	<0.0001	15.22
Cooling system	kWh/d	25.56	23.28 [a]	1.18	38.22 [b]	0.89	26.48 [a]	0.85	14.79 [c]	0.83	<0.0001	126.49
	Wh/kg Milk	13.81	12.50 [a]	0.66	20.06 [b]	0.49	14.93 [a]	0.47	7.97 [c]	0.46	<0.0001	110.35
Cooling unit	kWh/d	20.43	18.38 [a]	1.03	32.02 [b]	0.76	21.15 [a]	0.73	10.77 [c]	0.70	<0.0001	141.77
	Wh/kg Milk	11.03	9.86 [a]	0.57	16.82 [b]	0.42	11.92 [a]	0.40	5.78 [c]	0.39	<0.0001	126.80
Milk tank	kWh/d	5.28	4.65 [ac]	0.31	6.74 [b]	0.24	5.62 [c]	0.23	4.07 [a]	0.22	<0.0001	23.78
	Wh/kg Milk	2.87	2.57 [ac]	0.17	3.54 [b]	0.13	3.17 [bc]	0.13	2.19 [a]	0.12	<0.0001	21.20

The mean energy consumption of the milk cooling tank was 5.28 kWh/day, respective to 2.87 Wh/kg milk. Significant differences ($p < 0.01$) in the mean energy consumption per day were observed between the seasons.

According to this, seasonal variation of the energy consumption of the cooling system depends mainly on the cooling unit. The emptying of the milk tank every second day caused about 5.48 kWh/d (19%) increased energy consumption compared to days without emptying (Table 4). This is assumed to result from the cleaning system after emptying.

Table 4. Differences in the energy consumption regarding the tank emptying and cleaning of the ice bank cooling system; significantly different groups are indicated with letters ([a,b]).

Mean Energy Consumption	Unit	Cooling and Cleaning	SE	Cooling	SE	Difference	Difference in %	*p*-Value	F-Value
Total	kWh/d	28.33 [a]	0.99	22.85 [b]	0.98	5.45	19%	<0.001	15.5236
Total	Wh/kg Milk	15.30 [a]	0.53	12.36 [b]	0.52	2.94	19%	<0.001	15.5897
Cooling unit	kWh/d	21.35	0.89	19.55	0.87	1.79	8%	0.1511	2.0733
Cooling unit	Wh/kg Milk	11.54	0.47	10.55	0.47	0.98	9%	0.1418	2.1707
Milk tank	kWh/d	7.11 [a]	0.12	3.47 [b]	0.12	3.64	51%	<0.001	494.67
Milk tank	Wh/kg Milk	3.85 [a]	0.065	1.98 [b]	0.06	1.87	49%	<0.001	454.65

3.2. Energy Production and Balance Differences between Seasons

The observation of the energy production over the 48.00 h interval shows a bell-shaped curve with an increase until midday and a decrease in the evening hours (Figure 2). The intraday observation of the energy consumption reveals seasonally varying periods with energy deficiency that are assumed to be night hours with no or negligible energy production.

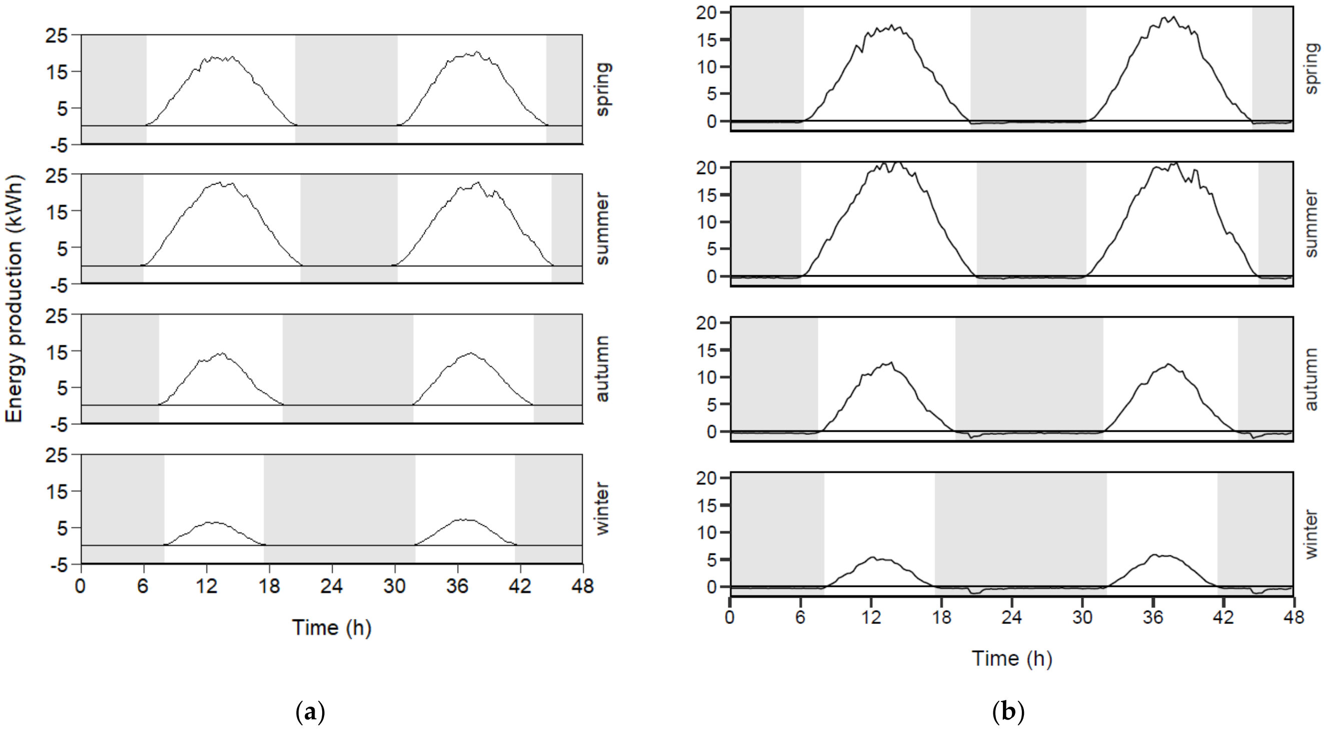

Figure 2. Energy production of the PV plant in 15 min resolution for a 48.00 h period (**a**); energy balance of the milk production system and the PV plant in a 48.00 h period (**b**). Periods with negative energy balance are indicated with grey areas.

Energy production is highest in summer and lowest in winter and the mean energy surplus during the 48.00 h period was the largest in summer (1371.2 kWh) and the lowest in winter (229.4 kWh) (Table 5).

Table 5. Mean energy deficiencies and surpluses of a 48 h interval and the mean daily energy production in the different seasons.

Season	Energy Deficiency	Energy Surplus	Mean Energy Production
	kWh	kWh	kWh/(kWp*d)
Spring	25.3	1094.8	3.05
Summer	25.2	1371.2	3.65
Autumn	41.4	586.2	1.74
Winter	47.5	229.4	0.70

The absolute surplus of energy production during the 48.00 h period is mathematically sufficient to compensate for the deficiency in every season. This represents the decreased daily energy production per kWp installed capacity between summer and winter. Periods in which there was a surplus of energy varied seasonally between 28.00 h (61%) in summer and 18.50 h (39%) in winter (Table 6). The time of energy deficiency of the 48 h interval, that needs to be equaled was between 18.75 h (39%) in summer and 29.50 h (61%) in winter.

Table 6. Mean ratio of energy surplus and deficiency times absolute and in % of a 48 h interval.

Season	Time of Surplus		Time of Deficiency	
	h	%	h	%
Spring	28.00	58%	20.00	42%
Summer	29.25	61%	18.75	39%
Autumn	22.75	47%	25.25	53%
Winter	18.50	39%	29.50	61%

The deficiency periods are the longest in winter between the hours of 0.00 and 8.25, 17.50 and 32.25 and 41.50 and 48.00, which results in a time with energy deficiency of 29.5 h in the 48.00 h observation period. In summer, the shortest times of energy deficiency were observed. The periods were distributed between the hours of 0.00 and 6.25, 21.00 and 30.50 and 45.00 and 48.00. Hence, the time of energy deficiency was 18.75 h in the 48 h observation period. Spring and autumn showed time periods between the two extremes. The ratio of time with deficiency is not equal to the ratio of the energy deficiency of the energy consumption of the milk production system, which could not be covered by the PV plant's energy production. According to this, the mean load during deficiency periods is lower than during daytime (Table 7).

Table 7. Mean ratio of energy self-supply and energy deficiency (purchase) regarding the energy consumption of the 48 h interval.

Season	Energy Consumption kWh	Energy Self-Supply kWh		Mean Load kW	Energy Deficiency kWh		Mean Load kW
Spring	121.9	96.6	79%	3.4	25.3	21%	1.3
Summer	155.0	129.8	84%	4.5	25.2	16%	1.3
Autumn	135.7	94.3	69%	4.1	41.4	31%	1.6
Winter	113.3	65.8	58%	3.5	47.5	42%	1.6

The amount of energy deficiency needs to be purchased from public providers. Based on the energy consumption, it can be concluded that an energy storage system must provide a capacity equal to the energy deficiency per day. However, there are differences in the energy consumption of two consecutive days (48 h periods). Hence, the capacity of a battery storage unit should take this into account, as well as conversion losses during the loading process of the storage.

3.3. Distribution of the Intraday Energy Consumption of the Milk Production System

To account for the milk emptying interval for the intraday analysis, a time interval of 48 h was chosen. The temporal resolution was 15 min. The energy consumption of the milk production system was on a mean level between 0.2 and 0.4 kWh/15 min during night hours (Figure 3). Depending on the season, the increase in the mean energy consumption starts at the earliest at 6:15 a.m. in summer and latest in winter at 8:15 a.m. This increase continued until 10:30 a.m., up to 2.0 kWh/15 min in summer. Subsequently, the energy consumption decreased moving on to evenings. However, between 3:30 p.m. and 5:00 p.m., as well as between 8:30 p.m. and 9:30 p.m., the energy consumption was increased. On the second day between hours 35.00 and 36.00 (corresponding to 11:00 a.m. to 12:00 a.m.), there was an additional energy consumption peak, which was especially remarkable in autumn and winter.

3.3.1. Intraday Analysis of the Milking System

The analysis of the mean energy consumption of the milking system showed basic energy consumption of 0.2 and 0.3 kWh/15 min. Additionally, three peaks during the day in spring, summer and autumn with a maximum of 1.4 kWh/15 min were observed (Figure 4).

A detailed consideration of the single system components revealed the peaks with increased energy consumption results mainly from the BWAC (Figure 5). The air compressor showed increased energy consumption in periodic intervals of 8.00 h, starting at 8.00. Considering the cleaning times, a correlation of the increased energy consumption of the air compressor is likely. Due to the milking pause while cleaning the milk tank, the vacuum pump and air compressor had a reduced energy consumption around hour 36.00. The milking robot did not show reduced energy consumption at this time, which might result from the low energy consumption level of the milking robot. The mean energy consumption of the milking robot varied between 0.05 kWh/15 min and 0.10 kWh/15 min continuously during the day.

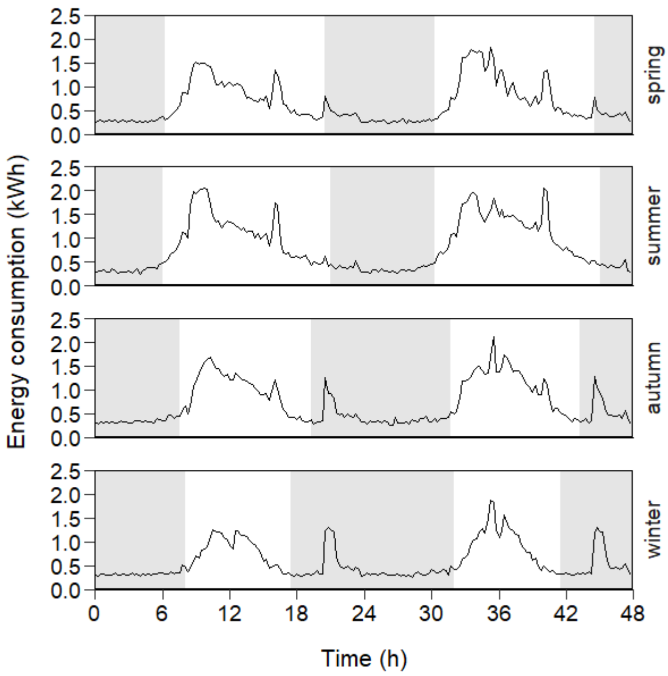

Figure 3. Mean energy consumption of the milk production system in 15 min resolution for a 48.00 h period; periods with negative energy balance are indicated with grey areas.

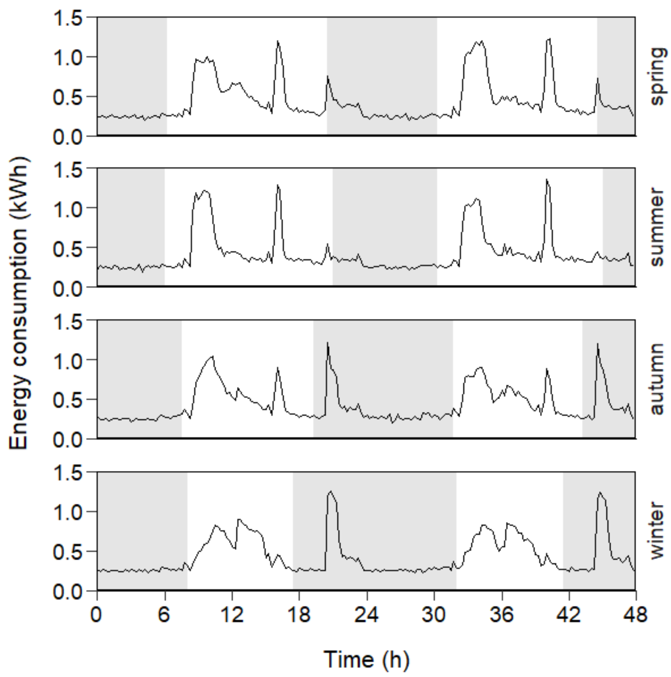

Figure 4. Mean energy consumption of the milking system in 15 min resolution for a 48.00 h period; periods with negative energy balance are indicated with grey areas.

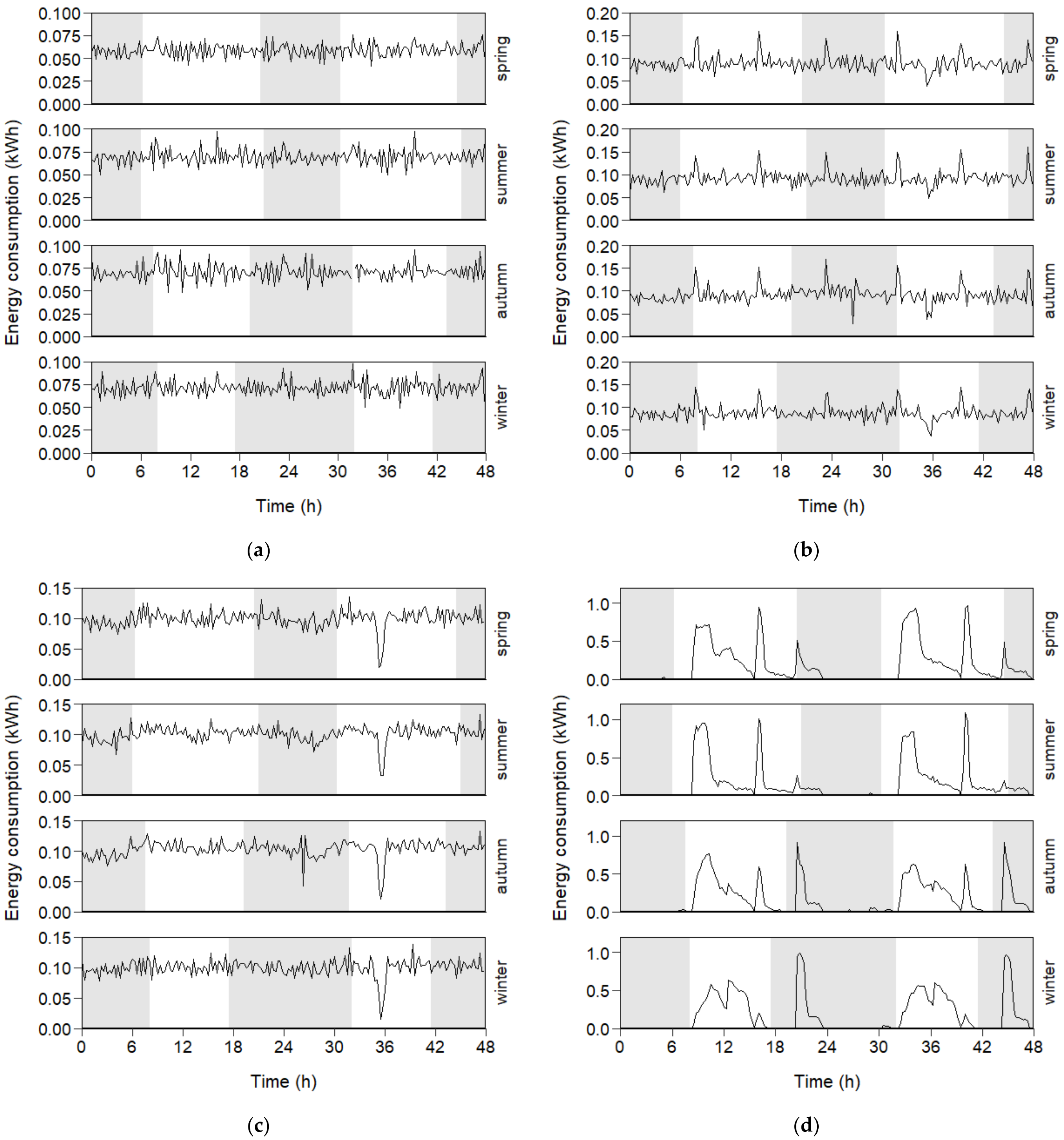

Figure 5. Mean energy consumption of the milking robot (**a**), the air compressor (**b**), the vacuum pump (**c**) and BWAC (**d**) during 48.00 h period with a resolution of 15 min; periods with negative energy balance are indicated with grey areas.

3.3.2. Intraday Analysis of the Milk Cooling System

The cooling system showed increased energy consumption during daytime hours, but especially on days with tank emptying. Hence, around hour 36.00, the energy consumption increased (Figure 6). The analysis of the mean energy consumption of the cooling system showed low basic energy consumption during deficiency periods.

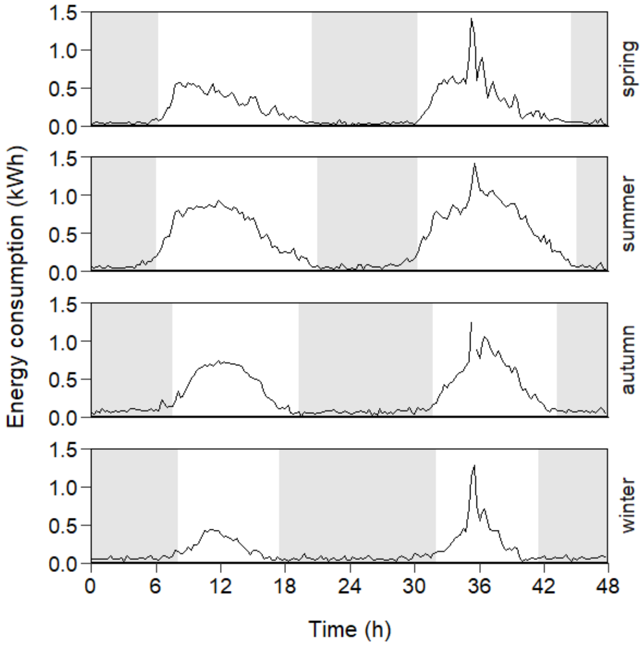

Figure 6. Mean energy consumption of the milk cooling system in 15 min resolution for a 48.00 h period; periods with negative energy balance are indicated with grey areas.

A separate examination of the cooling system components suggests that this is due to the characteristics of the energy consumption of the milk cooling tank while cleaning (Figure 7). The energy consumption of the cooling unit was distributed throughout the day, whereby the period was the shortest in winter and longest in summer, since the characteristics of the IB cooling system were supposed to adjust the energy consumption of the cooling unit according to the energy production. However, this was not possible for the milk cooling tank. The energy consumption peak of the milk tank occurs while cleaning after milk collection.

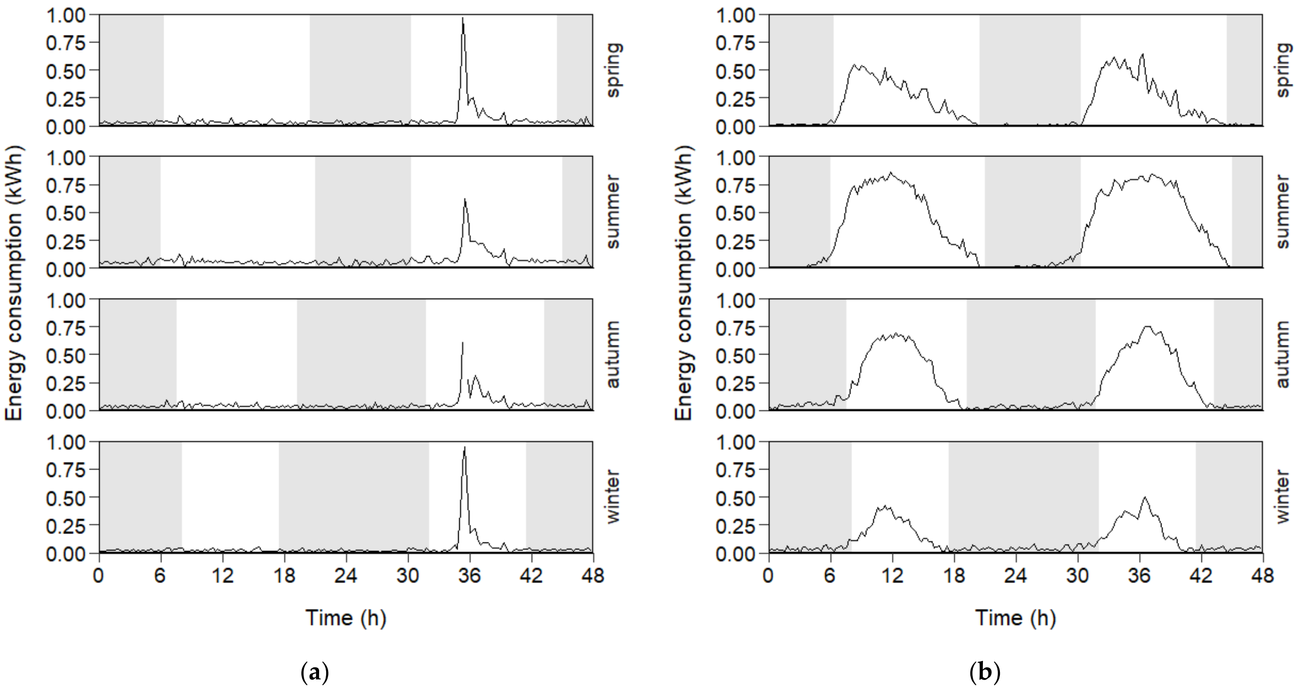

Figure 7. Mean energy consumption of the milk cooling tank (**a**) and cooling unit (**b**) during 48.00 h period with a resolution of 15 min; periods with negative energy balance are indicated with grey areas.

3.4. Energy System Scenarios

The daily energy consumption is lower in cooler seasons. Due to the lower energy yield per kWp installed capacity, a larger PV system is required to provide the energy demand. Consequently, a larger battery capacity is required to bridge the deficiency times as well. This results in different requirements for a self-sufficient energy system to meet the energy needs of the milk production system depending on the season (Table 8).

Table 8. Energy indicators according to the optimized season.

Optimized Season	Estimated PV Capacity	Battery Capacity	Season	PV Production	Energy Consumption	Daily Energy Balance
	kWp	kWh		kWh/d	kWh/d	kWh/d
Spring	20.0	12.7	Spring	61.0	61.0	0.0
			Summer	72.9	77.5	−4.6
			Autumn	34.7	67.8	−33.2
			Winter	14.0	56.6	−42.7
Summer	21.2	12.6	Spring	64.8	61.0	3.8
			Summer	77.5	77.5	0.0
			Autumn	36.9	67.8	−31.0
			Winter	14.8	56.6	−41.8
Autumn	39.1	20.7	Spring	119.3	61.0	58.3
			Summer	142.7	77.5	65.2
			Autumn	67.8	67.8	0.0
			Winter	27.3	56.6	−29.3
Winter	81.0	23.6	Spring	247.3	61.0	186.3
			Summer	295.8	77.5	218.3
			Autumn	140.6	67.8	72.8
			Winter	56.6	56.6	0.0

Optimization for winter leads particularly to a positive daily balance, respective to energy surpluses in the other seasons, which can be supplied to the public power grid. On the other hand, a configuration of the energy system optimized for summer leads to a negative daily balance in other seasons. The missing electricity must, therefore, be purchased from public suppliers, as the energy generation and storage capacities are not sufficient for a self-sufficient energy supply.

The costs for the energy supply arise from the costs for the energy supply system and the balance of the energy trade that results from purchased and retailed energy (Table 9). Related to the annual energy consumption of the milk production system, the mean energy price differs between 0.237 €/kWh and 0.335 €/kWh.

Table 9. Economic evaluation of the different systems.

Optimization Scenario	Costs of PV Plant	Costs of Battery Storage	Total Costs of System	Balance of Energy Trade	System and Energy Costs	Mean Energy Price	Costs of Public Energy Supply	
	€/a	€/a	€/a	€/a	€/a	€/kWh	€/a	€/kWh
Spring	1996	1613	3609	−2202	5810	0.242	7198	0.30
Summer	2121	1600	3722	−1968	5689	0.237	7198	0.30
Autumn	3905	2629	6534	−14	6548	0.273	7198	0.30
Winter	8096	2995	11,091	3049	8041	0.335	7198	0.30

Compared to the costs of fully sourcing electricity from the public power grid, the amortization period is between 22 and 89 years (Table 10). In the winter scenario, under the given conditions, investment amortization is not possible. Increases in electricity prices ranging from 5 to 15% would lead to a faster amortization, thus improving cost-effectiveness.

Table 10. Amortization period considering different public energy prices.

		Scenario			
Price Development	%	100%	105%	110%	115%
Energy Price	€/kWh	0.3	0.315	0.33	0.345
Optimization Scenario		Amortization Period			
Spring	years	23	19	17	15
Summer	years	22	18	16	14
Autumn	years	89	59	45	36
Winter	years	-	-	-	433

4. Discussion

4.1. Experimental Setup and Analysis

The presence of seasonal trends Shortall et al. (2018) [35] (p. 1577) found were considered by performing separate analyses of the data for each season. This also should cover environmental impacts on the behavior or technical systems, like fresh water temperature and day length. Although the observation period was one year, due to male functions of the data recording, transmission and the InfluxDB, the data recording did not work properly during the whole observation period. The missing values in the data set as well as outliers, were not considered for the analysis of the data. Therefore, methods that are robust against biased and not normally distributed data as well as different sample sizes were selected. According to this, bias due to seasonal issues was assumed to be negligible due to the amount of data. Nevertheless, the use of long-term meteorological databases in this kind of study is very important, contributing to more reliable conclusions [36] (p. 1368).

The temporal resolution of the energy consumption of 15-min intervals is suitable to characterize the energy consumption and production during the day. Also, Oberschätzl et al. (2015) [37] (p. 8) used temporally defined measurements at 15-min intervals for a closer look at the daily load profile of the energy consumption for automatic feeding systems (AFSs) [37] (p. 8). In contrast, the current study focuses on energy consumption. The power respective to the load profile of the milk production system is likely to differ from the energy consumption profile. The average power or load during these intervals can be easily calculated; however, it would make strong but short load peaks disappear. Therefore, an investigation of the load profile as well as the power profile of the PV system with a temporal resolution of about 1 s would be necessary. The data acquisition and recording equipment and analysis methods used were not capable of operating at this high resolution. For further research, this has to be taken into account and the recording system should be adapted.

4.2. Characteristics of Energy Consumption

Within the milk production system, the energy consumption was distributed on milking and cooling. The mean energy consumption of the milk production system including milking and milk cooling was 65.68 kWh/day, which was respective to 35.55 Wh/kg milk. Shortall et al. 2018 [35] (p. 1568) described an energy consumption of 62.6 Wh/L milk, which is nearly twice the mean energy consumption found in the current study. However, the detailed comparison of the milk cooling showed a 2.5 Wh/kg milk increased energy consumption in the current study that can be explained due to the IB cooling system, which has an approximately 20% higher electricity requirement [38]. A recording by Hörndahl (2008) [39] (p. 29) showed a total energy amount of 39.9 Wh/L milk. Divided up into milking, hot water and cooling, 21.1 Wh/L milk was required for milking and 13.6 Wh/L milk for cooling [39] (p. 29). These numbers match the measurements in the present study.

4.3. Optimization Potential in Energy Consumption

According to Upton et al. (2013), the decoupling of large energy users such as milk cooling and water heating from milking times and shifting them to off-peak periods will be required [5] (pp. 6496–6497). To improve the self-supply with power, Graf et al. (2016) [21] (pp. 19–20) recommend consumers to switch on and off power between high connected loads and low running times with automatic control technology and timers or manually during periods with sufficient in-house power production. The present system was intended to meet these requirements.

IB systems can be an effective tool to decouple the milk-cooling load from milking times if they are set up and managed correctly [40]. The energy storage as ice and ice water during low-cost periods and release during milking for cooling the milk to the desired storage temperature is an option [23,41]. In the present study, the ice production process for the IB cooling system was shifted to times with PV production by the energy management system (FullEnergy). In contrast to Forster et al. (2017) [42] (p. 5), ice storage does reduce the need for a battery storage system, but does not replace it entirely, since energy is needed for milk cooling during night hours (milk cooling tank).

The advantage of this type of storage is the formation of ice—thus ice does not wear out [42] (p. 5). To account for different energy tariffs, Upton et al. (2013) assumed an IB system would run on day tariff for 30% of their operating times, whereas the DX systems used 70% day tariff electricity [5] (p. 6493). Compared to the present research, where 58–84% of the required energy for the whole milk production system could be provided self-sufficient, mean self-sufficient energy consumption of 73% could be achieved. In contrast to Upton et al. (2013), this ratio does not describe the energy purchase at day or night tariff, but the ratio between the amount of the self-produced energy to its cost price and the price of the purchased energy from the external providers [5]. Additionally, in the present research, the whole milk production system is considered.

However, energy consumption during night hours was also observed to be caused by particularly the cooling unit. This indicates that the production of ice in the IB storage during the day was not able to cover the cooling demand during night hours. However, the energy production in consideration of the energy surplus should have been large enough to last for the milk cooling. A too-low energy input in the IB storage during the day or a too-small storage unit, as well as an interaction between these two factors, may be possible reasons for these observations. The fluctuation of energy production and the low total energy production in winter might enhance this factor. In contrast to Guul-Simonsen et al. (1996) [23], a larger compressor of the cooling unit might enable larger possibilities for load shifting during the day, considering fluctuating energy production from the PV plant. Additionally, decoupling the cooling load from peak tariffs would be useful in mitigating the impact of a smart-metering electricity pricing scenario [5] (pp. 6496–6497).

The three energy consumption peaks of the BWAC boiler are likely to be determined by the three cleaning routines per day. Usually, two to three main cleaning routines for the milking system are legally required [6,43,44]. Especially between the hours 20 and 24 as well as 44 and 48, the increase of one of these peaks is recognized outside of a period as a positive energy balance. This peak is particularly pronounced in winter and in the transitional seasons of spring and autumn. In summer, it is clearly reduced, but recognizable. According to Höhendinger et al. (2021), the amount of milk or the efficiency of milk production does not affect the energy consumption of the cleaning system [6].

However, the peaks of energy consumption should be shifted to the periods of energy self-supply with energy via the corresponding control technology. Regarding the surplus that was observed, this should be possible. Since the control technology for this is available with the Fullenergy control, it can be assumed that the storage volume of the BWAC boiler with 240 L is not sufficient to store enough boiling water for cleaning in the afternoon and subsequently at night. A larger boiler could, therefore, contribute to optimization. However, it should be noted that a complete postponement of the heating will probably still not be possible as the cleaning temperature must be ensured at night—which is why short-term reheating may be necessary.

All consumers except BWAC, milk tank, and milk cooling show relatively continuous energy consumption throughout the day. Only the pause for cleaning the milk tank leads to reduced energy consumption of the compressor and vacuum pump during this period. In contrast, the energy consumption of the milk tank is particularly high during this period, which is due to the heating of the cleaning water. The position of this energy consumption peak is determined purely organizationally by the tank emptying. In the specific case, from an energetic point of view, this time is favorably located in the periods with the highest energy production. However, this could be different for other farms. In this case, there is only the possibility to preheat and store the cleaning water via a boiler during the day. This could reduce the necessary reheating to cleaning temperature in the milk tank and either save energy consumption or make it more flexible. If such a form of energy storage is not possible, battery storage could be used to cover this energy demand. However, the requirement for batteries with small PV systems on dairy farms could be alleviated through thermal storage [45] (p. 10). It should be taken care to ensure appropriate dimensioning for the battery storage.

4.4. Economic Advantages for Smaller Energy Systems

The dimensioning of the energy system was modeled on the basis of energy consumption. The required size of the PV system is based on the energy generation potential in the respective season and at the respective location. Since the specific local conditions always need to be taken into account for the concrete use case, the goal was to determine the necessary requirements regarding power and energy yield for the PV system. The orientation and optimization of the system will then depend on each case.

Different system requirements were determined depending on the time of year. Due to the lower generation in winter and the longer deficiency period, the dimension is much larger here. On the other hand, there is greater excess capacity or overproduction in the summer. For these, the marketing of the energy was assumed. Optimization after summer requires a smaller plant, but in the other seasons, the purchase of energy is necessary.

Based on the different settings of the modeling, an average electricity price between 0.237 and 0.335 €/kWh was calculated for different combinations of self-supply and external purchase. A study by Upton et al. (2013) [5] (p. 6490) considered the electricity costs of individual farms and combined data on electricity consumption with daytime and nighttime tariffs (daytime tariff was 0.18 €/kWh; nighttime tariff was 0.08 €/kWh from 00:00 a.m. to 09:00 a.m.) [5] (p. 6490). However, in the present study, the focus was on the comparison with the pure grid purchase versus a mixture of self-sufficient energy supply and external suppliers for the milk production process. Therefore, the calculation of an average energy price was considered appropriate here, which can be used for comparison with public energy prices.

The modeling focused on the net demand for the energy system. This is intended to facilitate transferability to other scenarios and locations and to allow optimal selection of the respective technologies based on site potential.

The respective average seasonal values were used for the modeling. However, this does not cover all possible weather conditions. For example, energy production may be so low on several consecutive days, especially in winter, that storage capacity or production may also be insufficient. However, the modeling shows the structural requirements as well as their application in this practical example. In addition, the modeling shows that under the assumed market conditions, energy costs increase significantly when optimized according to the cooler seasons. This, in turn, illustrates the dependence on energy prices from electricity suppliers. In Germany, a continuous increase in the price of electricity has been observed in recent years [46]. According to official statistics, electricity prices fluctuated between €0.30/kWh and €0.31/kWh during the observation period [46]. Self-supply with electricity, e.g., from a PV system, is becoming more and more interesting from a financial point of view. The electricity production costs per kWh of PV systems vary between 0.03 €/kWh and 0.11 €/kWh [47]. Considering these circumstances, the self-sufficient energy supply is more and more interesting if energy prices are relatively high.

This is supported by the sensitivity analysis that showed, that even slight price increases of 5% to 15% in electricity consumption reduce the amortization period. Thus, the economic viability is mainly dependent on these external circumstances.

Nevertheless, the calculation shows advantages for smaller energy systems, which result from lower tariffs for electricity sales; the higher these are, the faster a corresponding plant will pay off.

4.5. Uncertainties Due to Recycling of PV Plants

The costs of disposal currently vary greatly from country to country and region to region, and depending on legal regulations and the development of suitable recycling technologies and companies, reliable figures are available.

Fthenakis (2000) estimated a total cost of collection and recycling in the range of $0.08 to 0.11/W [48] (p. 1056). This would be similar to the cost of hazardous waste disposal, which corresponds to $0.09 to 0.10/W [48] (p. 1056).

In contrast, Liu et al. (2020) found a benefit–cost ratio (BCR) of 1.023, which indicated that recycling is economically viable. However, to keep the smooth operation of recycling enterprises, the BCR is required to keep = 1.1 [49] (p. 498). High-value recycling methods depend on lowering processing costs and gaining high value from the materials [50] (p. 547). In this context, the sale benefits of silver, aluminum, and silicon were the most sensitive parameters affecting the project's economy [49] (p. 498).

Considering these circumstances, the widescale application of PV module recycling requires collaborative action of all stakeholders in the industry, governments and recyclers to build the recycling facility network to minimize transportation costs [50] (pp. 547–548).

According to this, costs for the disposal of the PV modules after their useful life were not taken into account, since the cost of this potential liability is difficult to quantify.

5. Conclusions

Due to the increased energy costs, agricultural enterprises are looking for alternatives or to secure the operational energy supply. The present work gives an approach to optimize the dimension of the energy system based on a PV system with battery storage. The electric energy production of a dairy farm with a rooftop PV plant can be sufficient, to provide enough energy for the milk production system. However, the temporal distribution is crucial to increase the self-sufficient energy supply. Energy storage in the production process is a method to compensate for this. In dairy farming, IB milk cooling represents a system to reduce energy consumption during times of energy deficiency. In this context, warm water heating can also provide energy flexibility.

However, the storage of electrical energy, e.g., night times, is not possible with these methods. Therefore, it is still necessary to store energy electrically in battery storage systems for operation at night to ensure a smooth production process. Hence, battery storage for electric power supply is mandatory to guarantee a reliable production process.

The cost structure is most favorable for smaller plants, even if energy would have to be purchased in other seasons. Taking into account the results of the study, from a purely economic perspective, the described energy system should be optimized for the summer season. The feed-in of surplus energy in larger energy systems can only partially compensate for the higher costs due to the low feed-in tariff. In consequence, increasing prices for public electricity supply is an important factor for the rentability of the self-sufficient system. If other factors, such as a higher degree of self-sufficiency in electricity supply, come into play, the components should be chosen to be larger and more powerful.

Considering these aspects, farmers are able to optimize the self-sufficient energy supply for an automatic milk production process based on a PV plant.

6. Directions for Further Research

Further investigations are now to demonstrate a reliable energy supply involving the existing stationary energy storage system, an emergency power function and, in consultation with the energy supply company, further grid services. The functional capability of the various technical installations of the farms and, in particular, the stables, will be tested both for new buildings and for existing installations.

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References

1. Rajaniemi, M.; Jokiniemi, T.; Alakukku, L.; Ahokas, J. Electric energy consumption of milking process on some Finnish dairy farms. *Agric. Food Sci.* **2017**, *26*, 160–172. [CrossRef]
2. Shine, P.; Upton, J.; Sefeedpari, P.; Murphy, M.D. Energy Consumption on Dairy Farms: A Review of Monitoring, Prediction Modelling, and Analyses. *Energies* **2020**, *13*, 1288. [CrossRef]
3. Pommer, R.; Eckel, H.; Hartmann, W.; Kämper, H. *Energiebedarf in der Milchviehhaltung*; Kuratorium für Technik und Bauwesen in der Landwirtschaft: Darmstadt, Germany, 2014; ISBN 9783945088005.
4. Rotz, C.A.; Coiner, C.U.; Soder, K.J. Automatic Milking Systems, Farm Size, and Milk Production. *J. Dairy Sci.* **2003**, *86*, 4167–4177. [CrossRef] [PubMed]
5. Upton, J.; Humphreys, J.; Groot Koerkamp, P.W.G.; French, P.; Dillon, P.; Boer, I.J.M. de. Energy demand on dairy farms in Ireland. *J. Dairy Sci.* **2013**, *96*, 6489–6498. [CrossRef] [PubMed]
6. Höhendinger, M.; Krieg, H.-J.; Dietrich, R.; Rauscher, S.; Stumpenhausen, J.; Bernhardt, H. Impacts of Divergent Moving Drives on Energy Efficiency and Performance of Various AMS in Operative Conditions. *Agriculture* **2021**, *11*, 806. [CrossRef]
7. Behnisch, M.; Münzinger, M.; Poglitsch, H.; Willenborg, B.; Thomas, H.K. Anwendungsszenarien von Geomassendaten zur Modellierung von Grünvolumen und Solarflächenpotenzial. 2021. Available online: https://slub.qucosa.de/api/qucosa%3A77137/attachment/ATT-0/ (accessed on 10 November 2023).
8. Centrales Agrar-Rohstoff Marketing- und Energie-Netzwerk e.V. Solarpflicht für Bayern ab März 2023—C.A.R.M.E.N. e.V. Available online: https://www.carmen-ev.de/2023/01/20/solarpflicht-fuer-bayern-ab-maerz-2023/ (accessed on 19 September 2023).
9. Neiber, J.; Neser, S. Energieeinsparung und Eigenstromnutzung in der Milchviehhaltung: Nutzung von Solarstrom für die Erzeugung von Eiswasser zum Abkühlen der Milch auf Lagertemperatur; Lfl-Information. 2016. Available online: https://www.lfl.bayern.de/mam/cms07/publikationen/daten/informationen/energieeinsparung-eigenstromnutzung-milchviehhaltung_lfl-information.pdf (accessed on 27 November 2017).
10. von Scheven, A. Flexibilitätsoptionen im industriellen Umfeld an verschiedenen Energiehandelsmarktplätzen im Smart Grid. Ph.D. Thesis, Technische Universität Darmstadt, Darmstadt, Germany, 2015.
11. Schwab, A.J. *Elektroenergiesysteme*; Springer Berlin Heidelberg: Berlin/Heidelberg, Germany, 2017.
12. Bernhardt, H.; Höhendinger, M.; Stumpenhausen, J. Development of the Technical Structure of the "Cow Energy" Concept. *Agronomy* **2021**, *11*, 1915. [CrossRef]
13. Mühlbauer, W.; Esper, A. Chapter 2 Energy for Biological Systems: Part 2.3 Solar Energy. In *CIGR Handbook of Agricultural Engineering*; Energy and Biomass, Engineering; Kitani, O., Jungbluth, T., Peart, R.M., Ramdani, A., Eds.; American Society of Agricultural and Biological Engineers: St. Joseph, MI, USA, 1999; Volume V, pp. 53–100.
14. Njoku, H.O.; Ekechukwu, O.V.; Onyegegbu, S.O. Analysis of stratified thermal storage systems: An overview. *Heat Mass Transf.* **2014**, *50*, 1017–1030. [CrossRef]

15. Peart, R.M. Chapter 1 Natural Energy and Biomass: Part 1.2 Natural Energy. In *CIGR Handbook of Agricultural Engineering*; Energy and Biomass, Engineering; Kitani, O., Jungbluth, T., Peart, R.M., Ramdani, A., Eds.; American Society of Agricultural and Biological Engineers: St. Joseph, MI, USA, 1999; Volume V, pp. 3–6.
16. Bauknecht, D.; Heinemann, C.; Koch, M.; Ritter, D.; Harthan, R.; Sachs, A.; Vogl, M. *Systematischer Vergleich von Flexibilitäts- und Speicheroptionen im Deutschen Stromsystem zur Integration von Erneuerbaren Energien und Analyse Entsprechender Rahmenbedingungen*; Gefördert durch das BMWi aufgrund eines Beschlusses des Bundestages: Darmstadt, Germany, 2016. Available online: https://www.oeko.de/publikation/systematischer-vergleich-von-flexibilitaets-und-speicheroptionen-im-deutschen-stromsystem-zur-integration-von-erneuerbaren-energien-und-analyse-entsprechender-rahmenbedingungen/ (accessed on 10 June 2020).
17. Gustafson, J.R.; Morgan, a.M.T. Solar and Wind Energy Sources for Electricity. In *Fundamentals of Electricity for Agriculture*, 3rd ed.; American Society of Agricultural and Biological Engineers: St. Joseph, MI, USA, 2004; pp. 379–397. ISBN 1-892769-39-5.
18. Alsing, I. *Lexikon Landwirtschaft: Pflanzliche Erzeugung, Tierische Erzeugung, Landtechnik, Betriebslehre, Landwirtschaftliches Recht*, *3., Überarb. und erw. Aufl.*; BLV Verl.-Ges: München, Germany, 1995; ISBN 3405145708.
19. Tillie, M. Part I Livestock Housing and Environment: Chapter 4 Equipment and Control. In *CIGR Handbook of Agricultural Engineering*; Bartali, E.H., Jongebreur, A., Moffitt, D., Wheaton, F., Eds.; American Society of Agricultural Engineers: St. Joseph, MI, USA, 1999; pp. 115–145.
20. Jungbluth, T.; Büscher, W.; Krause, M. *Technik Tierhaltung*, 2nd ed.; Verlag Eugen Ulmer: Stuttgart, Germany, 2017; ISBN 9783825242435.
21. Graf, J.; Hartmann, S.; Neiber, J.; Puchta, M.; Reinhold, G.; Remmersmann, T.; Wilms, D. *Strom Speichern, Eigenverbrauch Steigern: Technik-Auslegung-Kosten*; Kuratorium für Technik und Bauwesen in der Landwirtschaft: Darmstadt, Germany, 2016; ISBN 9783945088166.
22. Yi, W.; Dong, W. Modeling and Simulation of Discharging Characteristics of External Melt Ice-on Coil Storage System. *IJSH* **2015**, *9*, 179–192. [CrossRef]
23. Guul-Simonsen, F.; Christiansen, P.S.; Edelsten, D.; Kristiansen, J.R.; Madsen, N.P.; Nielsen, E.W.; Petersen, L. Cooling, Storing and Quality of Raw Milk. *Acta Agric. Scand. Sect. A-Anim. Sci.* **1996**, *46*, 105–110. [CrossRef]
24. Fuchs, C.; Fübecker, A.; Harms, J.; Hartmann, W.; Kaufmann, R.; Reinecke, F.; Rose-Meierhöfer, S.; Wolter, W.; Zäher, M. *Automatische Melksysteme: Verfahren-Kosten-Bewertung*; Kuratorium für Technik und Bauwesen in der Landwirtschaft (KTBL): Darmstadt, Germany, 2013; ISBN 978-3-941583-78-8.
25. Von Keyserlingk, M.A.; Martin, N.P.; Kebreab, E.; Knowlton, K.F.; Grant, R.J.; Stephenson, M.; Sniffen, C.J.; Harner Iii, J.P.; Wright, A.D.; Smith, S.I. Invited review: Sustainability of the US dairy industry. *J. Dairy Sci.* **2013**, *96*, 5405–5425. [CrossRef] [PubMed]
26. Loibnegger, T.; Bachler, A. Smart Meter und Energiemanagement in der Land- und Forstwirtschaft: Digitale Energielösungen für mehr Energieunabhängigkeit, Fürstenfeld, 2019.
27. Murgia, L.; Caria, M.; Pazzona, A. Energy use and management in dairy farms. In Proceedings of the International Conference, Innovation Technology to Empower Safety, Health and Welfare in Agriculture and Agro-food Systems, Ragusa, Italy, 15–17 Sepember 2008; Schillaci, G., Monarca, D., Eds.;
28. Peebles, R.W.; Reinemann, D.J.; Straub, R.J. Analysis of Milking Center Energy Use. *Appl. Eng. Agric.* **1994**, *10*, 831–839. [CrossRef]
29. Calcante, A.; Tangorra, F.M.; Oberti, R. Analysis of electric energy consumption of automatic milking systems in different configurations and operative conditions. *J. Dairy Sci.* **2016**, *99*, 4043–4047. [CrossRef] [PubMed]
30. Kamper, A. *Dezentrales Lastmanagement zum Ausgleich kurzfristiger Abweichungen im Stromnetz*; Universität Karlsruhe: Karlsruhe, Germany, 2010.
31. Strobl, M. EEG 2023: Was dürfen Photovoltaik (PV)-Dachanlagen mit Volleinspeisung bis 100 kWp im Zeitraum Januar 2023 bis Januar 2024 Kosten? Available online: https://www.lfl.bayern.de/iba/energie/165093/index.php (accessed on 12 May 2023).
32. Centrales Agrar-Rohstoff Marketing- und Energie-Netzwerk e.V. Marktübersicht Batteriespeicher. Available online: https://www.carmen-ev.de/service/marktueberblick/marktuebersicht-batteriespeicher/ (accessed on 12 May 2023).
33. Strobl, M. EEG 2023: Förderung der Photovoltaik-Stromeinspeisung für den Zeitraum Januar 2023 bis Januar 2024. Available online: https://www.lfl.bayern.de/iba/energie/161645/index.php (accessed on 12 May 2023).
34. Statistisches Bundesamt. Daten zur Energiepreisentwicklung: Lange Reihen von Januar 2005 bis Januar 2023. Available online: https://www.destatis.de/DE/Themen/Wirtschaft/Preise/Publikationen/Energiepreise/energiepreisentwicklung-pdf-5619001.html (accessed on 12 May 2023).
35. Shortall, J.; O'Brien, B.; Sleator, R.D.; Upton, J. Daily and seasonal trends of electricity and water use on pasture-based automatic milking dairy farms. *J. Dairy Sci.* **2018**, *101*, 1565–1578. [CrossRef] [PubMed]
36. Steidle Neto, A.J.; Lopes, D.d.C. Technical analysis of photovoltaic energy generation for supplying the electricity demand in Brazilian dairy farms. *Environ. Dev. Sustain.* **2021**, *23*, 1355–1370. [CrossRef]
37. Oberschätzl, R.; Haidn, B.; Neiber, J.; Neser, S. Automatic feeding systems for cattle—A study of the energy consumption of the techniques. In *Environmentally Friendly Agriculture and Forestry for Future Generations, XXXVI CIOSTA CIGR V Conference 2015, Saint Petersburg, Russia, 26–28 May 2015*; Popov, V., Belyakov, V., Eds.; Saint Petersburg, Russia, 2015.
38. Verband der Landwirtschaftskammern e., V. Energieeffizienzverbesserung in der Landwirtschaft. 2009. (accessed on 29 October 2019).

39. Hörndahl, T. Energy Use in Farm Buildings: A Study of 16 Farms with Different Enterprises Revised and Translated Second Edition. 2008. Available online: https://pub.epsilon.slu.se/3396/1/Eng-rapport145-v1.pdf (accessed on 26 April 2021).
40. Milk Development Council. Bulk Milk Tanking Cooling Efficiency; Project No. 95/R1/19; 1995. Available online: https://www.teagasc.ie/media/website/rural-economy/farm-management/mdc_report.pdf (accessed on 9 December 2021).
41. Jordan, R.A.; Cortez, L.A.B.; Silveira, V., Jr.; Cavalcanti-Mata, M.E.R.M.; Oliveira, F.D. de. MODELING AND TESTING OF AN ICE BANK FOR MILK COOLING AFTER MILKING. *Eng. Agríc.* **2018**, *38*, 510–517. [CrossRef]
42. Foster, R.; Jensen, B.; Dugdill, B.; Mwove, J.; Faraj, A.; Knight, B. Direct Drive Photovoltaic Milk Chilling: Two Years Field Experience in Kenya. Proceedings of SWC2017/SHC2017, ISES Solar World Conference 2017 and the IEA SHC Solar Heating and Cooling Conference for Buildings and Industry 2017, Abu Dhabi, United Arab Emirates, 29 October–2 November 2017; Romero, M., Mugnier, D., Renné, D., Guthrie, K., Griffiths, S., Eds.; International Solar Energy Society: Freiburg, Germany, 2017; pp. 1–6.
43. Mütze, K.; Wolter, W.; Bonsels, T.; Bernhardt, H. Melkhygiene und Milchqualität in hessischen AMS-Betrieben. *LANDTECHNIK* **2009**, *64*, 436–438.
44. *ISO 20966:2007*; Automatische Melksysteme—Anforderungen und Prüfung. 65.040.10 (20966:2008-04); Beuth Verlag GmbH: Berlin, Germany, 2008.
45. Breen, M.; Upton, J.; Murphy, M.D. Photovoltaic systems on dairy farms: Financial and renewable multi-objective optimization (FARMOO) analysis. *Appl. Energy* **2020**, *278*, 115534. [CrossRef]
46. Statistische Bundesamt. Preise: Daten zur Energiepreisentwicklung-Lange Reihen von Januar 2005 bis Februar 2022 No. *5619001221024*; 2022; (accessed on 6 April 2022).
47. Fraunhofer Institut für Solare Energiesysteme ISE. *Studie: Stromgestehungskosten Erneuerbare Energien*; Fraunhofer Institut für Solare Energiesysteme ISE: Freiburg, Germany, 2021.
48. Fthenakis, V.M. End-of-life management and recycling of PV modules. *Energy Policy* **2000**, *28*, 1051–1058. [CrossRef]
49. Liu, C.; Zhang, Q.; Wang, H. Cost-benefit analysis of waste photovoltaic module recycling in China. *Waste Manag.* **2020**, *118*, 491–500. [CrossRef] [PubMed]
50. Deng, R.; Chang, N.L.; Ouyang, Z.; Chong, C.M. A techno-economic review of silicon photovoltaic module recycling. *Renew. Sustain. Energy Rev.* **2019**, *109*, 532–550. [CrossRef]