ABSTRACT
Idaho was the 3rd largest milk producer in the United States in 2019, and the dairy industry remains one of the most considerable sections of the state’s economy. The dairy industry itself has many effects on the environment, and there are many opportunities within this industry to improve its environmental impact. This paper explores a dairy processing facility (under current operating norms and an improved set of operating conditions) to assess techno-economic aspects, determine the gate-to-gate environmental impacts, and identify critical process parameters. In this study, the environmental impact was determined using the life cycle assessment method to evaluate greenhouse gas emissions in kg CO₂ equivalents per kg of packaged milk. The economic assessment was performed, using a life cycle costing analysis method for estimating the net present value, payback period, and total profit of the various scenarios, as well as determining the major cost drivers to the process. The results show that the total environmental impact of 1 kg of packaged milk was between 0.0102 to 0.0125 kg CO₂ equivalents. It was also determined that the proposed adjustments to the operating conditions could reduce the heating costs by 84% and the overall annual costs by 16.3%. This study can help provide justification for further research when determining the optimum operating conditions and energy sources for dairy processing equipment and facilities. This includes investigating both real-world and theoretical models when making plans for improving dairy processes.

Keywords: Milk Production, Dairy Processing, Heat Exchangers, Greenhouse Gas Emissions, Life Cycle Assessment, Techno-Economic Analysis, Sustainability.

NOMENCLATURE
Parameters
- Bₜ: Benefits in year t in US dollars/yr
- Cₘₜ: Cooling energy in kJ/hr (Base Case)
- Cₘ₁: Cooling energy in kJ/hr (Proposed Case)
- Cₑₑ: Energy conversion factor in kWh/kJ
- Cₜ: Costs in year t in US dollars/yr
- Eₘₜ: Emissions from cooling energy in kg CO₂ eq. per kg of packaged milk (Base Case)
- Eₘ₁: Emissions from cooling energy in kg CO₂ eq. per kg of packaged milk (Proposed case)
- Eₑₑ: Emissions from electric power in kg CO₂ eq./kWh
- Eₑₑ: Emissions from fuel power in kg CO₂ eq./kWh
- Eₑₑₑ: Emissions from heating energy in kg CO₂ eq. per kg of packaged milk (fuel based, Base Case)
- Eₑₑ₁: Emissions from heating energy in kg CO₂ eq. per kg of packaged milk (fuel based, Proposed Case)
- Eₑₑₑ: Emissions from heating energy in kg CO₂ eq. per kg of packaged milk (electric based; Base Case)
- Eₑₑ₁: Emissions from heating energy in kg CO₂ eq. per kg of packaged milk (electric based; Proposed case)
E\textsubscript{R} Emissions from refrigerant losses in kg CO\textsubscript{2} eq. per kg of packaged milk
E\textsubscript{P} Emissions from packaging products and materials in kg CO\textsubscript{2} eq. per kg of packaged milk
H\textsubscript{E}\textsuperscript{0} Heating energy in kJ/hr (Base Case)
H\textsubscript{E}\textsuperscript{1} Heating energy in kJ/hr (Proposed Case)
I\textsubscript{r} Real interest rate, expressed as a percentage
NPV Net present value in US dollars
NPV\textsubscript{Bt} Net present value of benefits in year t in US dollars
NPV\textsubscript{Ct} Net present value of costs in year t in US dollars
P\textsubscript{f} Production flow in kg of packaged milk per hour
PP Payback Period in years
T Total time for financial calculation in years
t Year
T\textsubscript{ef}\textsuperscript{0} Total emissions for milk processing and packaging (electric based; Base Case)
T\textsubscript{ef}\textsuperscript{1} Total emissions for milk processing and packaging (electric based; Proposed Case)
T\textsubscript{ef}\textsuperscript{o} Total emissions for milk processing and packaging (fuel based; Base Case)
T\textsubscript{ef}\textsuperscript{1} Total emissions for milk processing and packaging (fuel based; Proposed Case)
TP Total profit in US dollars

1. INTRODUCTION
The dairy industry in the United States (U.S.) is large and produces a wide variety of products, such as yogurt, cheese, butter, cream, and milk products (skim, 1%, 2%, and whole milk). Production and consumption of milk and milk-related products are high in the U.S. and have increased over time. In 2019, the U.S. produced over 218 billion pounds of milk, and the state of Idaho produced over 15.5 billion pounds, making it the 3\textsuperscript{rd} largest producer of milk in the U.S. [1].

In recent years dairy manufacturing has experienced a trend of moving from lots of smaller plants to larger, but fewer plants with less staff. This trend towards large-scale manufacturing increases the environmental burden on smaller areas. This increases the impact of the liquid waste disposal, noise, and gas emissions in the vicinity of the plant. The production and processing of fluid milk require numerous resource inputs and environmental outputs, contributing to greenhouse gas (GHG) emissions [2]. In addition, the centralized production facilities that service large geographic areas lead to a great need for long-distance distribution chains, which also have environmental impacts due to the release of more GHG emissions [3].

A dairy processing plant has several environmental impacts, such as GHG emissions, biological waste, refrigerant chemicals, packaging, and wastewater. The Intergovernmental Panel on Climate Change (IPCC) has indicated that the risk of catastrophic climate effects increases from anthropogenic releases of GHGs [4]. Dairy plants are also highly energy-intensive as they employ several physical and thermal processes that must be controlled precisely in order to not destroy the desired products and avoid bacterial growth that would render any product produced unsafely.

Globally, there is great potential to improve the dairy plants’ operations due to the different applied technologies and practices. Xu et al. (2011) reported that there is a considerable potential for enhancing sustainability benefits through energy savings in the dairy processing industry worldwide [5]. It was estimated that there could be an annual reduction of 9-14 million metric tons carbon eq. if the specific energy consumption values of the plant could be reduced by 50-80% in half of the global dairy plants [5].

In the interest of exploring this theory, a dairy manufacturing plant was modeled, using Aspen HYSYS modeling software, and then various production settings were adjusted and optimized to see the effect on the energy needs of the plant. The changes made were then investigated to see their ultimate impacts on GHG emissions or the carbon footprint of the process.

A carbon footprint is a measure of the overall amount of carbon dioxide (CO\textsubscript{2}) and other GHG emissions associated with producing a given product [6] or service [7]. In looking at the dairy processing plant, GHG emissions are considered for various production processes and milk packaging. Besides, the environmental impacts of refrigerants are considered due to the high energy consumption and released GHG emissions. All flows were calculated in carbon equivalent units in order to effectively compare the environmental impacts of the original operation with the proposed procedure.

Sustainability assessment explores the economic, social, and environmental aspects of different operations and practices through various methods, such as life cycle assessment (LCA) [8], [9]. Particularly, environmental impacts assessment evaluates GHG emissions, water and soil contamination, and noise pollution to determine their impacts on the environment [10], [11]. Economic impacts assessment analyzes the monetary aspects of the processes. Social impacts assessment investigates the pros and cons of a product, operation, and service to the community, as well as health and safety benefits and concerns [12].

An LCA method looks at the entire process from the cradle to the grave, including upstream, midstream, and downstream segments. The upstream segment includes raw materials supply, and requires energy, tools, and machinery for collection and transportation [13]. The midstream segment includes pre-/post-operations and requires various production technologies. The downstream segment includes distribution, end use, and waste management, and requires machinery for transportation and
recycling. All these segments have several inputs (e.g., raw materials and energy) and outputs (e.g., energy loss, emissions, wastes, byproducts, and final products). The conducted LCA in this study focuses on gate-to-gate system boundary, which includes midstream segment operations throughout the dairy products life cycle. In addition, a real case study in southeast Idaho is conducted to obtain the data for the LCA, and input and output analysis, and subsequently sustainability assessment.

2. MATERIALS AND METHODS

2.1 Environmental Assessment

In this study, the environmental impacts of the liquid milk dairy process were determined, using the LCA method. Particularly, the environmental impacts (i.e., carbon footprint) of a low-pressure differential (Base Case) and high-pressure differential liquid dairy process (Proposed Case) were evaluated. LCA method has four phases: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation, which are further explained below.

Goal and Scope Definition. This study aims to conduct a sustainability assessment study to determine the GHG emissions of a liquid milk process and compare it with the proposed process with different operational configurations. Figure 1 shows the inputs and outputs, as well as the required operations for milk production and packaging. The scope of this study encompasses the gate-to-gate system boundary, focusing on the midstream operations for milk processing. Particularly, the start of the process would be when the raw milk from the dairy farm is put into the dairy processing plant’s refrigerated silos. The end of the process would be when the milk is packaged before being shipped. The upstream and downstream operations are excluded from this study, including transportation of the raw milk to the facility and final products to various distribution centers. The primary objective is to examine the environmental impacts of the production process itself, not the associated transportation effects. Different areas will have larger and smaller supply and market areas. Additionally, wastewater environmental impacts were not considered in the conducted LCA.

The processing facility was assumed to be in southeast Idaho; thus, power and waste assumptions were made from the local power and water grids. The functional unit is 1 kg of milk finished packaged product. In allocating the resources, there was an assumption of maximum production of market milk with one other side product being the whole cream. In this regard, the energy and resources for the cream were not considered in the LCA and sustainability assessment.

Data includes plant energy consumption from all sources, such as electricity and fuel, as well as refrigerant consumption and packaging materials. Assumptions were made on the amount of waste or loss in the refrigeration and packaging process streams, and the full amounts, whether they are part of materials or wastes, will be considered as contributing to the overall carbon footprint of the process. Thus, the conducted LCA herein covers raw milk receiving/storage, separation, homogenization, pasteurization, package formation, package filling, and final product storage. The transport of the milk product, distribution, and use of the product are not included.

Life Cycle Inventory. In order to determine the GHG emissions, the data was obtained from prior studies and OpenLCA databases for two main streams, which are (i) the raw milk process and (ii) the packaging process (Figure 2). The required equipment and tools for raw milk processing include: (a) large refrigerated tanks for storage, (b) separator for milk and cream separation, (c) homogenizer for homogenization, and (d) pasteurizer for pasteurization. The required equipment and tools for the packaging process are: (a) HDPE plastic blower for package formation, (b) fillers for cream and milk for package filling, and (c) large refrigerators for the storage of packaged materials. The inputs for raw milk and packaging processes include:

- Storage: raw milk, refrigerant, and electricity
- Milk and cream separation: raw milk, electricity, and water
- Homogenization: separated milk and electricity
- Pasteurization: homogenized milk and separated cream, and electricity
- Package formation: HDPE plastic and electricity
- Package filling: processed milk and cream, packaging, lids, and electricity

![Figure 1: BLOCK DIAGRAM OF INPUTS AND OUTPUTS FOR LIQUID MILK PROCESSING PLANT](image-url)

* PLANT SERVICES INCLUDE CLEANING, LIGHTENING, HVAC, REFRIGERATION, AND BOILING
Figure 2: PROCESS FLOW FOR MILK AND CREAM PRODUCTION WITH GATE-TO-GATE SYSTEM BOUNDARY

- Storage: packaged milk and cream, electricity, and refrigerant

  The outputs for raw milk and packaging processes include:
  - Storage: raw milk and refrigerant loss/waste
  - Milk and cream separation: milk, cream, wastewater, and biological waste
  - Homogenization: homogenized milk
  - Pasteurization: pasteurized milk and cream, and GHGs
  - Package formation: plastic containers for milk and cream, waste HDPE materials
  - Package filling: packaged milk and cream, waste formed HDPE containers, and lids
  - Storage: packaged milk and cream, and refrigerant

  Life Cycle Impact Assessment. In this study, OpenLCA GaBi Food and Feed database was used to provide information for the milk and cream processing [14]. For the packaging process, OpenLCA, ELCD Database 3.2 was used, and the Ecoinvent 3.2 LCIA methods were applied for conducting sustainability assessment. In this study, the packaged milk is considered as the primary product, and all inputs and outputs will be measured in terms of kilograms of milk packaged. Cream is a secondary product produced from the milk, and energy and packaging materials are allocated based on the assumption that there is approximately 40g of cream produced per kg of packaged milk [15]. Additionally, the impact category for environmental impacts assessment is determining the global warming potential impacts in 50 years (GWP50). Particularly, the required energy (e.g., electricity) for heating along with raw materials for the packaging in these processes are calculated to estimate the released GHG emissions (i.e., kg of CO₂ eq. per kg packaged milk) and compare the environmental impacts of traditional and proposed processes.

  Total GHG emission for cooling is calculated using Equation (1), where \( E_{C\text{e}}^{n} \) is GHG emissions from cooling energy used and \( C_{\text{e}}^{n} \) is the cooling energy value. Notations of parameters and variables are provided in the Nomenclature.

\[
E_{C\text{e}}^{n} = C_{\text{e}}^{n} / P_{f} \times C_{f} \times E_{E} \tag{1}
\]

\[
P_{f} = 10,000 \text{ kg of packaged milk/hr}
\]
\[
C_{f} = 0.0002778 \text{ kWh/kJ}
\]
\[
E_{E} = 0.669 \text{ kg CO₂ eq./kWh}
\]

Total GHG emission for heating is calculated using Equations (2) and (3), where \( H_{E}^{n} \) is the heating energy value and \( E_{\text{HE}}^{n} \) is GHG emissions from electricity-based heating energy used, and \( E_{\text{HE}}^{n} \) is GHG emissions from fuel-based heating energy used.

\[
E_{\text{HE}}^{n} = H_{E}^{n} / P_{f} \times C_{f} \times E_{E} \tag{2}
\]
\[
E_{\text{HE}}^{n} = H_{E}^{n} / P_{f} \times C_{f} \times E_{E} \tag{3}
\]

\[
P_{f} = 10,000 \text{ kg of packaged milk/hr}
\]
\[
C_{f} = 0.0002778 \text{ kWh/kJ}
\]
\[
E_{E} = 0.669 \text{ kg CO₂ eq./kWh}
\]
\[
E_{E} = 0.0022 \text{ kg CO₂ eq./kWh}
\]

Total GHG emission is calculated using Equations (4) and (5), where \( E_{C\text{e}}^{n} \) is the GHG emissions from cooling energy used, \( T_{\text{IC}}^{n} \) is total emissions from electricity-based energy used, and \( T_{\text{IP}}^{n} \) is total emissions from fuel-based energy used.

\[
T_{\text{IC}}^{n} = E_{C\text{e}}^{n} + E_{\text{HE}}^{n} + E_{R} + E_{P} \tag{4}
\]
\[
T_{\text{IP}}^{n} = E_{C\text{e}}^{n} + E_{\text{HE}}^{n} + E_{R} + E_{P} \tag{5}
\]

\[
E_{R} = 0.0001 \text{ kg CO₂ eq./kg packaged milk}
\]
\[
E_{P} = 0.0054 \text{ kg CO₂ eq./kg packaged milk}
\]

2.2 Economic Assessment

The economic assessment was performed, using a life cycle costing (LCC) analysis method. The assessment presented here evaluates the net present value (NPV), payback period (PP), and total profit (TP) of the various scenarios to determine the largest cost contributors to the process. The scope includes the initial investment, including raw material costs, annual operating costs, packaging material costs, and utility/resource costs, such as refrigerant, water, and electricity and/or fuel, depending on the
case. It also included a final demolition of the facility. For the economic case studies, a 10-year life cycle was chosen (Table 1). The data for conducting LCC inventory was obtained from prior studies [1], [16], [17].

### Table 1: LIFE CYCLE COST INVENTORY

<table>
<thead>
<tr>
<th>Stream</th>
<th>Cost ($/yr)</th>
<th>Benefit ($/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dairy Plant (Initial Investment)</td>
<td>3,618,355</td>
<td></td>
</tr>
<tr>
<td>Destruction</td>
<td>150,000</td>
<td></td>
</tr>
<tr>
<td>Operation</td>
<td>1,957,300</td>
<td></td>
</tr>
<tr>
<td>Packaging Materials</td>
<td>2,272,845</td>
<td></td>
</tr>
<tr>
<td>Raw Milk</td>
<td>28,292,821</td>
<td></td>
</tr>
<tr>
<td>Refrigerant (R-134a)</td>
<td>2,350</td>
<td></td>
</tr>
<tr>
<td>Wastewater (Base)</td>
<td>12,476</td>
<td></td>
</tr>
<tr>
<td>Wastewater (Proposed)</td>
<td>11,261</td>
<td></td>
</tr>
<tr>
<td>Cooling Electric (Base)</td>
<td>34,004</td>
<td></td>
</tr>
<tr>
<td>Cooling Electric (Proposed)</td>
<td>27,530</td>
<td></td>
</tr>
<tr>
<td>Heating Electric (Base)</td>
<td>7,923</td>
<td></td>
</tr>
<tr>
<td>Heating Electric (Proposed)</td>
<td>7,276</td>
<td></td>
</tr>
<tr>
<td>Heating Fuel (Base)</td>
<td>1,263</td>
<td></td>
</tr>
<tr>
<td>Heating Fuel (Proposed)</td>
<td>1,160</td>
<td></td>
</tr>
<tr>
<td>Milk Product</td>
<td>62,872,936</td>
<td></td>
</tr>
</tbody>
</table>

Using the collected cost estimates and assuming a 7% interest rate, the following equations were used to calculate the NPV and PP.

\[
NPV = \sum_{t=0}^{T} \frac{[B_t - C_t]}{(1 + r)^t}
\]  

(6)

\[
PP = \frac{\mu}{(TP/C)}
\]  

(7)

\[
TP = \sum_{t=0}^{T} [NPVBt - NPVCt]
\]  

(8)

The equations used allowed for the calculation of the payback period for each of the different case studies, as well as determining the cost drivers of the process. These were used to perform economic comparisons of the various case studies.

### 3. RESULTS AND DISCUSSION

#### 3.1 Case Study

The case studies looked at a virtually modeled liquid milk processing plant placed in Idaho. The facility itself processes liquid raw milk to industry standards and then packages prior to shipment. In this case study, the main processes are receiving, storing, separating, purifying, homogenizing, pasteurizing, and packaging. The inputs include raw milk, energy, and refrigerants. The emission factors were obtained from prior studies [18], [19]. The emissions for refrigerant R-134a were obtained from the Ecoinvent value for R134a [20], [21].

The following assumptions have been made based on the obtained data and information from prior studies for conducting LCA and HYSYS modeling software for both case studies [22], [23]:

- Heating media was water heated in either an electric or gas-fired boiler
- Cooling media was an ethylene glycol and water mix (3.78%/96.22%) mass basis
- Hot water was delivered at 80°C to the process
- Cooling water mix was provided at 2°C to the process
- Production rate of 10,000 kg of packaged milk per hour
- Operating pressure entering the heat exchanger was assumed to be 400 kPa with 10 kPa drops across four stages of the heat exchanger
- 20 hr production period per day
- 350 production days in a year
- 10,000 kg of packaged milk/hr production rate

After exergy analysis on the various processes, it was found that one of the most significant opportunities for reducing energy usage is to optimize the heat exchanger performance, particularly the optimum temperatures and pressures that the heat exchanger could be run at. After testing different operating conditions and calculating the energy consumption, the following assumptions are made to improve the Base Case study:

- Operating pressure entering the heat exchanger was assumed to be 5,800 kPa
- Operating pressure exiting the third stage of the heat exchanger was assumed to be 4,800 kPa
- Operating pressure exiting the fourth stage of the heat exchanger was assumed to be 380 kPa

#### 3.2 Results and Discussion

Table 2 presents the energy used and exergy generation results from Aspen HYSYS for each operation on the Base Case and Proposed Case. The proposed assumptions created a high-pressure heat exchanger that can maximize pressure drops.

### Table 2: ENERGY USED AND OVERALL EXERGY ANALYSIS OF BASE CASE AND PROPOSED CASE

<table>
<thead>
<tr>
<th>Operations</th>
<th>Energy Usage (KJ/hr)</th>
<th>Overall Exergy Generation (KJ/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Base Case</td>
<td>Proposed Case</td>
</tr>
<tr>
<td>Cooler</td>
<td>201,700</td>
<td>163,300</td>
</tr>
<tr>
<td>Heater</td>
<td>47,000</td>
<td>43,160</td>
</tr>
<tr>
<td>Heat Exchanger Stage 1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Heat Exchanger Stage 2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Heat Exchanger Stage 3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Heat Exchanger Stage 4</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
through the product stream, and consequently improve energy usage and exergy generation results. These results were taken to calculate the released GHG emissions factors for the dairy processing plant by using either an electric or fuel energy basis. (Table 3).

**TABLE 3: RELEASED EMISSIONS (KG CO2 EQ./KG OF PACKAGED MILK) FROM MILK PRODUCTION**

<table>
<thead>
<tr>
<th>Operations</th>
<th>GHG Emissions</th>
<th>Base Case</th>
<th>Proposed Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling</td>
<td>0.0037</td>
<td>0.0030</td>
<td></td>
</tr>
<tr>
<td>Heating (Electric)</td>
<td>0.0008</td>
<td>0.0008</td>
<td></td>
</tr>
<tr>
<td>Heating (Fuel)</td>
<td>0.0024</td>
<td>0.0022</td>
<td></td>
</tr>
<tr>
<td>Total Energy (Electric)</td>
<td>0.0109</td>
<td>0.0102</td>
<td></td>
</tr>
<tr>
<td>Total Energy (Fuel)</td>
<td>0.0125</td>
<td>0.0116</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3 compares the total GHG emissions result of each process operation for milk processing. The emissions from the packaging process were by far the highest, generating 0.0054 kg CO2 eq./kg of packaged milk or approximately 50% of the total emission. This is in line with other studies where the combined emissions of the packaging were almost equivalent to the electrical emissions [19]. After the packaging process, energy (electricity and fuel) consumption for heating and cooling contributes significantly to releasing GHG emissions during the milk processing. Dairies can use either electric- or fuel-powered boilers to generate the heat they need, and the overall emissions from each step will change based on which source is used. Figure 4 shows the generated emissions, using both Base Case and Proposed Case for only raw milk processing.

When summing the total emissions from both Base Case and Proposed Case studies, the total GHG emissions from the electricity-based cases, estimated at 0.0109 and 0.0102 kg CO2 eq./kg of packaged milk, respectively. When looking at the emissions from the fuel-based cases, both Base Case and Proposed Case studies yielded 0.0125 and 0.0116 kg CO2 eq./kg of packaged milk, respectively.

**Figure 3: GHG EMISSIONS FROM EACH PROCESS IN BASE CASE (KG CO2EQ./KG OF PACKAGED MILK)**

**Figure 4: RELEASED GHG EMISSIONS FROM MAIN OPERATIONS WITHOUT CONSIDERING THE PACKAGING PROCESS (A AND B FOR BASE CASE; C AND D FOR PROPOSED CASE)**
This study based its improvements on optimizing the heat transfer of a standard dairy multi-stage heat exchanger. The results show that employing electric systems has approximately 13% less emissions than fuel power source systems. In addition, the Proposed Case is able to reduce the emissions up to 6.4%. In other studies, the largest environmental impacts come from the transportation part. By deliberately cutting out transportation step, the study examined the possibility of reducing the emissions from the milk processing plant itself. In doing this, it was found that it agreed with other studies where, transportation aside, the significant emissions came from the cooling and packaging processes [24].

The conducted techno-economic assessment investigates NPV and PP values for each case study. The overall economic trends were similar in all four cases, so an example of NPV calculations for the case studies is presented in Table 4. Results for TP and PP for each case study can be seen in Table 5.

### Table 4: NET PRESENT VALUE CALCULATIONS FOR BASE ELECTRICITY CASE STUDY

<table>
<thead>
<tr>
<th>Year</th>
<th>Benefits Sum ($)</th>
<th>Costs Sum ($)</th>
<th>NPV ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-</td>
<td>3,618,355</td>
<td>-(3,618,355)*</td>
</tr>
<tr>
<td>1</td>
<td>58,759,753</td>
<td>38,478,654</td>
<td>20,281,099</td>
</tr>
<tr>
<td>2</td>
<td>113,675,411</td>
<td>75,779,175</td>
<td>37,896,236</td>
</tr>
<tr>
<td>3</td>
<td>164,998,455</td>
<td>115,690,731</td>
<td>49,307,723</td>
</tr>
<tr>
<td>4</td>
<td>212,963,917</td>
<td>158,396,097</td>
<td>54,567,820</td>
</tr>
<tr>
<td>5</td>
<td>257,791,451</td>
<td>204,090,838</td>
<td>53,700,613</td>
</tr>
<tr>
<td>6</td>
<td>299,686,343</td>
<td>252,984,211</td>
<td>46,702,132</td>
</tr>
<tr>
<td>7</td>
<td>338,840,448</td>
<td>305,300,121</td>
<td>33,540,327</td>
</tr>
<tr>
<td>8</td>
<td>375,433,069</td>
<td>361,278,144</td>
<td>14,154,925</td>
</tr>
<tr>
<td>9</td>
<td>409,631,780</td>
<td>421,174,628</td>
<td>(11,542,848)</td>
</tr>
<tr>
<td>10</td>
<td>441,593,193</td>
<td>485,263,867</td>
<td>(43,670,674)</td>
</tr>
<tr>
<td>11</td>
<td>441,593,193</td>
<td>485,579,594</td>
<td>(43,986,402)</td>
</tr>
</tbody>
</table>

* Numbers in brackets are negative

Additionally, Pareto analysis was performed for economic assessment, which compares the major cost drivers, following 80/20 rule, 20% of the operation cause 80% of the total cost (i.e., cooling process), as shown in Figure 5.

### Table 5: TOTAL PROFIT AND PAYBACK PERIOD RESULTS FROM ECONOMIC ANALYSIS

<table>
<thead>
<tr>
<th>Case Study</th>
<th>Total Profit ($)</th>
<th>Payback Period (yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Electric</td>
<td>207,332,596</td>
<td>0.14</td>
</tr>
<tr>
<td>Base Fuel</td>
<td>207,918,039</td>
<td>0.14</td>
</tr>
<tr>
<td>Proposed Electric</td>
<td>208,064,575</td>
<td>0.14</td>
</tr>
<tr>
<td>Proposed Fuel</td>
<td>208,602,989</td>
<td>0.14</td>
</tr>
</tbody>
</table>

Several things were learned from these calculations. First, the heating energy source makes a difference as using fuel automatically dropped the heating costs in both Base and Proposed Case studies and moved it down to the lowest cost contributor. When comparing the costs of heating by electric to heating by fuel, the cost reduction for the heating was 84%. When comparing the cost reduction of Base Cases to Proposed Cases, the overall cost reduction was between 15.3%-16.3%.

When examining the economic assessment, it was found that the case that produced the overall highest TP and smallest PP was the Proposed Case, using an electricity based heating system. Overall, the changes made to the processing conditions did provide economic improvements regardless of which fuel source was used, including up to 16.3% maximum decrease in heating costs from changing the processing conditions. However, even with the changes, none of the case studies was economically feasible for a 10-year period used in this study, and all cases yielded a negative NPV (Table 6).

The assumed costs of this study were found to be comparable to other studies, taking production size into account [24], [25]. The overall costs and assumed production of this
study were found to be double that of the largest proposed facility in a study done in Vermont assessing the operational feasibility of a small-scale dairy plant [25]. That study’s production size was about half that used in this study, and the Vermont study also found that strictly liquid milk production was not economically feasible in the long run and would have a negative NPV.

**TABLE 6: NET PRESENT VALUE OVER 10 YEAR PERIOD SENSITIVITY ANALYSIS**

<table>
<thead>
<tr>
<th>Case Study</th>
<th>NPV (-50%)</th>
<th>NPV (basic)</th>
<th>NPV (+100%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base (Electric)</td>
<td>22,842,278</td>
<td>(43,986,402)</td>
<td>36,323,371</td>
</tr>
<tr>
<td>Base (Fuel)</td>
<td>22,793,048</td>
<td>(43,887,943)</td>
<td>36,500,597</td>
</tr>
<tr>
<td>Test (Electric)</td>
<td>22,780,645</td>
<td>(43,863,299)</td>
<td>36,545,184</td>
</tr>
<tr>
<td>Test (Fuel)</td>
<td>22,735,437</td>
<td>(43,772,749)</td>
<td>36,707,937</td>
</tr>
</tbody>
</table>

* Numbers in brackets are negative

In order for a strictly liquid milk production plant to be economically feasible, the production rate would need to be at least double that used in this study, such as the production rate used in a Maine study that assessed profitability measures for large-scale plants. In that study, it was found that with a plant at least double the size of the one proposed in this study, economies of scale came into play to reduce costs, and a liquid milk processing plant would become economically feasible [26]. A sensitivity analysis was performed based on this information by both halving and doubling the production rate used in this study.

Additionally, it was determined that the overall profitability was low for the proposed process in this study. The economic analysis was affected by the limited scope of the study, and further investigation is needed to see what affects the production of other dairy products would have both on the economic success, as well as the environmental impacts of the proposed case studies.

**4. CONCLUSION**

This study examined the GHG emissions generated from the milk processing, focusing on gate-to-gate system boundary, particularly when it arrives at the plant to the time it is packaged and ready for delivery. Several assumptions were made in developing the models for environmental impacts assessment (using LCA method) and sustainability improvements by changing the process parameters. The results indicate that the packaging process and energy consumption are the two major environmental drivers with approximately 50% and 41% emissions released, respectively. Four cases were examined in this study to evaluate different technologies employed by dairies, which are electric-based and fuel-based for Base Case and Proposed Case studies. All case studies generated between 0.0102 and 0.0125 kg CO2 eq./kg of packaged milk, depending on the process conditions and energy sources.

After comparing the results, the electric-based Proposed Case study reduced the most GHG emissions and environmental impacts, and part of that conclusion is based on the data used for emissions from electricity production. In many U.S. western states, this number is low, for instance, in Idaho, where this study was based much of the electricity comes from hydroelectric dams, which produces far less emissions than natural gas-fired power plants. The emission factor used in this study for Idaho is nearly 20% less than the national average. Therefore, while it could be concluded that one way to improve dairy plant emissions would be to use electric power, special attention would need to be paid to the source of the electricity. If a dairy could utilize a fuel source, such as biodiesel or biogas in their boiler, the potential emissions could also be reduced. We have also examined what the effect of changing the production conditions would have on the economic aspect of producing liquid milk. Overall, the proposed changes could produce an 84% reduction of heating costs and a maximum of 16.3% reduction in the annual variable costs of production.

Further study would be needed to see how this could impact the overall carbon footprint of the dairy. The heating and cooling media could also be investigated and optimized. While water, ethylene glycol, and R-134a were considered in this study, the amounts and operating temperatures were not optimized, and as such, there remain additional avenues of investigation. One major area this study did not investigate was the emissions from transportation, particularly for raw milk and final products delivery.

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**REFERENCES**


