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Assessment of Whole Milk Powder Production by a Cumulative Exergy Consumption Approach

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Abstract: The production of food is a sector that consumes a significant amount of energy and encompasses both agricultural and industrial processes. In this study, the energy consumption of whole milk powder production, which is known to be particularly energy-intensive, was examined. The study used a cumulative exergy consumption approach to evaluate the overall production process of whole milk powder, including the dairy farm (raw milk production) and dairy factory (powder production) stages. The results showed that raw milk production dominated energy and exergy consumption and carbon dioxide emissions. An amount of 68.3% of the total net cumulative exergy consumption in the system was calculated for raw milk production. In the dairy factory process, the highest energy/exergy consumption occurred during spray drying, followed by evaporation and pasteurization. In these three processes, 98.3% of the total energy consumption, 94.6% of the total exergy consumption, and 95.7% of the total carbon dioxide emissions in powder production were realized. To investigate the improvement potentials in the system, replacing fossil fuels with renewable energy sources and using pasture feeding in animal husbandry were evaluated. While using alternative energy sources highly influenced powder production, pasture feeding had a high impact on consumption in raw milk production. By using renewable energy and pasture feeding, the exergy efficiency, cumulative degree of perfection, renewability index, and exergetic sustainability index values for the overall process increased from 40.5%, 0.282, −0.22, and 0.68 to 68.9%, 0.433, 0.65, and 2.21, respectively.

Keywords: dairy; exergy; spray drying; carbon dioxide emission

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1. Introduction

Food production, which consists of many stages including agriculture and food processing, is one of the sectors with the highest energy consumption and includes several energy-intensive and/or low-efficiency processes. The most remarkable processes are the evaporation and drying applied for food preservation. While evaporation is employed to obtain concentrated liquid foods and drying is applied to produce solid foods, both are based on the removal of water via transferring latent heat. The energy consumption of these processes is estimated to constitute 15–25% of the total energy consumption in developed countries, and the most energy-intensive method among them is spray drying after freeze drying [1]. The major food sector using spray dryers is the dairy sector, and it was reported that evaporation and powder production in a typical German dairy plant consumed 32% of the total electricity and 58% of the total thermal energy. Similar values were obtained for the Dutch and Irish dairy industries [2–4]. The dairy sector uses spray dryers in the production of dairy powders; dairy powder production increased by an average of 2.2% annually between 2000 and 2018, and the total dairy powder production reached 12 million tons [5].

As governments are currently implementing incentive policies for developing sustainable agricultural and food production practices, studies carried out to improve food production systems' sustainabilities by identifying the irreversibilities are gaining importance, and exergy analysis is one of the most effective tools for this purpose [6].

The applications of exergy analysis in the scientific literature for food production systems can be evaluated in three main groups: (i) a specific operation/instrument analysis, (ii) a specific product/factory analysis, and (iii) the overall production process including the primary (agriculture) and secondary (food production) stages. In the operation/instrument analyses, the experimental data (usually instantaneous data) obtained from the equipment are evaluated to realize the locations and dimensions of the exergy losses/destructions. Although there are many different studies conducted using this approach in the literature, most of them focused on the drying process and dryers [7]. However, studies on the exergetic evaluation of spray-drying systems are relatively rare [8–11].

In product/factory analyses, data based on the average of a certain period are obtained from a production line consisting of many operations/instruments, and the performance of each component is evaluated after separating the production line into main components. In this context, most studies in the food production sector have been published regarding the products/factories of the dairy sector [12–18].

In overall production process analyses, the exergetic performance of the food production process was calculated starting with the primary production of the food material (agricultural stage) and ending with the packaging of the final product. With this approach, cumulative exergy analysis methods are used to assess the system performance, and all the energy sources, whether renewable or not, are evaluated. However, these studies are relatively new and few exist in the literature [19–22]. While vegetable oil (olive oil, sunflower oil, and soybean oil), flavored yogurt, bread, and tea (black tea, instant tea, and ice tea) productions were examined in these studies, there is a need to increase the number and variety of studies in this scope for other specific products. Additionally, in related studies, performance parameters were not applied to evaluate the sustainability of the process as a result of cumulative exergy consumption.

In recent years, animal-based food production has been questioned and its environmental impact has been widely discussed. In this study, the energy needs in the primary and secondary production stages of an animal-derived powder (whole milk powder (WMP)), in which one of the most energy-intensive unit operations (spray drying) is also used, are compared and evaluated. This study is the first study conducted with this approach and in this context for dairy powders. Moreover, the exergy use, carbon dioxide emission, exergy efficiency, cumulative degree of perfection, renewability indicator, exergetic improvement potential, and exergetic sustainability index in the production of WMP are investigated. This study also examines how the process is affected in the case of replacing fossil fuels with renewable alternatives and benefiting from pasture feeding. With these calculations, a thermodynamic analysis of WMP production is performed, the environmental effects based on CO_2 emissions are examined, and suggestions are made for more sustainable production.

2. Methodology

2.1. Whole Milk Powder Production

The production of WMP was designed and evaluated in the present study. The overall system was separated into two main parts: raw milk production (dairy farm stage) and powder production (dairy factory stage). The WMP production was designed with a 1 ton/h production capacity. Mass balances were established, not only based on general mass flows but also based on dry matter and fat content for the overall system and each part of the production system.

The raw milk is obtained as a result of livestock activities on a dairy farm. The raw milk requirement for one ton/h of WMP production was 7956.7 kg/h and the amount of feed required for this was 8571.8 kg/h. A detailed analysis of the dairy farm operations was performed by Koknaroglu (2010). The data obtained in that study were converted to an hourly basis and used in the present study [23]. In this raw milk production process, an average of 134.5 kg/h of diesel fuel was consumed, and an average of 71 kg/h of calves was obtained with 540 kg/h of organic manure [20,23]. The input and output streams for raw milk production in the dairy farm are shown in Figure 1.

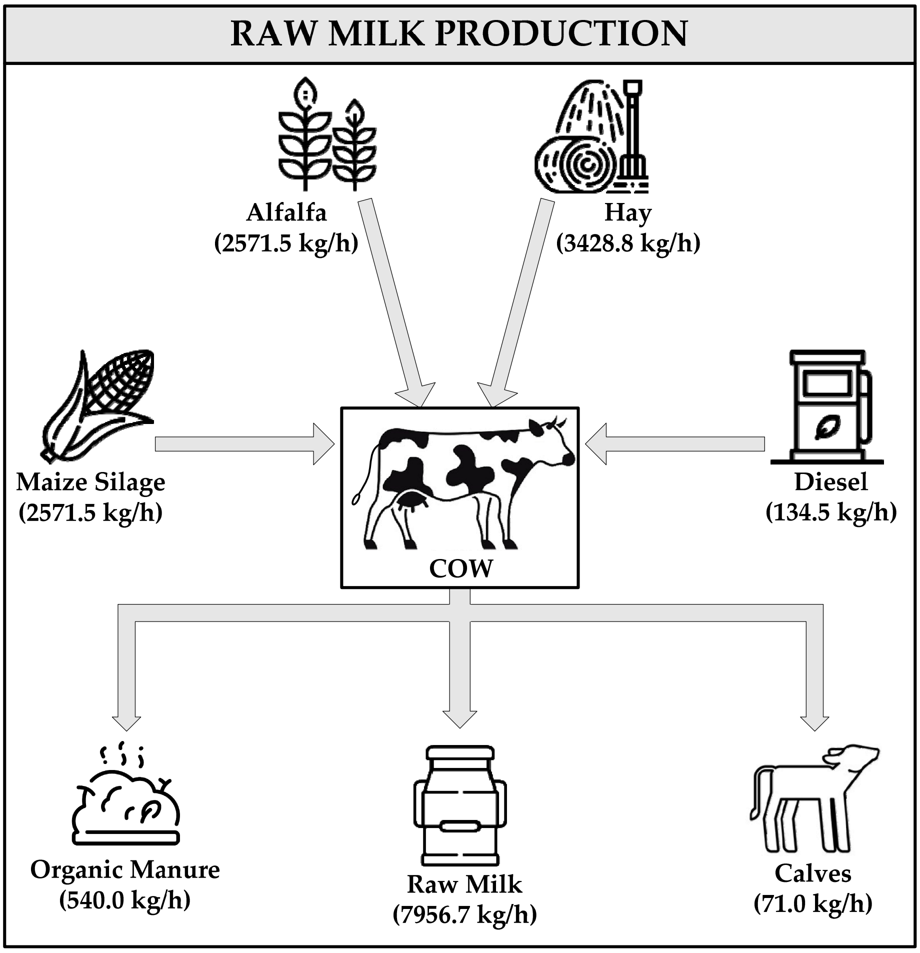

Figure 1. Input and output streams for the raw milk production in a dairy farm.

The raw milk is converted to powder in a dairy factory. The flow chart for the processing of raw milk to produce WMP in a dairy factory is given in Figure 2. The flow streams and their mass flow rates were calculated according to 1 ton/h WMP production capacity. For 1 ton/h of WMP production, 7956.7 kg/h of raw milk needs to be processed, and the raw milk composition properties were determined according to values in the literature [24]. The raw milk accepted for production in the dairy factory was first cleaned via a clarifier, and 0.1% (v/v) of the raw milk was separated as sludge. It has been accepted that sludge contains 0.3% fat and 15% dry matter [25]. Clarified raw milk with 4% fat content was standardized to 3.57% fat content in the cream separator. During the standardization, 108.75 kg/h of cream with 35% fat content was obtained as a by-product [26]. The standardized milk was pasteurized in a plate heat exchanger pasteurizer and the vegetative forms of pathogenic microorganisms in the raw milk were killed. Subsequently, the pasteurized milk was concentrated to 48% dry matter in the evaporator [27]. Afterward, the concentrated milk was homogenized and fed into the spray dryer to produce 1 ton/h of WMP with 28% fat and 98% dry matter content. The produced WMP was packaged in 25 kg kraft packages. The weight of each kraft package was 0.6 kg, and it was assumed that 8.3% polyethylene was used in its production. The calculated/accepted composition of the products used within the scope of the present study is listed in Table 1.

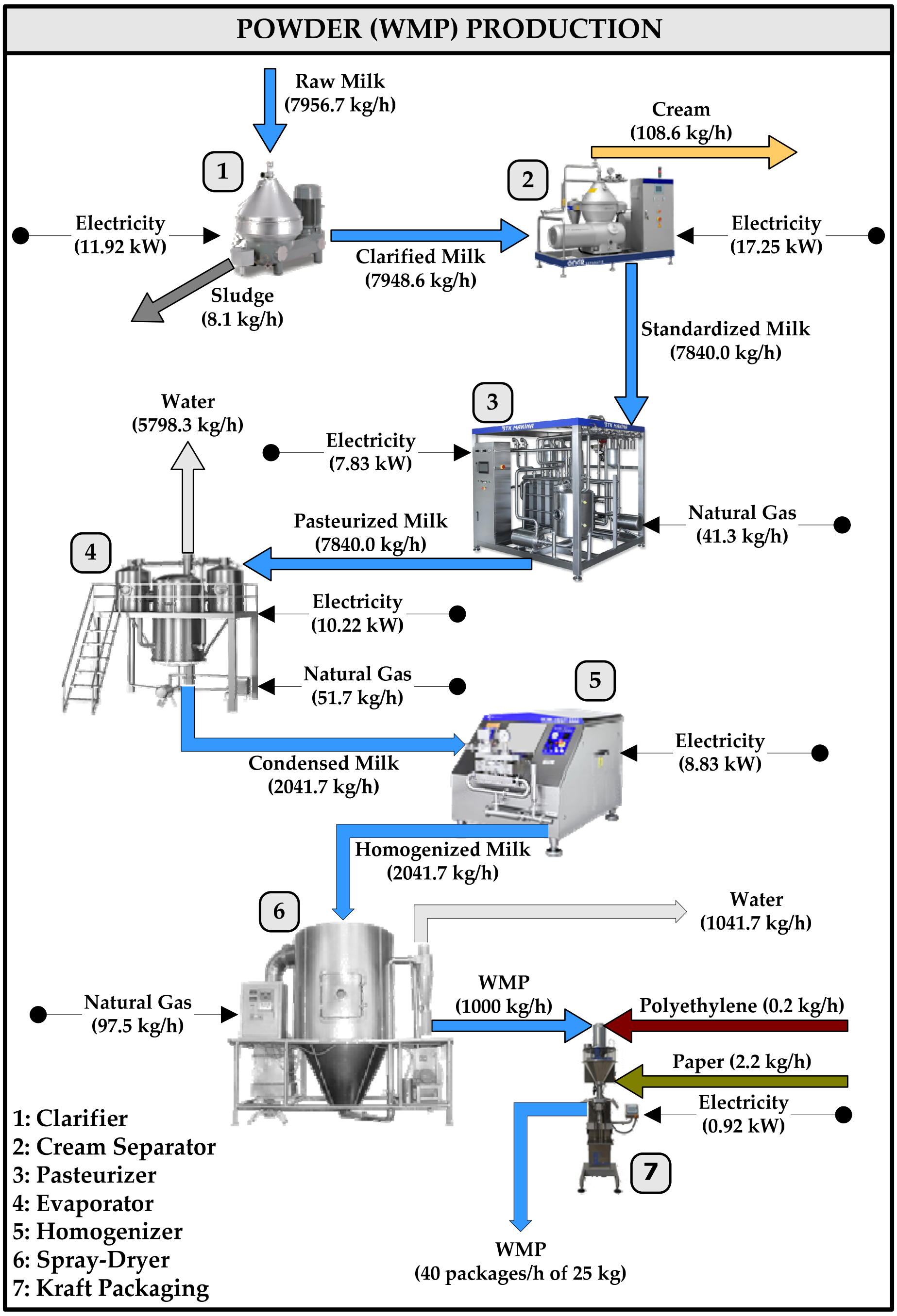

Figure 2. Input and output streams for whole milk powder production in a dairy plant.

Table 1. Composition of the products used in the calculations.

Performance Parameter	Carbohydrate	Protein	Fat	Ash
Raw Milk	4.65	3.37	4.00	0.82
Sludge [1]	5.25	5.00	0.30	4.45
Clarified Milk	4.65	3.37	4.00	0.82
Cream	1.45	0.69	35.28	0.10
Standardized Milk	4.69	3.41	3.57	0.83
Condensed Milk	18.02	13.08	13.71	3.18
Whole Milk Powder	36.80	26.70	28.00	6.50
Organic Manure [20]	60	12	5	9
Calves [20]	5	19	3	2

[1] Waste removed from raw milk during the clarification process.

2.2. Cumulative Exergy Consumption Method

Production processes differ greatly in their energy use and energy-saving potential depending on the inputs used. In this study, a performance analysis was undertaken by including all the components of whole milk powder production, including the agricultural and industrial processes, to provide a holistic approach. For this purpose, the cumulative exergy consumption was analyzed. The cumulative exergy consumption approach is an important technique used to determine the saving potential of the inputs used in food production processes. As the term exergy means useful work potential, the efficiency of the energy used in any process can be determined numerically using exergetic assessments [22,28]. In studies focused on the performance of food and agricultural production, the quality of the inputs and the conversion process have generally been neglected. In this regard, exergy analysis is of importance as an approach to be applied for decision-making toward sustainable and energy-efficient food production [29,30]. As a result, the methodology used in this study allowed a thorough evaluation of the whole milk powder production process. Moreover, different scenarios (renewable energy and pasture use) were implemented parametrically via numerical calculations within the scope of increasing the performance.

Exergy accounting methods have been developed by Szargut et al. (1988) and the concept of cumulative exergy consumption (CExC) has been defined [31]. The concept was developed to measure the total exergy consumption degree, including the fuel resources and raw materials, during the manufacture of a specific product. In a production flow chart, all the streams have CExC values, which are expressed by calculating the exergy rate (Ex) of the stream per unit mass (m) of the final product [32]:

$$\mathrm{CExC} = \frac{\sum \mathrm{Ex}}{m} \tag{1}$$

As a general approach in the calculation, the proportion of exergy to the heating value is used to calculate the exergy of the energy resources and/or fuels, whereas the chemical exergy is calculated for raw materials and manufactured products [6]. In the literature, standard chemical exergy values have been defined for substances in general. In addition, chemical exergy refers to the maximum amount of work at the end of the process, depending on the initial state of any process.

Specific energy and exergy consumption and specific carbon dioxide emissions of all the inputs for the production of WMP are listed in Table 2.

Table 2. Specific energy and exergy consumption and specific CO_2 emissions of all the inputs for the production of WMP.

Input Type	Inputs	Specific Energy Consumption	Specific Exergy Consumption	Specific CO_2 Emission
Renewable	Alfalfa	1.59 MJ/kg [33]	7.90 MJ/kg [34]	0.240 kg/kg [35]
	Maize Silage	2.33 MJ/kg [33]	7.90 MJ/kg [34]	0.060 kg/kg [35]
	Hay	2.77 MJ/kg [33]	7.90 MJ/kg [34]	0.140 kg/kg [35]
Non-Renewable	Diesel Oil	41.8 MJ/kg [36]	44.7 MJ/kg [36]	3.180 kg/kg [37]
	Electricity	1.00 MJ/MJ [20]	4.17 MJ/MJ [20]	0.173 kg/MJ [38]
	Natural Gas	50.1 MJ/kg [36]	52.1 MJ/kg [36]	0.050 kg/MJ [38]
	Polyethylene	8.53 MJ/kg [39]	86.0 MJ/kg [40]	0.450 kg/kg [20]
	Paper	12.1 MJ/kg [41]	34.6 MJ/kg [41]	0.300 kg/kg [42]
Products	Carbohydrate	-	17.5 MJ/kg [43]	-
	Protein	-	25.4 MJ/kg [43]	-
	Fat	-	39.6 MJ/kg [43]	-
	Ash	-	1.006 MJ/kg [44]	-
	Water	-	0.53 MJ/kg [44]	-

The CExC term involves the total exergy cost of the heat transfer, work, raw materials, and transportation, and was associated with an ecological cost by Szargut et al. [31]. However, the net exergy consumption cannot be represented in this term. Therefore, the net exergy consumption (CNEx) term is suggested to take the exergy of the final product into account and to present more significant results [45]:

$$\text{CNEx} = \text{CExC} - \text{Ex}_{\text{product}} \tag{2}$$

where $\text{Ex}_{\text{product}}$ is the desired output resulting in each component or process for which the CExC is calculated.

2.3. Performance Parameters

In this study, the CExC values were calculated for each stream in the production of WMP. The exergetic performance of the WMP production was evaluated using various parameters. The exergy efficiency (ε) and cumulative degree of perfection (CDP) were calculated as follows:

$$\varepsilon = \sum \text{Ex}_{\text{products}} \Big/ \sum \text{Ex}_{\text{fuels}} \times 100 \tag{3}$$

$$\text{CDP} = \text{Ex}_{\text{product}} \Big/ \left(\sum \text{Ex}_{\text{raw materials}} + \sum \text{Ex}_{\text{fuels}}\right) \tag{4}$$

The ratio of total exergy output to total exergy input is expressed as the exergy efficiency. Generally, "*output*" represents the "*desired value*" or "*product*", whereas "*input*" represents "*used*" or "*fuel*". Therefore, exergy efficiency is also defined as the ratio of the exergetic products/benefits to the exergetic fuels. CDP is the proportion of the chemical exergy of the final product and the overall input exergy streams, including the raw materials and fuels consumed during production. In the present study, CDP was calculated for the final product (packaged WMP), whereas exergy efficiency was calculated for all the products and by-products.

Recently, renewability has become an important term to define the sustainability of processes and/or sources. When non-renewable resources are degraded during the processes of energy cycles, work is needed to restore these degraded non-renewable resources. This consumed work, which is named restoration work (W_r), should be considered in measuring/determining the extent of the renewable character of the overall process. If the useful work obtained from an energy source is larger than the work consumed to restore, that energy source can be expressed as renewable. Based on this statement, a renewability indicator (I_r) is proposed, as follows [46]:

$$I_r = \left(\text{Ex}_{\text{product}} - W_r\right) \Big/ \text{Ex}_{\text{product}} \tag{5}$$

where W_r represents the non-renewable fuels consumed during the production processes. The highest I_r values should be aimed for, whereas theoretically, it is not possible to obtain an I_r value higher than 1. If $I_r < 0$ for a process, this means that more than the useful work produced is consumed for restoration purposes, and the process is defined as a "non-renewable process". In other words, according to the value of I_r, the process can be defined in four ways:

(i) if I_r is less than 0, the process is defined as a non-renewable process.
(ii) if I_r equals 0, the process is defined as equal to restoration work.
(iii) if I_r is between 1 and 0, the process is defined as partially renewable.
(iv) if I_r is greater than 1, the process is defined as a fully renewable process.

The maximum potential for the improvement of the system was calculated in the present study according to the method described by Van Gool [47]. The highest improvement potential means that there is a remarkable inefficiency and/or irreversibility in the system. To decrease the improvement potentials in the system, the maximum exergy efficiency with a minimum exergy loss or irreversibility should be obtained. Van Gool defined this term as the exergetic improvement potential (IP) rate and calculated it as follows:

$$IP = (1 - \varepsilon)\left(\sum Ex_{fuels} - \sum Ex_{products}\right) \tag{6}$$

Moreover, the waste exergy ratio (WER), environmental effect factor (EEF), and exergetic sustainability index (SI) values were calculated as described by Midilli and Dincer [48] to examine the sustainability degree of the WMP production:

$$WER = \sum(Ex_{loss} + Ex_{destruction}) \Big/ \sum Ex_{fuels} \tag{7}$$

$$EEF = \sum(Ex_{loss} + Ex_{destruction}) \Big/ \sum Ex_{products} \tag{8}$$

$$SI = \sum Ex_{products} \Big/ \sum(Ex_{loss} + Ex_{destruction}) \tag{9}$$

In the present paper, the exergy loss and destruction rates were calculated together as a single term.

2.4. Evaluating Different Scenarios: Use of Renewable Energy and Pasture Feeding

In this study, a WMP production process was evaluated using the cumulative exergy analysis approach. The system under examination was referred to as the "actual process". Additionally, a modified system was designed, in which the energy requirements were met through the use of renewable resources instead of fossil fuels. This modified system was named the "renewable energy" system, and its impact was evaluated. It was assumed that biodiesel would be used in place of diesel and natural gas and that electricity would be generated from hydraulic sources. The specific exergy consumption of biodiesel was assumed as 8.8 MJ/kg [49], and that of hydroelectricity was 0.006 MJ/MJ [46]. Additionally, alternative approaches were evaluated in terms of feed production/consumption, which is determined to be the main consumption in the overall WMP production. According to the literature, approximately 15% of the exergy consumption for the production of feeds such as wheat, gluten, and soy protein concentrate resulted from fossil fuels (15% was electricity, 20% was natural gas, and the remainder was diesel) [44]. Furthermore, it is stated in the same literature that 10% of the consumption arose from irreversible agricultural chemicals (agrochemicals) and chemical fertilizers [44]. Based on these values, the use of biodiesel and hydroelectricity in feed production is assumed. The results obtained after replacing fossil fuels with renewable alternatives are presented in the scenario named "renewable energy" in the present study.

Since a significant impact of primary production on the total consumption was detected, the case of "pasture feeding" as an alternative animal feeding approach in the primary production process and its effect on the performance was evaluated as another scenario. It has been reported in the literature that by adjusting the ratio of pasture in an animal's diet, the energy intensity in milk production can be improved by up to 17% [50]. In order to achieve this reduction in energy consumption, it was assumed that 25% of the feed used in raw milk production could be saved through pasture feeding, and the WMP production process was reanalyzed under these conditions.

3. Results and Discussion

In the present study, WMP production was analyzed as the actual process, and two more scenarios ("renewable energy" and "pasture feeding") were evaluated to discuss and compare the weight of the different stages in an animal-based production process according to the energy/exergy balance and carbon dioxide emissions. In this sense, the dairy sector is one of the most important animal-based food production sectors, and dairy powders are some of the most important processed foods in this sector. Therefore, this study focused on whole milk powder production, including the agricultural and industrial stages. The overall system was separated into two main parts: raw milk production and powder production.

3.1. Dairy Farm Stage: Raw Milk Production

In a dairy farm, energy is consumed for animal feeding, care, and welfare; milking practices; the comfort of the barn/environment; and transportation purposes. In addition to milking from livestock, calves are also obtained and incorporated into the production cycle. Moreover, organic manure is obtained from the animals and utilized as a by-product.

In animal husbandry, maize silage and alfalfa are the leading forage crops. In particular, maize silage is vital for the energy needs of animals, and alfalfa plays an important role in their crude protein needs. Moreover, hay (mainly from wheat and barley) is widely used in Turkey. Therefore, it was assumed that the animal feed consisted of 30% alfalfa, 30% maize silage, and 40% hay [51].

The results show that 1661.9 kg of carbon dioxide emissions, 25,198.6 MJ of energy, and 73,728.1 MJ of exergy consumption were calculated during raw milk production. As shown in Figure 3, most of the consumption and emissions occurred in the raw milk production stage, and the highest values stemmed from the feed. Amounts of 77.7% of energy consumption, 91.9% of exergy consumption, and 74.3% of carbon dioxide emissions calculated in the raw milk production arose from the feed. The dairy feed calculations are based on the entire feed production process, and it was observed that energy, exergy, and CO_2 consumption related to dairy feed are remarkable. These results reveal that the basic input in milk production is the feed and the importance of reducing consumption in feed production processes. Sainz (2003) reported that feed was the largest component of the total energy consumption (in the range of 40–78%) in different animal production systems, including poultry meat, eggs, swine, dairy, beef, and sheep, and feed in the raw milk production process had the highest ratio [33]. Similarly, Koknaroglu (2010) calculated that 76.9% of the total cultural energy expenditure was expended on feed for a dairy farm [23].

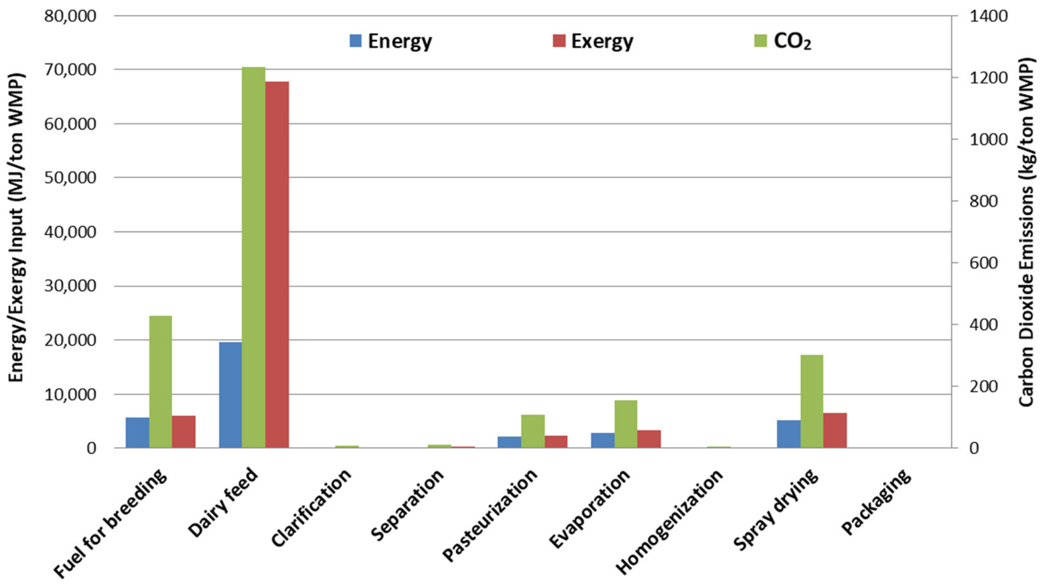

Figure 3. Comparison of the energy and exergy inputs (MJ/ton WMP) and carbon dioxide emissions (kg/ton WMP) in the overall WMP production.

3.2. Dairy Factory Stage: Powder Production

The equipment used in production, according to the projected production capacity, was determined by market research conducted in Turkey. The production line consists of a milk clarifier (capacity = 12 ton/h, power utilization = 54 MJ/h, Sait 350 TXL model, Oner Separator, Adana, Turkey), a cream separator (capacity = 7.5–10 ton/h, power utilization = 79.2 MJ/h, Powerplus 400CXL model, Oner Separator, Adana, Turkey), a pasteurizer (capacity = 10 ton/h, power utilization = 36 MJ/h and 800 kg/h vapor, S-ST033 model, STK Makina, Sakarya, Turkey), an evaporator (capacity = 10 ton/h, power utilization = 180 MJ/h and 1000 kg/h vapor, STK Makina, Sakarya, Turkey), a homogenizer (capacity = 12.5 ton/h, power utilization = 194.4 MJ/h, Hommak N-HM100 model, STK Makina, Sakarya, Turkey), a spray dryer (capacity = 1 ton/h, power utilization = 324 MJ/h and 130 m^3/h natural gas, Sütaksan, Sakarya, Turkey), and a packaging unit (capacity = 4 bag/min, power utilization = 19.8 MJ/h, VBF-1 model, Esit, İstanbul, Turkey).

As mentioned previously, the energy and exergy input rates and carbon dioxide emissions during the overall process are shown in Figure 3. However, since the values were very high in the primary production stage, the differences arising from the processes applied in the secondary production stage cannot be seen clearly. Therefore, the energy and exergy input rates and carbon dioxide emissions in the secondary production stage (WMP production) are separately presented in Figure 4. As seen in Figure 4, spray drying stands out as the most energy-intensive process, followed by evaporation and pasteurization. In these three processes, 98.3% of the total energy consumption, 94.6% of the total exergy consumption, and 95.7% of the total carbon dioxide emissions in the secondary production were realized. The energy consumption for spray drying was 5208.7 MJ, in exergy consumption it was 6430.8 MJ, and for carbon dioxide emissions it was 300.3 kg. The energy consumption, exergy consumption, and carbon dioxide emission values were 2728.6 MJ, 3279.3 MJ, and 153.8 kg for the evaporator and 2098.2 MJ, 2270.3 MJ, and 108.4 kg for the pasteurizer. Similar results were reported in the literature [2,52].

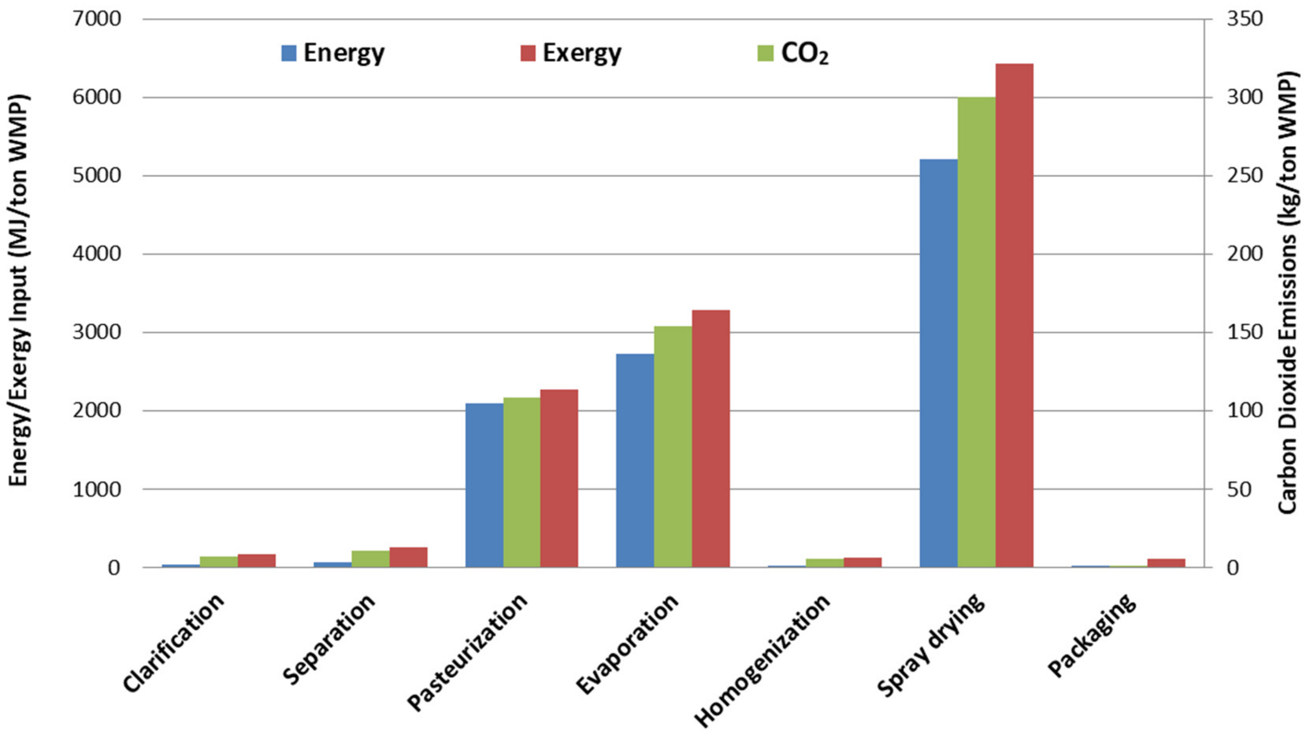

Figure 4. Comparison of the energy and exergy inputs (MJ/ton WMP) and carbon dioxide emissions (kg/ton WMP) in the powder (WMP) production for a dairy plant.

Generally, processes based on the removal of water via evaporation are energy-intensive processes as latent heat must be provided during each process. In the drying processes, especially when the moisture content of the product decreases and the liquid and/or vapor diffusions due to the moisture concentration difference and internal conditions become the dominant diffusion mechanism, the energy consumption increases exponentially. In spray drying, the liquid feed entering the dryer leaves the dryer in powder form with a water content of less than 10% for food powders (less than 5% for WMP). As a result, the spray drying process has been the most energy-intensive process in the secondary production stage. While process optimization is very important to increase the energy efficiency in spray dryers [53], it is possible to recover energy and exergy by returning the exhaust air discharged from the system to the environment [54,55]. Accordingly, it is necessary to develop designs in which the exhaust air can be fed back to the system through filters or used to heat the inlet air by employing a heat exchanger. In this way, it has been shown in studies that 9.6–12.4% of the exergy used in the system can be recovered [56].

In evaporators and pasteurizers, the prominent components are the heat exchangers. Irreversibilities in the heat exchangers can occur due to the temperature differences between the fluids, pressure losses, flow imbalances, and heat transfer with the environment [57]. In the present study, a plate heat exchanger was used in the pasteurization process, and the design of the number of plates considering the exergy consumption and exergoeconomic limitations may be important to decrease the irreversibilities.

3.3. Performance of the Actual Process

The scenario for the examined process conditions was named the "actual process", and the performance parameters calculated are listed in Table 3. It can be seen that the exergetic efficiency of the overall production process was 40.5% and the CDP was 0.282. The I_r value was calculated as −0.22, and it was observed that the WMP production under the examined conditions should be evaluated as a "non-renewable process". The IP rate for the overall production process was 30,594.5 MJ and the SI value was 0.68.

Table 3. Performance parameters calculated for the overall WMP production for different scenarios.

Performance Parameter	Actual Process *	Renewable Energy	Pasture Feeding
ε (%)	40.5	52.1	68.9
Non-Renewable Fuel (MJ)	29,869.2	10,226.0	8533.1
CDP (-)	0.282	0.330	0.433
I_r (-)	−0.22	0.58	0.65
WER (-)	0.60	0.48	0.31
EEF (-)	1.47	0.91	0.45
SI (-)	0.68	1.10	2.21
IP (MJ)	30,594.5	15,119.4	4926.6

* The terms "actual process", "renewable energy", and "pasture feeding" are used to express the calculations using actual data, using only renewable energy sources, and using pasture feeding in animal husbandry, respectively.

It has been observed that the CExC values in the overall production process are mostly formed during raw milk production. The CExC value in raw milk production constitutes 85.3% of the total consumption at 73,728.1 MJ. According to the CNEx values (calculated by taking into account the products formed during the production process), this rate decreases to 68.3% with a value of 35,106.6 MJ. It was clearly shown that energy and exergy are consumed most intensively in the agricultural stage of the production process (in raw milk production). Similar results were obtained in the literature and suggest reducing the CExC values by applying good agricultural practices and by replacing fossil fuels with renewable alternatives [19–21].

3.4. Renewable Energy Sources and Pasture Feeding

Apart from the “actual process” conditions, two more scenarios (“renewable energy” and “pasture feeding”) were evaluated in the present study. The first solution (the scenario named “renewable energy”) to increase efficiency and sustainability in the overall WMP production process under current technological conditions involves replacing fossil fuels with renewable alternatives. In this context, replacing diesel and natural gas consumed in the overall WMP production process with biodiesel and generating electricity from hydraulic sources were evaluated. Moreover, the utilization of biodiesel and hydroelectricity in the feed production was assumed. The second approach (the scenario named “pasture feeding”) involved using “pasture feeding” to increase efficiency and sustainability in the animal husbandry stage and observing the impact on milk production on the dairy farm.

The results were presented by dividing the WMP production process into two stages: raw milk production and powder production. Raw milk production (first stage) includes activities on the dairy farm, while powder production (second stage) includes operations in the dairy factory. In this sense, the production in the first stage constitutes the raw material of the second stage. According to the results, the consumption values for WMP production can be significantly reduced by using renewable energy sources, such as biodiesel and hydroelectricity, in the production process (Table 3 and Figure 5). The use of renewable energy sources instead of fossil-based renewable energy sources in production processes makes production processes more sustainable. The inclusion of renewable energy sources in production processes makes the production process more environmentally friendly [58–61]. With the use of renewable energy, the CNEx value in the raw milk production process was reduced by 24.9%, whereas the CNEx value in powder production decreased by 66.8% (Figure 5). In the “renewable energy” conditions, 83.0% of the total CNEx was accumulated in raw milk production. In the case of the “renewable energy” state, the exergetic efficiency of the overall production process increased to 52.1%, and the CDP increased to 0.330 (Table 3). In addition, WER, EEF, and SI values were calculated by exergy analysis within the scope of the second law of thermodynamics, and the WER, EEF, and SI values were calculated based on the exergy losses and destructions. Based on the fact that any process with low exergy losses and destructions leads to a more environmentally friendly and more sustainable process, an increase in the SI along with a decrease in the WER and EEF values are desired. While the SI value increased to 1.10, the IP rate decreased to 15,119.4 MJ. The results show that the I_r value became positive and reached 0.58, and the overall process could be defined as “partially renewable”. The SI calculations for agriculture and food production processes are rare in the literature. According to the literature, the SI values of a pilot-scale spray dryer used in cheese powder production were in the range of 1.50–1.89 [56], while the EEF and SI values of 1-ton apple production were calculated as 1.67 and 1.59, respectively [62].

With the application of pasture feeding in animal husbandry, a decrease of 70.4% in the CNEx values in raw milk production compared to the beginning and 60.5% according to the values calculated after the use of renewable energy sources were obtained. In this way, it was seen that 65.8% of the total CNEx values calculated in the overall WMP production were realized in the raw milk production (Figure 5). In this case, the calculated exergetic efficiency for the overall production process was 68.9%, the CDP was 0.433, the SI was 2.21, and the IP rate was 4926.6 MJ. Finally, the I_r value increased to 0.65. Briefly, it is concluded that consumption and emissions in raw milk production can be significantly reduced with pasture feeding.

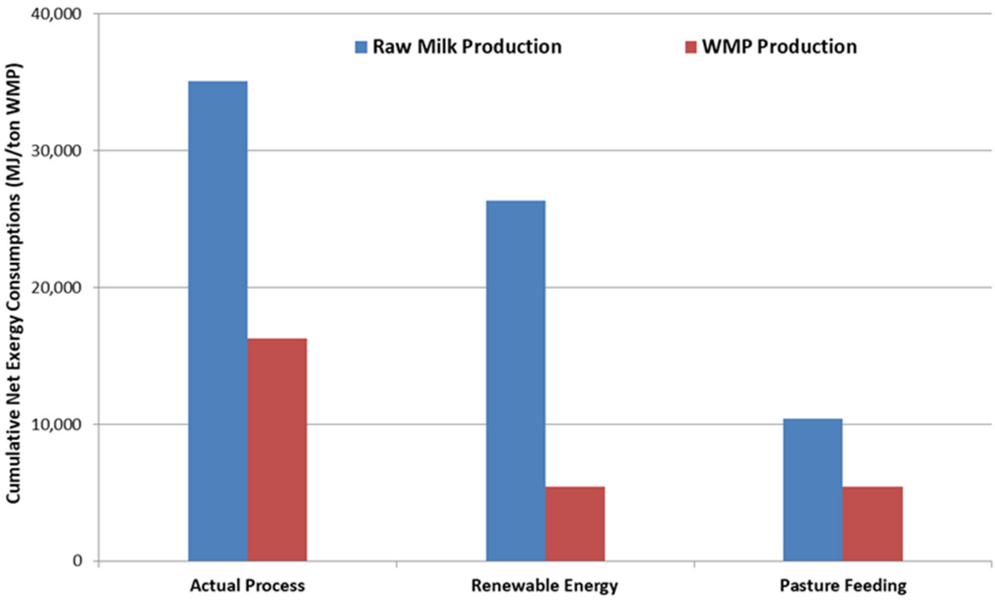

Figure 5. Comparison of cumulative net exergy consumption (CNEx) in overall WMP production for different scenarios: (actual process) for calculations based on actual data; (renewable energy) for calculations using only renewable energy sources; and (pasture feeding) for calculations using pasture feeding in animal husbandry.

4. Conclusions

In the present study, the overall WMP production, including the primary production (agricultural production stage, raw milk production) and secondary production (industrial production stage, powder production) was evaluated via the cumulative exergy consumption approach. According to the results, energy and exergy consumption and carbon dioxide emissions were dominated by the primary production stage, namely raw milk production. In the secondary production stage (powder production), the most important equipment was the spray dryer according to the cumulative exergy consumption, followed by the evaporator and pasteurizer. While the use of renewable energy sources can provide significant benefits, especially in the secondary production stage, the total CNEx values can be reduced by applying pasture feeding in animal husbandry during the primary production process.

In this study, all the processes, from the milk powder production process to the packaging processes, were examined (including the agricultural processes) with a holistic approach. Renewable energy sources are of great importance in the development of more environmentally friendly and sustainable methods in the food production processes. In this study, an analysis of the whole milk powder production process according to renewable energy and pasture feeding was conducted. The results showed that renewable energy and pasture-feeding practices have significantly improved the whole production process.

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Nomenclature

CDP	cumulative degree of perfection (-)
CExC	cumulative exergy consumption (MJ/kg)
CNEx	net cumulative exergy consumption (MJ/kg)
EEF	environmental effect factor (-)
Ex	exergy rate (MJ)
I_r	renewability indicator (-)
IP	improvement potential rate (MJ)
m	mass (kg)
SI	exergetic sustainability index (-)
W_r	restoration work (MJ)
WER	waste exergy ratio (-)
WMP	whole milk powder
Greek symbols	
ε	exergy efficiency (%)

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