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Can Small-Scale Dairy Farm Profitability Increase with the Use of Solar Energy Technology? An Experimental Study in Central Tunisia

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Abstract: The dairy sector in Tunisia is based on small-scale farms, with 81% of the breeders owning less than five cows. On these farms, milk is stored in plastic containers, resulting in post-production losses estimated at 10% in the studied region. Due to high temperatures, the present paper aims to study the implementation of an innovative solar-powered milk cooling system in Central Tunisia and assess its profitability for dairy farmers. The methodology is based on a comparison of three small-scale farm business models: a farm without any milk cooling equipment, a farm using an innovative milk cooling technology, and a farm using an electrical cooling tank. Results showed the significance of milk cooling in reducing milk rejection to 0%, leading to a total production of 6400 L per cow by the fifth year. Additionally, milk sales were found to increase due to the premium of 0.010 TND/L for cooled milk paid. In addition, farms utilizing solar-powered milk cooling technology exhibited superior profitability in terms of financial indicators. This research offers a sustainable energy solution for milk cooling on small farms, specifically addressing the challenges faced by these farms located in isolated areas where access to electricity is limited and the availability of milk cooling equipment is lacking.

Keywords: business model; electricity; milk cooling; solar energy; small-scale farms; Tunisia

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1. Introduction

Since its independence in 1956, Tunisia has experienced rapid population growth and a notable increase in urbanization. Consequently, there has been a significant rise in the demand for dairy products [1]. Undoubtedly, livestock and the dairy subsector play a significant role in the Tunisian economy, serving as crucial components of the agricultural economy. Over the last five decades, the milk and derivatives sector has undergone a remarkable evolution, transitioning from a state of chronic undersupply with a national monopoly to self-sufficiency state and exporting to neighboring countries. The observed transformation has been made possible by several key factors, including the establishment of a greater number of milk collection centers and the expansion of the national milk collection network. Additionally, significant efforts have been made in the genetic improvement of the cattle herd, enhancing animal health services, boosting forage production, and establishing multiple private milk processing plants. These combined initiatives have paved the way for the important progress achieved by the industry. The implementation of the national dairy strategy in 1994, aimed at substituting milk imports, led to substantial growth in milk production, which led to self-sufficiency in milk fluid in the late 1990s thus showing a potential for further expansion [2].

According to recent available data [3], the dairy sector contributed approximately 11% to total agricultural production, 25% to total animal production, and 7% to the value of the food industry in 2017. Moreover, this sector plays a crucial role in employment, serving as the main source of livelihood for many farmers in rural areas of Tunisia. It employs 112,000 dairy farmers (more than 30% of agricultural jobs), in addition to jobs generated by the dairy industry and the sector as a whole. From an economic perspective, the dairy industry holds a significant position in the country's economy, accounting for 42% of agricultural employment [3,4], with a total production of 1.42 million liters of milk in 2020. Furthermore, daily milk consumption has been steadily increasing, rising from 268,000 L in 1985 to 1.4 million liters per day in 2015. The dairy sector is also given substantial attention due to its potential to improve farmers' income and overall welfare [5].

Despite these promising statistics, the dairy sector faces several structural constraints, including poorly organized value chains and limited financial accessibility. The sector predominantly relies on small dairy farmers, with more than 81% of breeders owning less than five cows (Figure 1). These farmers lack the necessary equipment to cool milk on-farm, as the quantities produced per day are often very low. While larger farms typically store milk in cooling tanks at low temperatures, smaller units encounter difficulties in investing in cooling system equipment, making it very challenging for them to cool on-farm.

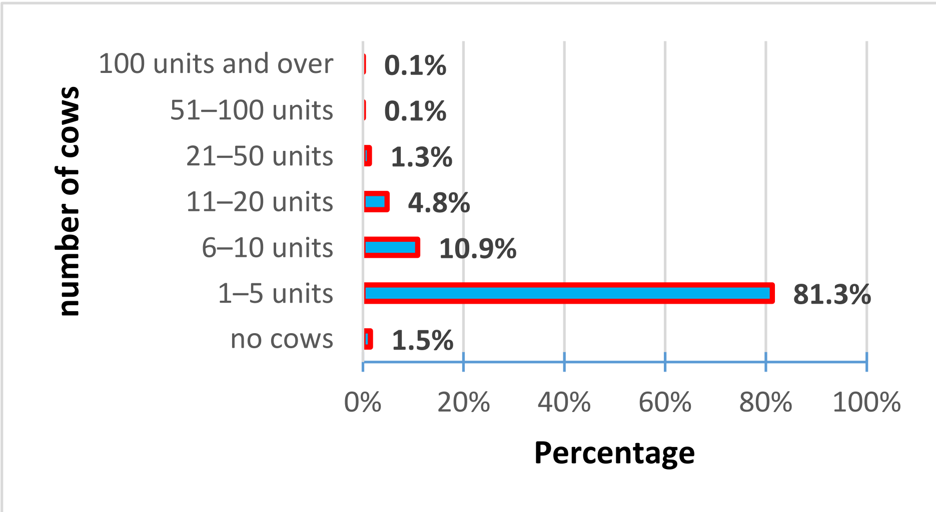

Figure 1. Distribution of cattle producers by number of female units (%). Source [6].

Generally, in remote areas, milk collectors visit farms to collect uncooled milk. Due to high temperatures, particularly during the summer season, milk becomes an ideal environment for microbial growth due to its physicochemical composition. The milk may be rejected by collectors if there are signs of spoilage, resulting in additional on-farm losses. Therefore, it is crucial to cool the milk to 2–3 °C as quickly as possible after milking to maintain its quality. This rapid cooling significantly reduces the growth rate of any bacteria present. Moreover, most of the farmers milk their cows by hand and store the milk in buckets or cans at room temperature while waiting for middlemen to transport it to milk collection center. The inability to cool the milk is a tremendous challenge for smallholder dairy farmers [7]. Thus, on-farm milk cooling becomes a critical step.

Within this context, an innovative system utilizing solar energy for on-farm milk cooling was developed by Hohenheim University (Germany) and implemented on small-scale dairy farms in Central Tunisia. The project "Field testing of an innovative solar-powered milk cooling solution for the higher efficiency of the dairy subsector in Tunisia" supported the development of this groundbreaking technology. The objective of this system is to fulfill the refrigeration requirements of small-scale dairy farmers with limited access to the power grid, enabling them to cool small quantities of milk on farms [8]. In rural areas, where power cuts are still common, this solar cooling system provides an attractive solution for maintaining milk at low temperatures on the farm [9].

With the utilization of this system, farmers can effectively store the evening milk and deliver it together with the morning milk to the milk collector, which enables them to enhance the quantity of milk sold while minimizing the amount of milk rejected by collectors. Consequently, this leads to an increase in their overall income. To support these claims and determine the financial viability of the developed system for small-scale farmers, three business models were compared in the Sidi Bouzid region in Central Tunisia: a traditional dairy farm without milk cooling facilities (project 1), a dairy farm with the solar-powered milk cooling innovation (project 2), and a standard electricity-based dairy farm with conventional milk cooling tanks (project 3). The main objective of this article is to study these business models at the farm level and assess the effectiveness of solar-based cooling energy systems.

The article is structured into five sections. Section 1 serves as an introduction. Section 2 provides background information on renewable energy, particularly solar energy in farming, and its use in the dairy sector. Material and methods are presented in Section 3. Results are shown in Section 4 comparing the three business models. Finally, concluding remarks and policy implications are drawn in Section 5.

2. Renewable Energy and Applicability in the Dairy Sector

Given the global condition of climate change, it has become crucial to drastically change fossil fuel-based energy systems as economic progress depends on energy efficiency [10]. Furthermore, there has been a steady increase in energy prices worldwide, resulting in higher electricity costs [11]. Recent spikes in oil and gas prices, exacerbated by the war in Ukraine, will inevitably impact agriculture, which heavily relies on energy, particularly in advanced nations [12]. To counteract these global trends, green solutions are needed to lower costs and replace electricity, necessitating a leap forward in the energy transition. In 2015, the United Nations embraced the Sustainable Development Goals (SDGs) as a global initiative to eradicate poverty and promote environmental protection. SDG 7 specifically focuses on achieving "affordable, reliable, sustainable, and modern energy for all" within the next decade, aligning with the objectives of the Paris Agreement on climate change. SDG 7 aims to significantly increase the proportion of sustainable energy in total energy consumption and double the global rate of energy efficiency improvement.

According to the energy progress report [13], the world is not on track to achieve the SDG 7 objectives by 2030 at the current rate of advancement. Particularly in the most vulnerable and lagging nations, progress has been hindered. Additionally, these technologies encounter various social, economic, and structural obstacles that require, not only continued technological advancements, but also a thorough understanding of the factors contributing to their success as well as the barriers impeding their widespread adoption [14].

As a Consequence, the use of renewable energies has become a necessity [15]. These sources have the potential to enhance energy accessibility for farmers coping with numerous challenges in maintaining competitive businesses, including the impacts of climate change and rising production costs [15]. In such circumstances, renewable energy technologies are highly advantageous as they offer a decentralized and small-scale energy supply, making them suitable to meet the energy needs of populations most severely impacted by energy poverty [16].

The energy demand in agriculture has experienced a notable increase to cater to the requirements of a growing population and rising food needs. This surge in demand, coupled with the need to power agricultural machinery such as pumps, generators, motors, and tillers, calls for an alternative energy solution to reduce reliance on fossil fuels and conventional energy sources. To progress toward farming sustainability, small farmers should adopt a business model based on alternative energy sources such as photovoltaic, wind power, or biomass to reduce operational expenses associated with energy [17]. Among renewable energy sources, solar energy has the potential to bring about a groundbreaking transformation in the agricultural sector. Its adoption can contribute to the preservation of water resources, reduction in the reliance on the electrical grid, and the generation of a long-term cost savings in power consumption.

Solar energy offers significant advantages compared to other types of renewable energy sources. It is more easily accessible to the average consumer, as panels can be easily purchased, whereas adding a wind turbine or hydroelectric power plant to one's backyard is more challenging. Solar energy continues to stand out among all renewable energy resources and is widely recognized as the best way to improve the efficiency of non-renewable energy sources.

According to the Solar Energy Industries Association [17], the use of solar energy has substantially increased by 68% in the last decade, making it the fastest-growing source of power [1]. There is a considerable interest in designing efficient photovoltaic (PV) systems to replace conventional ones [18]. Hence, it is significant to assess the impact of such projects once the initial pilot phase concludes. This evaluation allows to derive insights from the outcomes and enhance the effectiveness of these technologies.

Among the different fields of agriculture, renewable energy has applications in the dairy sector [19]. For farmers, adopting renewable energy systems leads to reduced electricity consumption and provides a competitive advantage by producing milk at a lower cost compared to the use of conventional systems. Renewable systems eliminate expenses related to fuel, heat, and electricity by utilizing their own resources [20]. This is important because the unpredictability of input factors and instabilities in fuel prices constitutes a substantial risk to long-term sustainability of milk production systems [21].

Increased milk output has been associated with improved energy use efficiency at the farm level [17,22,23] and solar panels play a crucial role in optimizing non-renewable energy use. Indeed, one of the most potent elements favorably affecting the energy efficiency of dairy farms is the volume of milk produced. The utilization of solar panels on farms is the most crucial component in increasing the effectiveness of non-renewable energy use. Solar energy is particularly suitable for countries with ample solar resources and is used in various production activities in the food and dairy industry, such as cooling, heating, lighting, pumping, and drying [24,25].

The adoption of appropriate solar-powered technology can positively impact the energy balance of the dairy industry [26]. Cooling systems, for instance, are significant energy consumers in dairy production [17]. Solar cooling devices offer a convenient and efficient solution along the milk value chain [27], particularly in areas with frequent power cuts. The use of solar energy for milk cooling can minimize operating costs by 25–30% compared to conventional systems [19]. Overall, efforts to enhance energy efficiency in the dairy sector generate additional income due to lower energy bills [26].

Natural gas, petroleum, and phosphate are the main conventional energy sources in Tunisia [28], accounting for 97% of total energy consumption, while alternative energy sources contribute only 3% to the country's electrical energy mix [29,30].

The proportion of renewable energy in total consumption has declined from 1990 to 2019 (Figure 2). A report published by the International Renewable Energy Agency (IRENA) in 2021 [31] indicates that Tunisia has witnessed a growing energy balance deficit in the past two decades (amounting to 50% in 2019 compared to 7% in 2010), largely as a result of relying on fossil fuel sources (oil and natural gas) to meet its increased energy demand. This dependence on imported fossil energy resulted in an energy deficit, leading the country to become more dependent on imported fossil energy. At the same time, renewable energy did not follow the trend, causing a decline in the share of renewable energy in the total final energy consumption.

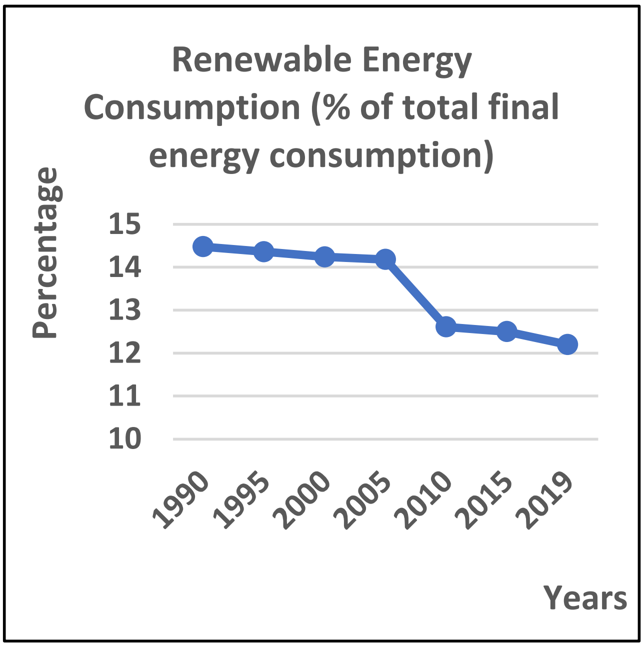

Figure 2. Percentage share of sustainable energy in overall consumption (1990–2019) [16].

Despite efforts to encourage the production of renewable energy equipment, the share of sustainable energy in overall consumption remained at only 12% in 2019 [16]. Tunisia is committed to pursuing an energy transformation plan focused on the advancement of sustainable energy sources. Indeed, the Tunisian government set some incentives through Government Order no 389 of 2017 [32], which enacted that the public authorities would provide a 50% subsidy for the purchase of equipment in clean technologies, including milk cooling. In addition, imported equipment utilized for renewable energy for which no comparable equipment is produced locally was exempt from VAT, and customs taxes were reduced from a general rate of 18% to a minimum rate of 10%.

In this regard, Tunisia has excellent potential for solar energy, allowing the development of solar capacities to sustain economic development. Governmental aid introduced solar power energy in the early 2000s to rural communities, specifically targeting families living off the national electricity grid. Moreover, in 2009, the Tunisian authorities adopted the "Tunisian Solar Plan" which aims to achieve a renewable energy capacity of 4.7 GW in the next decade [32].

This comprehensive strategy focuses on stimulating the growth of the solar energy sector by offering financial and fiscal incentives, with the ultimate goal of reducing reliance on imported energy sources. Among various sectors, agriculture will particularly benefit from the installation of PV panels in remote areas.

The Tunisian government, in collaboration with international cooperation programs, has started implementing small-scale pilot projects for demonstrations to encourage communities to adopt green technologies. Nevertheless, despite the excellent potential for solar energy and the government's efforts to promote renewable energy, Tunisia is still heavily reliant on conventional energy. The urgent need to address climate change and rising energy prices calls for a transition from fossil fuel-based energy systems to green solutions. Renewable energy, especially solar energy, has the potential to revolutionize agriculture by preserving resources and improving efficiency.

This article explores the possibility of using solar energy in the dairy sector to meet the cooling needs of small-scale farmers with limited access to conventional cooling equipment. The objective is to assess the financial profitability of a solar PV-powered milk cooling system compared to traditional milk cooling methods. The article highlights the importance of renewable energy, particularly solar energy, in the agricultural sector and its potential to reduce operational costs and increase energy efficiency.

3. Material and Methods

The research was conducted as part of the project titled "Field testing of an innovative solar-powered milk cooling solution for the higher efficiency of the dairy subsector in Tunisia," which is an international collaboration between the International Center for Agriculture in Dry Areas (ICARDA), the National Institute of Agricultural Research of Tunisia (INRAT), and Hohenheim University, Germany.

The project aims to assess the effectiveness of a solar-powered milk cooling solution specifically tailored to fulfill the refrigeration needs of small farms. This innovative cooling solution was developed to address the challenges encountered during the temporary on-farm storage of milk and during its transfer to collection centers.

The study was conducted in Regueb, situated in the region of Sidi Bouzid, Central Tunisia (Figure 3), a city located approximately 200 km south of Tunis (34°51′34′′ N, 9°47′12′′ E). As per the Köppen-Geiger climate classification [33], this region falls under the hot desert climate category (BWh). Regueb experiences high temperatures during the summer and cold winters with predominantly clear skies. The temperature in this area typically ranges from 5 °C to 36 °C, rarely dropping below 2 °C or exceeding 41 °C [34].

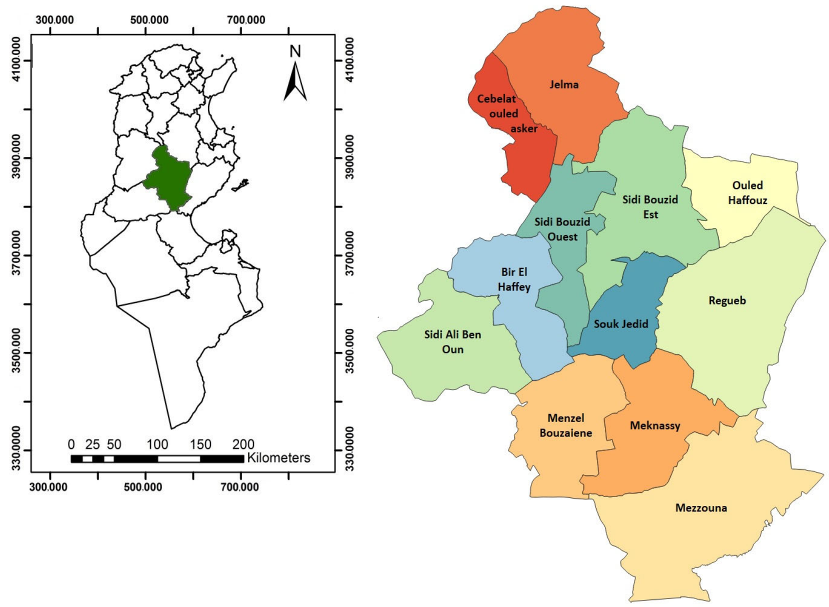

Figure 3. Location of Sidi Bouzid, Central Tunisia [35].

A dedicated solar-powered system was developed for on-farm milk cooling purposes. In Tunisia, seven small farms have been equipped with a total of 10 solar-powered milk cans.

The device, developed by Hohenheim University, comprises a commercially available DC refrigerator that has been enhanced with an adaptive control unit to transform it into a smart icemaker and is powered by photovoltaic (PV) solar panels that convert sunlight into electricity (Figure 4). The system comprises 25 reusable plastic blocks of 2 kg capacity each and two 30 L insulated milk cans that feature removable ice compartments. The smart icemaker utilizes thermal energy storage provided by the 25 ice blocks. Depending on the availability of solar power, the device adjusts its operation to ensure efficient ice production while minimizing energy consumption. The system requires 6 kg of ice to cool 30 L of the morning milk by 21 °C in less than 90 min and preserve it for up to 6 h. The freezer will work at its maximum during the day, and then it will go into "sleep mode" after dark to keep the ice generated during the day. The freezer has a storage capacity of 50 kg of ice, providing up to 4 days of self-sufficiency, even during periods of cloudy weather. Thanks to this device, the evening milk is no longer spoiled and can be stored for up to half a day using 8 kg of ice. In addition, neighboring farmers could benefit from the system by borrowing an insulated can filled with ice, allowing them to cool the morning milk without owning a solar cooling system [36].

Figure 4. Solar-powered milk cooling innovation developed by Hohenheim University (PV panels, 2 batteries, control panel, solar freezer, 25 ice blocks, and 2 milk cans) [37].

Implementing a photovoltaic (PV) cooling system presents a promising prospect for small-scale dairy farmers to expand their businesses, increase their income, and ultimately improve their quality of life [38]. Studies have demonstrated the good efficiency, reliability, and technical viability of PV refrigeration plants in various climatic conditions and when subjected to different load disturbances [39].

Due to frequent power cuts in the Sidi Bouzid region causing the rapid alteration of milk in the cooling tank, solar energy-based technology presents an excellent alternative with high profitability. Solar-powered cans can be manufactured by local industries in Tunisia, leading to a progressive decrease in their cost, while the cost of electric-based technology is expected to increase due to rising electricity prices and the cost of imported milk tanks.

In this context, the project was implemented to develop the concept of milk cooling at the farm level using solar-powered devices. To highlight the importance of this technology, three different business models inspired by the INVESTA Project [40] were considered to compare financial profitability and feasibility in the Sidi Bouzid region: a traditional dairy farm without milk cooling equipment (project 1), a farm with solar-powered milk cans (project 2), and a standard electricity-based project (project 3).

The concept of a business model has expanded since the emergence of the Internet in the late 1990s [41] and is defined as "stories that explain how enterprises work" [42]. Recently, it has been portrayed as a concept describing how a company generates, seizes, and gives market value [43]. It can be used to evaluate a company's value chain [44] and manage strategic and innovative work, and assess its financial performance [42].

To determine which project is the most profitable, a financial analysis was conducted, including the estimation of two indicators: The Net Present Value (NPV), which is the difference between the present value of cash inflows and outflows discounted at a specific rate, and the Internal Rate of Return (IRR), which represents the interest rate at which the present value of projected cash inflows for a project equals the present value of cash outflows.

Finally, a sensitivity analysis was conducted for projects 2 and 3 to focus on the consequences that may occur in case of alterations in the Milk Rejection Rate (MRR) and the Interest Rate (IR) on profitability.

4. Results

In this section, the three business models will be compared using four main indicators: investment, turnover, expenses, and financial results (Table 1). The first business model (BM) considers a small dairy farm in the Sidi Bouzid region. This BM is a standard dairy cattle project of five heifers, as it best represents typical dairy farmers on small-scale farms and uses only standard technologies and equipment such as a milking machine and milk cans [45]. There is no on-farm milk cooling for this type of farm. The second business plan concerns the farms with the innovative solar-powered technology to cool milk on site. The third business plan has the same elements as project 2, except for the energy component. This project uses milk cooling tanks connected to the power grid to store collected milk.

Table 1. Investment and funding for the three business models (in TND).

	Total Investment	Self-Financing	Subsidies	Credit
Five heifers	25,000	2500	7500	15,000
Milking machine	1000	100	250	650
Insurance	1070	107		963
Working capital	2554	2554		
Total investment project 1	29,624	5261	7750	16,613
Solar-powered milk cooling system components				
PV Modules 600	1225	122.5	612.5	490
Frame	280	28	140	112
Battery	756	75.6	387	293.4
Charger controller	707	70.7	353.5	282.8
Freezer	777	77.7	0	699.3
Control unit	606	60.6	303	242.4
Cables	210	21	105	84
Two milk cans (60 L/day)	500	50	250	200
Twenty-five ice blocks	38	3.8	0	34.2
Protection	241	24.1	120.5	96.4
Service	420	42	0	378
Total investment in solar-powered milk cans	5760	576	2271.5	2912.5
Total investment project 2	35,384	5837	10,021.5	19,525.5
Milk cooling tanks price	6490	649	1622.5	4218.5
Total investment project 3	36,114	5910	9372.5	20,831.5

Source: based on field data, 2019.

4.1. The Total Investment and Funding for the Three Projects

The various components of a new small-scale breeding project were identified beginning with the number of heifers, which was fixed at five animals per farm. Each heifer would cost TND 5000, for a total investment of TND 25,000.

The government subsidizes the purchase of heifers at a rate of 30% and dairy equipment at a rate of 25%. The insurance per heifer is fixed at TND 214, and the self-financing for the farmer is set at 10%. Each element of the project has a depreciation period and value. The depreciation period for the heifers is set at 5 years, which accounts for the theoretical project lifetime. Indeed, the longevity of a dairy cow is characterized by the length of its productive life [46]. Although the life expectancy for dairy cattle is nearly twenty years, the average total lifespan of dairy cows is only 5.5 years [47]. The cumulative depreciation value for the project components is nearly TND 4300 (USD 100 = TND 308.978 [48]). All these elements are common to the three business models.

To accomplish the first project, the farmer would need self-financing of TND 5261 and must get a credit of TND 16,613 (Table 1). Concerning the equipment used, it consists of a milking machine and two or three milk cans.

The total investment needed for this project is TND 29,624; while the subsidies allocated by the government are TND 7750, the remaining amount will be TND 21,874.

This implies that the farmer would contribute 26.4% less capital than he actually needed. This is very advantageous for small livestock keepers with constrained means. This business model was later considered a reference for comparing two on-farm milk cooling technologies.

The second business model is based on the same components as the first, but with one difference: the use of innovative solar-powered milk cooling cans. The total investment for this business model is TND 35,384, which includes the total investment for project 1 and the total cost of the solar-powered technology evaluated at TND 5760 (Table 1). Smallholders do not have this amount of money, for this reason, the government subsidizes both the heifers and dairy equipment; the subsidies are estimated for this BM at TND 10,021.5. Indeed, according to Decree No 2009-362, this particular investment category is specifically designated for agricultural projects that are not connected to the electricity grid. For such projects, the government offers a subsidy of 40% of the total cost, up to a maximum limit of TND 20,000. Farmers can also benefit from numerous bank credits, calculated to be TND 19,525.5 in total. Thus, farmers only require TND 5837 to start a project worth TND 35,384.

The third business model has the same elements as project 1, but with a difference affecting the energy component. This BM is based on a small dairy farm using a milk cooling tank to store the collected milk. The total investment for this project includes the investment in project 1 and the cost of a milk cooling tank, estimated at TND 6490. The total investment is TND 36,114, with TND 9372 in subsidies, TND 20,831 in credit, and TND 5910 in self-financing.

4.2. The Turnover for the Three Business Models

The project turnovers of the three business models are presented in Table 2. Three assumptions were considered for the calculations. The first one concerns milk production, which will start at 5000 L per cow, increase with age, and then stabilize at 6400 L per cow per year.

The milk rejection rate is set at 10% since it represents the highest observed rate in the region, as determined through field surveys. The second assumption is that milk prices at the production level will increase annually at a pace of 0.02 TND/L per year, starting at 0.766 TND/L in year 1 and increasing to 0.846 TND/L in year 5. The third assumption considers the average calving interval of cows in Tunisia, which ranges from 13 to 18 months. This interval is expected to provide livestock keepers with an average of 0.86 calves per year, ensuring a consistent breeding cycle with a 5% increase per year in the selling price for the calves, based on data from the baseline survey. The calves' selling price starts at TND 700 in the first year and goes up to TND 883.734 in the fifth year.

Manure represents a crucial by-product in the agricultural sector. Local farmers typically do not sell this product but instead offer it at a nominal price due to its classification as animal waste. However, we expect that the farmer would sell the manure produced on his farm. On average, each cow is expected to produce 7 tons of manure per year, which can be sold at a rate of 20 TND per ton, with an increased rate of 6%.

The total turnover for project 1 would be the total milk sales, to which we add the calves and manure sales. Each cow will produce 5000 L of milk; from which we deduct 10% due to the rejection of spoiled milk because of the lack of milk cooling equipment on the farm. The estimated total milk production for five cows would be 4500 L at a rate of 0.766 TND per liter, resulting in total sales of TND 17,235. As for the calves, the total sales would amount to TND 3010 for five cows. Additionally, the total sales from the manure would be 20 TND per ton, totaling TND 700. The total turnover for the first year would be TND 20,945 and would increase to TND 28,907.2 in the fifth year.

Concerning the project turnovers for projects 2 and 3, the same assumptions were made as in the first business model. In these projects, there is no rejection of the milk as it is cooled with the solar-powered cooling cans after milking for project 2, while the milk is cooled in the tanks for project 3. The farmers would gain an additional advantage of 0.01 TND/L of cooled milk as an incentive granted by the government; it will start at

TND 50 (5000 L of milk × 0.01 TND/L) and will rise to TND 64 in the fifth year. The total turnovers for both projects 2 and 3 would start at TND 22,910 in the first year and increase to TND 31,678.4 in the fifth year.

Table 2. The turnover for the three business models (in TND).

	Year 1	Year 2	Year 3	Year 4	Year 5
Number of cows			5		
Milk production per year (L)	5000	5800	6400	6400	6400
Milk rejection rate (%)			10%		
Collected milk for project 1 (L)	4500	5220	5760	5760	5760
Milk selling price/L (TND)	0.766	0.786	0.806	0.826	0.846
Milk sales project 1(A)	17,235	20,514.6	23,212.8	23,788.8	24,364.8
Milk sales projects 2 and 3	19,150	22,794	25,792	26,432	27,072
Premium for cooled milk for projects 2 and **3 (TND)**	50	58	64	64	64
Total milk sales for projects 2 and 3 (B)	19,200	22,852	25,856	26,496	27,136
Calves selling price in TND (5% increase/year)	700	735	771.75	810.3375	850.854
Total sales for calves (0.86 calf per year × 5 cows) (C)	3010	3160.5	3318.525	3484.4513	3658.67
Manure selling price in TND (6% increase/year)	20	21.2	22.472	23.82032	25.2495
Total sales for manure (7 tons per year × 5 cows) (D)	700	742	786.52	833.7112	883.734
TOTAL TURNOVER for project 1 (A + C + D)	20,945	24,417.1	27,317.85	28,106.962	28,907.2
TOTAL TURNOVER for projects 2 and 3 (B + C + D)	22,910	26,754.5	29,961.05	30,814.162	31,678.4

Source: based on field data, 2019.

4.3. The Project Expenses for the Three Business Models

Along with the different assumptions made previously, the different charges for each activity were calculated. The main expenditure was feed costs (Table 3), which will depend on the physiological stage of the five dairy cows (lactating or dry cows). Indeed, the nutritional needs of dairy cattle are different; lactating cows require a diet that supplies the nutrients needed for good milk production (hay, concentrated fodder, and green fodder), whereas, for dry cows, the ration consists of a combination of straw, hay, and concentrated feed primarily made from maize and barley. The daily feeding costs for milking cows are twice as much as for dry cows. The concentrated feed is essentially imported, so we estimate that the feeding cost will increase.

Milk production increases with age [49]. Consequently, the milk production of a dairy cow will increase according to its number of lactations, leading to an increase in the number of working days from the initial 275 days to 305 days, which is an optimal scenario. The insurance policy is set at 214 TND per cow/year, with an increased rate fixed at 7% every 2 years.

Assuming that each heifer requires a minimum of two veterinary treatments per year, the total veterinary costs were estimated at TND 600 in the first year, rising to TND 700 in the fifth year.

Concerning water supply, although drinking water is subsidized in Tunisia, rural areas do not have access to this vital resource. Purchasing water is done through the acquisition of cisterns, with a cost that is determined according to the proximity of the farm to the water resource. The total expense of water per year was computed using the quantity of water needed for cow drinking and the cleaning of the milking equipment and cow sheds. During the initial year, the total would amount to TND 300 and gradually increases to TND 351 by the fifth year. The other costs of the three business models cover the depreciation of the heifers and equipment; financial expenses; miscellaneous costs; operating social charges; and energy. This is the only cost that will differ between the three projects according to our assumptions. The energy cost for projects 1 and 3 is almost identical, as the energy is used for common activities (i.e., power consumption for the milking machine, tank, and illuminating sheds). The government in Tunisia is subsidizing electricity; hence, the annual energy cost for projects 1 and 3 is the same. We estimated the initial annual amount at TND 600, reaching TND 700 in the fifth year. The solar-powered milk cooling system is slightly different as there is little use of electricity. The total cost would be TND 300 in the first year and TND 400 in the fifth year. The increase rate for the energy cost is fixed at 4% per year.

The overall yearly expenditures of the projects are comparatively significant; they were estimated in the first year at TND 18,994.5, reaching TND 21,603 in the fifth year for projects 1 and 3. Project 2 expenses were estimated at TND 18,694 in the first year and TND 21,303 in the fifth year.

Table 3. The project expenses for the three business models (in TND).

	Year 1	**Year 2**	**Year 3**	**Year 4**	**Year 5**
Number of working days per year (1)	275	305	305	305	305
Ordinary feeding cost (2)	6.4	6.72	7.056	7.409	7.779
Dry cows: number of days (3)	90	60	60	60	60
Dry cows: feeding cost (4)	3.15	3.308	3.473	3.647	3.829
Feed cost = ((1 × 2) + (3 × 4)) × (5 cows)	10,217.5	11,240.25	11,802.26	12,392.38	13,011.99
Depreciation heifers/equipment	3950	3950	3950	3950	3950
Financial expenses	1427	1170	959	787	645
Insurance (7% increase per 2 years)	1000	1000	1070	1070	1145
Veterinary fees	600	624	650	675	700
Water	300	312	324	337	351
Miscellaneous cost	380	430	480	530	580
Operating social charges			**520**		
Energy (4% increase/year) for projects 1 and 3	600	624	650	675	700
Energy (4% increase/year) for project 2	300	324	350	375	400
Total expenses for projects 1 and 3	18,994.5	19,871.3	20,406.2	20,936.6	21,603
Total expenses for project 2	18,694.5	19,571.3	20,106.2	20,636.6	21,303

Source: based on field data, 2019.

4.4. The Financial Results for the Three Business Models

The financial outcomes of the three projects are displayed in Table 4. Cash outflows and cash inflows were calculated, and then net annual revenues were estimated based on various assumptions. Project 1 is financially profitable and would generate an annual revenue of TND 8803.6 after the first year, from which the initial credit payment will be deducted following a grace period of one year. Ultimately, the annual revenue is projected to reach TND 6411.1 after 5 years.

Project 2 stands out as the most lucrative, yielding a net annual revenue of TND 11,068.6 in the first year and a monthly net result of TND 922.4. By the fifth year, the project is expected to generate an annual revenue of TND 9808.8. The annual credit repayment is set at TND 4866, and the equipment depreciation (i.e., the PV system) is estimated at TND 4299. The business model demonstrates strong feasibility and profitability, allowing farmers to generate attractive profits without incurring substantial debt.

Project 3 generates slightly lower financial net benefits compared to project 2 due to electricity fees. However, this discrepancy only results in minor differences in the net results (Table 4).

The on-farm milk cooling process makes a noticeable impact in terms of milk rejection rate (MRR), cooling premiums, and milk quality. The energy source used for milk cooling brings about differences from financial, social, and, most significantly, environmental perspectives.

Table 4. The financial results for the three projects (in TND).

		Year 1	Year 2	Year 3	Year 4	Year 5
Project 1	Total turnover (1)	20,945	24,417.1	27,318	28,107	28,907.2
	Working capital (2)	2554				
	Depreciation (3)	4299	4299	4299	4299	4299
	A = Cash inflow (1 + 2 + 3)	27,798	28,716.1	31,617	32,406	33,206.2
	B = Cash outflow (total expenses)	18,994.5	19,871.3	20,406.2	20,936.6	21,603
	Cash flow = A − B	8803.6	8844.8	11,210.6	11,469.4	11,603.2
	Credit refund		5192.125	5192.125	5192.125	5192.125
	Net annual revenue	8803.6	3652.6	6018.5	6277.2	6411.1
	Net monthly income	733.6	304.4	501.5	523.1	534.3
Project 2	Total turnover (1)	22,910	26,754.5	29,961	30,814.2	31,678.4
	Working capital (2)	2554				
	Depreciation (3)	4299	4299	4299	4299	4299
	A = Cash inflow (1 + 2 + 3)	29,763	31,053.5	34,260	35,113.2	35,977.4
	B = Cash outflow (total expenses)	18,694.5	19,571.3	20,106.2	20,636.6	21,303
	Cash flow (A − B)	11,068.6	11,482.2	14,153.8	14,476.6	14,674.4
	Credit refund		4866	4866	4866	4866
	Net annual revenue	11,068.6	6616.5	9288.2	9610.9	9808.8
	Net monthly income	922.4	551.4	774.0	800.9	817.4
Project 3	Total turnover (1)	22,910	26,754.5	29,961	30,814.2	31,678.4
	Working capital (2)	2554				
	Depreciation (3)	4299	4299	4299	4299	4299
	A = Cash inflow (1 + 2 + 3)	29,763	31,053.5	34,260	35,113.2	35,977.,4
	B = Cash outflow (total expenses)	18,994.5	19,871.3	20,406.2	20,936.6	21,603
	Cash flow (A − B)	10,768.6	11,182.2	13,853.8	14,176.6	14,374.4
	Credit refund		5192.125	5192.125	5192.125	5192.125
	Net annual revenue	10768.6	5990	8661.7	8984.4	9182.3
	Net monthly income	897.4	499.2	721.8	748.7	765.2

Source: based on field data, 2019.

4.5. Financial Analysis (IRR and NPV)

Two financial indicators were used to assess the profitability of the three projects: IRR and NPV. The IRR is a commonly employed tool in financial planning that assesses investment viability. The NPV represents the disparity between the present value of cash inflows and cash outflows within a designated period. The IRR for all three business plans was computed using a uniform discount rate of 10%, enabling a meaningful comparison.

Among the three projects, project 2 emerged as the most lucrative, with an NPV of TND 8497.87 and an IRR of 17% (Table 5). The next most financially rewarding project was project 3, with an NPV of TND 3295 and an IRR narrowly surpassing the 10% threshold. Regarding project 1, the outcomes were unambiguous, with an NPV of TND 2000, making the project appear financially rewarding. However, given that the IRR fell below the symbolic threshold of 10%, it suggests that proceeding with this project would entail an avoidable financial hazard.

Table 5. Financial indicators of projects 1, 2, and 3.

Project	IRR (%)	NPV (TND)
Project 1	9	2000.92
Project 2	17	8497.87
Project 3	10.4	3295.31

Source: based on field data, 2019.

4.5.1. Payback Period Analysis

The time needed to recover the expenses of an investment is known as the payback period. Longer payback times are often unfavorable for investment situations; therefore, they play a significant role in deciding whether to proceed or not with a project. Simplified summaries of the payback periods for the three projects with an IR set at 10% are shown in Figure 5. Project 1 exhibits the longest payback duration, encompassing a span of 4.5 years. Project 2, with the innovative cooling device, has the shortest payback period at 3.5 years. For project 3, the payback time is 4 years. These results confirm the conclusions drawn in previous sections, further supporting the superior profitability of the PV system.

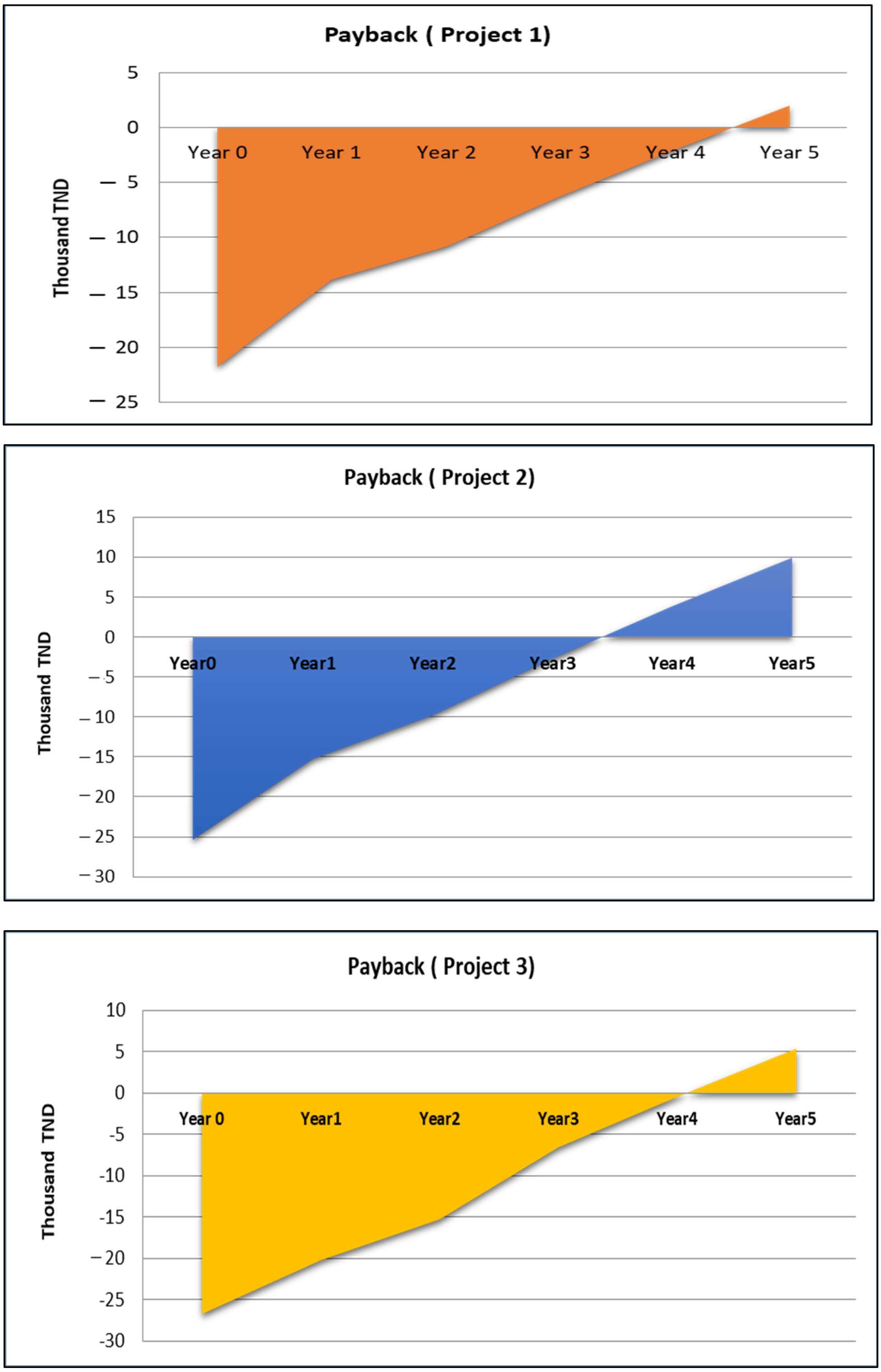

Figure 5. Payback period of the three projects. Source: based on field data, 2019.

4.5.2. Sensitivity Analysis

This tool is an analytical approach employed to assess the effects of varying values in an independent variable on a specific dependent variable while holding a predetermined set of assumptions constant. Within this framework, the impact of the MRR and IR on the NPV for projects 2 and 3 is presented.

This sensitivity analysis relied on two key assumptions: the first assumption considered the impact of milk rejection resulting from a system malfunction, such as an intense weather disturbance or an extended power outage, which could make the milk unsuitable for delivery. The second assumption considered a substantial spike in the interest rate, possibly resulting from the adoption of a new economic strategy or a severe devaluation of the national currency. These assumptions are not mere speculation since a disruption took place during the experimental phase of Project 2. Furthermore, certain Tunisian associations exhibit an IR surpassing 20%, such as "ENDA Tamweel (ENDA Tamweel is a Tunisian micro-finance company, it works for the financial inclusion of vulnerable populations, especially women and young people by providing loans. However, the interest rate is high as it goes up to 20%)".

Figure 6 emphasizes the NPV for both projects 2 and 3 according to the MRR and IR, combined with Tables 6 and 7, which present the NPV values for every conceivable modification. The best- and worst-case scenarios are shown in Table 8: the cases of MRR 0% and IR 2% and MRR 20% and IR 20%.

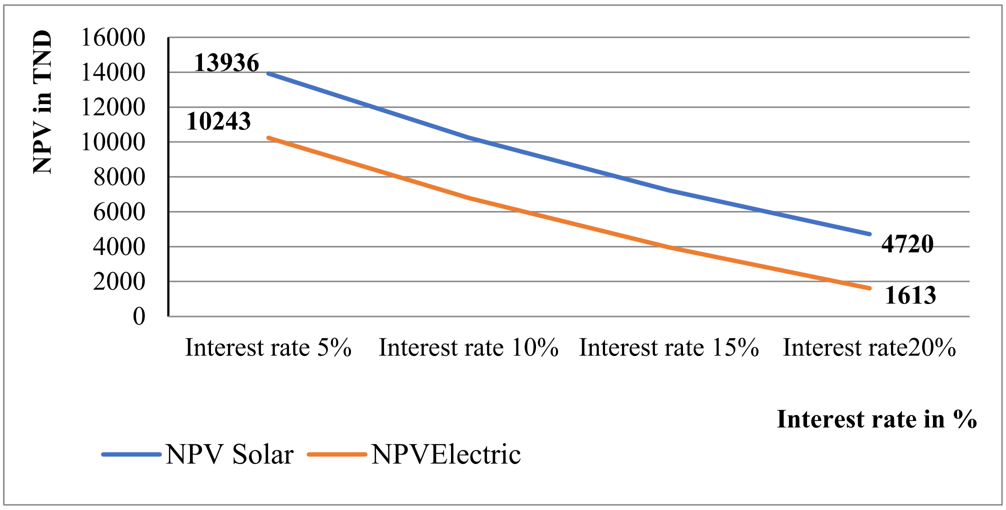

Figure 6. NPV of projects 2 and 3 according to interest rates. Source: based on field data, 2019.

In the best-case scenario, the farmer would have the privilege of credit access with an extremely favorable interest rate from public financial institutions as part of a national strategy to subsidize and promote on-farm cooling systems utilizing various power sources. Additionally, the milk rejection rate was set at zero, indicating high milk quality compared to conventional systems.

To assess the resilience of the financial model, it is crucial to explore an extreme scenario. In this particular case, both the MRR and IR were set at their maximum values, namely 20% each. The key presumptions underlying this scenario included a prolonged technical malfunction of the systems, such as the unavailability of spare parts, and the possibility of the farmer seeking credit from the parallel market or a private association with an exceptionally high IR.

Surprisingly, the outcomes for the PV system yielded a positive NPV due to its lower investment cost compared to the electrical system. In contrast, the electrical system showed a negative NPV of TND −1587.

Table 6. NPV based on milk rejection rate and interest rate (project 2).

	Milk Rejection Rate (%)								
Interest rate (%)	0	1	2	3	4	5	10	15	20
2	16,560	16,372	16,183	15,995	15,807	15,619	14,678	13,736	12,795
5	13,936	13,753	13,570	13,387	13,204	13,021	12,107	11,193	10,279
10	10,243	10,069	9894	9720	9545	9371	8498	7625	6752
15	7223	7056	6889	6722	6555	6388	5553	4719	3884
20	4720	4560	4400	4240	4080	3920	3120	2320	1520

Source: based on field data, 2019.

Table 7. NPV based on milk rejection rate and interest rate (project 3).

	Milk Rejection Rate (%)								
Interest rate (%)	0	1	2	3	4	5	10	15	20
2	12,699	12,511	12,322	12,134	11,946	11,758	10,817	9875	8934
5	10,243	10,060	9877	9694	9511	9328	8414	7500	6586
10	6786	6612	6437	6263	6088	5913	5041	4168	3295
15	3958	3791	3624	3457	3290	3123	2288	1454	619
20	1613	1453	1293	1133	973	813	13	−787	−1587

Source: based on field data, 2019.

Table 8. Different scenarios (NPV and IRR values).

	Best Scenario (MRR 0%, IR 2%)		Moderate Scenario (MRR 10%, IR 5%)		Worst Scenario (MRR 20%, IR 20%)	
	NPV	IRR	NPV	IRR	NPV	IRR
Project 2	16,560	24%	12,107	21%	1520	10%
Project 3	12,699	18.7%	8414	15.9%	−1587	6.2%

Source: based on field data, 2019.

Table 9 provides a summary of the financial outcomes for the three projects. In particular, project 2 stands out with a total investment of TND 35384. It shows a higher net monthly income, starting at TND 922 in the first year and gradually decreasing to TND 817 in the fifth year. Furthermore, project 2 demonstrates the highest Net Present Value (NPV) with TND 8497. Notably, project 2 also boasts the highest Internal Rate of Return (IRR) among the three projects, reaching 17%. Additionally, the solar-powered milk cooling project has the best payback period at 3.5 years, indicating the shortest duration required for the project's cash inflows to recover the initial investment.

Table 9. Financial outcomes of the three projects.

		Year 1	Year 2	Year 3	Year 4	Year 5
Project 1	Total investment			29,624		
	Net monthly income	733.6	304.4	501.5	523.1	534.3
	IRR (%)			9		
	NPV (TND)			2000.92		
	Payback period (years)			4.5		
Project 2	Total investment			35,384		
	Net monthly income	922.4	551.4	774.0	800.9	817.4
	IRR (%)			17		
	NPV (TND)			84,97.87		
	Payback period (years)			3.5		
Project 3	Total investment			36,114		
	Net monthly income	897.4	499.2	721.8	748.7	765.2
	IRR (%)			10.4		
	NPV (TND)			3295.31		
	Payback period (years)			4		

Source: based on field data, 2019.

4.6. Advantages of Solar PV Cooling Systems and Environmental Impact

The solar PV cooling system offers several specific advantages over the electric cooling system, making it a more sustainable and adaptable solution in the long run. These advantages encompass the fact that this system is based on a renewable energy source, unlike the electric cooling system that relies on conventional energy sources, such as fossil fuels. The solar PV system reduces greenhouse gas emissions and contributes to a cleaner and more sustainable energy supply. Moreover, this system is cost-saving; by utilizing solar energy, which is totally free, farmers can reduce or even eliminate electricity costs associated with the electric cooling system. This can have a positive impact on the profitability of dairy farms, especially in regions with high electricity prices.

This system is particularly well-suited for the region of Sidi Bouzid compared to electric technology as this region experiences power cuts, which can represent a significant risk to the milk stored in the cooling tank that may lead to its spoilage. Under such conditions, the reliability and independence of the solar-powered system ensures that milk is consistently cooled, mitigating the negative impacts of power outages on dairy farmers. In rural areas where electricity supply is unstable, the solar PV system ensures continuous milk cooling without relying on external power sources. This innovation is also adapted to local conditions; the modular nature of solar panels allows for scalability, enabling farmers to expand the system based on their specific needs and available space.

The financial viability of green technology will increase as investment costs gradually decline, driven by the growth of domestic producers. In contrast, the expenses associated with electric technology will escalate as electricity prices and the cost of imported milk cooling tanks rise.

Concerning the environmental impact, the solar-powered milk cooling technology minimizes its environmental footprint. It produces clean energy without emitting harmful pollutants or contributing to climate change. The adoption of a solar PV-powered milk cooling system offers several environmental benefits and the potential for a significant reduction in carbon footprint compared to a conventional electrical cooling system. Indeed, the solar PV-powered systems rely on renewable energy from the sun, which produces zero greenhouse gas emissions during electricity generation. In contrast, conventional electrical cooling systems are typically powered by grid electricity, which often comes from fossil fuel sources such as coal or natural gas. These fossil fuels release carbon dioxide and other greenhouse gases when burned, contributing to climate change. By using solar energy, the solar PV-powered system can reduce or eliminate CO2 emissions associated with electricity consumption.

Maintenance requirements and associated costs for the solar PV-powered milk cooling system and the electric cooling system can differ significantly. In fact, for the solar PV powered milk cooling system, the maintenance requirements should include the solar panels, which require regular cleaning to ensure optimal performance, and the electrical components of the system, which should be inspected periodically to identify any faults or malfunctions. The freezer requires routine maintenance as per the manufacturer's guidelines. On the other hand, the electric cooling system relies on grid electricity; hence, the maintenance requirements are more complicated because it needs the expertise of an electrician. It includes routine inspections, cleaning, and potential repairs or replacements of electrical parts. The cost will depend on the complexity of the system and the labor rates in the local area.

In general, the maintenance costs for a solar PV-powered milk cooling system can be lower compared to an electric cooling system. Solar PV systems have fewer moving parts, reducing the likelihood of mechanical failures. However, it is essential to note that the specific maintenance requirements and associated costs can vary depending on the system's size, complexity, and local context. Regular maintenance and timely repairs are crucial for both types of systems to ensure their optimal performance, longevity, and reliability.

4.7. Barriers to Solar PV Cooling System Adoption

While the solar PV cooling system offers numerous advantages for small-scale dairy farmers, there are potential barriers that may hinder its widespread adoption. The most common barriers observed in the field concerned the fact that this technology is only a prototype for now and that the solar energy system suppliers have not shown substantial interest in its large production at this stage. Although the prototype demonstrates promising potential, further development and market demand are necessary factors for the industry to consider investing in its manufacturing.

In addition, the acquisition of photovoltaic panels, which is a significant part of the initial investment in this technology, can be a financial hurdle for small-scale farmers, who often have limited access to funding. To overcome this challenge, the Tunisian government, NGOs, and financial institutions can provide financial incentives such as subsidies, grants, or low-interest loans specifically targeted at small-scale dairy farmers.

An additional obstacle is the lack of sufficient technical knowledge and skills needed for the installation and maintenance of small-scale solar PV systems among farmers. To overcome such barrier, capacity-building programs can be implemented to provide training and education on solar technology, system installation, operation, and maintenance. Extension services, farmer cooperatives, and partnerships with technical institutions can play a vital role in disseminating knowledge and skills. There is also a lack of awareness and information about the benefits and feasibility of solar PV cooling systems. Awareness campaigns, workshops, and farmer-to-farmer knowledge sharing programs can be organized to disseminate information about the technology, its advantages, and successful case studies. Utilizing local media channels, agricultural extension services, and farmer cooperatives can effectively reach out to farmers.

Furthermore, some farmers may perceive the solar PV cooling system as a risky investment due to uncertainties related to technology performance, maintenance, and the potential for return on investment. To address this, demonstration projects and case studies showcasing successful implementations, such as the Sidi Bouzid experience, can be shared with farmers to build confidence and trust in the technology. Providing warranties, technical support, and after-sales services can also mitigate perceived risks.

By addressing these barriers through a comprehensive approach that combines financial support, capacity building, awareness campaigns, technical assistance, and supportive policies, the adoption of solar PV cooling systems can be improved among small-scale dairy farmers. This will not only benefit individual farmers by reducing costs and improving productivity, but also contribute to sustainable agricultural practices and the transition to clean energy in the dairy sector.

The adoption of solar-powered milk cooling technology can be affected by various social and cultural factors. The level of awareness and understanding of solar PV technology among small-scale dairy farmers can impact its adoption. Farmers who are more aware of the benefits, functioning, and maintenance of the technology are more likely to consider its adoption. Providing educational programs, training, and information sessions about solar PV systems can increase awareness and knowledge.

Additionally, farmers' perceptions of the benefits associated with the solar PV-powered milk cooling system are crucial. These benefits may include reduced electricity costs, increased reliability and independence from the grid, environmental sustainability, and improved milk quality. Highlighting these advantages and demonstrating successful case studies can positively influence farmers' perceptions and willingness to adopt the technology.

Small-scale dairy farmers often rely on trusted sources of information and advice within their social networks. Positive experiences and recommendations from peers, neighboring farmers, or agricultural extension services can play a significant role in influencing the adoption decision. Building trust and disseminating success stories within the farming community can help overcome skepticism and promote adoption.

Cultural factors, including traditional farming practices and beliefs, can influence the acceptance of new technologies. Understanding how the solar PV system aligns with existing cultural norms and practices in the farming community is crucial. If the technology can be integrated into the farmers' daily routines and is perceived as compatible with their values, it is more likely to be adopted.

5. Conclusions and Policy Implications

The availability of sustainable and affordable energy services plays a crucial role in alleviating poverty in developing nations. Small-scale and community-based renewable energy projects are acknowledged as significant forms of developmental aid, particularly in providing energy access to smallholder farmers. Nevertheless, there are a limited number of empirical evaluations that have comprehensively analyzed and compared the impact of these projects on local living conditions and their sustainability after implementation.

This article involved a feasibility analysis and explored the business model of an on-farm milk cooling system powered by photovoltaic (PV) energy in central Tunisia. The system is entirely powered by solar energy and was developed to enable dairy farmers to preserve their milk before delivery, henceforth overcoming difficulties during temporary on-site storage. The research aims to provide insights into the financial viability of this type of innovation on small-scale dairy farms in Tunisia.

The findings unequivocally demonstrated the significance of milk cooling in lowering the MRR and, as a result, boosting monthly earnings and ultimately improving small farmers' livelihoods. Indeed, the analysis of the three business models showed that the project with cooling systems demonstrated superior profitability in terms of monthly earnings, NPV, and IRR.

The solar PV cooling system offers long-term sustainability for dairy farms. As technology advances and the cost of solar panels continues to decline, the system becomes increasingly affordable and financially viable. It offers a reliable and sustainable solution for milk cooling, contributing to the sustainability and resilience of the dairy industry.

Overall, the solar PV cooling system provides advantages in terms of renewable energy utilization, cost savings, independence from the grid, adaptability to local conditions, reduced environmental impact, and long-term sustainability.

However, this transition to renewable energies cannot happen without government support. Ultimately, the Tunisian government should provide greater support for the implementation of PV-powered milk cooling systems. This can be achieved through policy frameworks with supportive regulations for renewable energy systems, financial incentives such as subsidies, raising the premium for milk cooling, and low-interest loans specifically targeted at the installation and operation of these systems. In addition, implementing tax benefits such as exemptions or reduced rates on equipment, components, and installation costs associated with PV-powered milk cooling systems can further incentivize farmers to adopt the technology. The government can enhance capacity building and technical assistance programs to educate farmers about the benefits of PV-powered milk cooling systems. This can be achieved through training programs, workshops, and knowledge-sharing platforms that involve government agencies, agricultural extension services, and technical institutions.

The government should encourage public-private partnerships, including those with equipment suppliers, installers, and service providers, which can help create a conducive ecosystem for the adoption of this system. Public-private partnerships can facilitate the availability of quality equipment, installation services, and after-sales support, ensuring the successful implementation and operation of the systems.

Furthermore, the government can launch awareness and outreach campaigns to educate farmers about the advantages and feasibility of PV-powered milk cooling systems. This can be done through various channels, such as mass media, agricultural exhibitions, farmer cooperatives, and extension services.

Nevertheless, despite the findings presented in this study, it is important to acknowledge and consider the various limitations that may impact the interpretation of the results. One of the limitations concerns the encountered technical malfunctions, as some farmers demonstrated a lack of clear understanding regarding the proper usage and implementation of the innovation. In addition, the solar PV-powered milk cooling system needed to be adapted to local conditions, including climate, milk production volume, and infrastructure availability. This required careful selection and sizing of components, such as solar panels, batteries, and cooling equipment, to ensure optimal performance in the specific context.

The financial viability of implementing a solar PV-powered milk cooling system can be a challenge, especially considering the initial investment costs. Access to financing options, such as low-interest credit or government subsidies, will play a crucial role in making the system financially feasible for farmers.

Engaging relevant stakeholders, including farmers, local communities, and government agencies, is vital for the successful implementation of the solar PV-powered milk cooling system. Consulting with local experts and conducting feasibility studies will help in making informed decisions and adapting the system accordingly. By addressing these limitations and challenges, the field testing of the solar PV-powered milk cooling system will optimize its performance, increase its reliability, and demonstrate its potential as a sustainable solution for milk cooling in rural areas.

Future research and development in the field of solar energy technologies for small-scale dairy farms in developing countries should focus on improving the efficiency and cost-effectiveness of solar energy technologies for milk cooling systems. This includes the development of more efficient solar panels, innovative storage solutions, and advanced control systems that optimize energy use and system performance.

In addition, further research is needed to assess the long-term economic viability of this technology, including the evaluation of different financing models and investment strategies. Analyzing the financial benefits, payback periods, and return on investment can provide valuable insights to farmers, financial institutions, and policymakers in other developing countries with the objective of promoting sustainable and resilient agricultural practices.

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Informed Consent Statement: For the data obtained through the survey, we confirm that informed consent was obtained from the respondent before the beginning of the interview.

Data Availability Statement: The authors confirm that the data supporting the findings of this study are available on request from the corresponding author, [BD]. The data are not publicly available because they are containing information that could compromise the privacy of research participants.

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