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Sustainable Energy Transition toward Renewable Energies in the New Zealand Dairy Industry: An Environmental Life Cycle Assessment

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The dairy processing industry is considered as energy-intensive processes between New Zealand industries that use fossil fuels as a primary energy source which results in greenhouse gas emissions as well as raising other environmental impacts. To mitigate the environmental impacts of fossil fuels that are used in dairy processing plants, it is essential to design a pathway moving from fossil-based energies towards renewable energy sources in a transition period. To do so, Life Cycle Assessment (LCA), as a standardised approach, has been implemented to quantify the environmental profile of different products by evaluating the environmental impacts of product systems. In this paper, three impact categories are considered adopting accessible inventory databases that match the regional and local data along with ReCiPe as the life cycle impact assessment method. These impact categories are 1) human health; 2) ecosystem; and 3) resources. Each category contains subcategories; seven different-statistically discernible energy mix scenarios (moving from coal through natural gas towards biomass) assisted by Monte Carlo simulation are defined to assess environmental impacts. Furthermore, Cumulative Exergy Demand (CExD) as an aggregated criterion has been exploited to indicate the sustainability of the whole system. Results show that for a cheese production process a biomass based scenario has the lowest environmental burden impact in 13 impact categories out of 14 studied impacts. Indeed, it has the lowest CExD with 1.05×10^{-5} MJ-Eq while surprisingly natural gas based scenario has the highest environmental burden with CExD of 3.85×10^{-1} MJ-Eq followed by coal with 4.73×10^{-4} MJ-Eq.

1. Introduction

The food industry (including dairy and beverage) was the highest energy consumer between New Zealand industries in 2016 with approximate use of 49 PJ energy (Tarighaleslami, 2018). New Zealand dairy processing factories as energy-intensive plants use coal and natural gas as the primary energy source that results in emissions that raise environmental concerns. Greenhouse gasses (GHG), especially CO_2, are byproducts of the fossil fuel combustion that is used to produce the required process heat and electricity of a dairy plant. GHGs significantly contribute to climate change impacts. Therefore, it is essential to plan a sustainable transition from fossil fuels towards available renewable energy sources. Besides fossil fuel combustion, the dairy processing process itself lead to additional environmental impacts.

Life Cycle Assessment (LCA) is a commonly utilised tool to analyse environmental impacts. By definition, LCA is a holistic approach for quantifying the environmental impacts of products (ISO 1404, 2006). As it is known as a cradle-to-grave analysis, it can help to assess the environmental impacts associated with all stages of a product's life in a cycle from extraction of raw material through to transport to manufacturing factory, processing and production, distribution, use, disposal and recycling. However, each step can also be studied considering the gate-to-gate or cradle-to-gate concept (Islam et al., 2015).

LCA has been considered as a reliable tool to evaluate environmental impacts in the dairy industry. Rotz et al. (2010) studied the carbon footprint of a dairy production system through LCA. Recently, Finnegan et al. (2018) reviewed environmental LCA studies examining cheese production. They reviewed sixteen LCA studies since

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the year 2000 and the production of raw milk was consistently found to be the most significant contributor to the environmental impacts followed by processing. However, none of the studies considers energy transition for cheese processing. González-García et al. (2013) studied environmental LCA of yoghurt processing implementing Energy Cumulative Demand (CED). Due to the different varieties of yoghurt processing, they considered the process as a black box to be able to focus on the environmental impacts by the energy consumption within the plant.

An LCA approach considering Cumulative Exergy Demand (CExD) supported by Monte Carlo simulation (MCS) for statistically discernible energy mix scenarios was proposed by Ghannadzadeh (2018a). The method was implemented on the ethylene dichloride–vinyl chloride production process as well as polyol ether production process (Ghannadzadeh, 2018b) during the transition period from residual fuel oil, as a fossil fuel, to biomass, as a renewable energy source, through several energy mix scenarios. Later, the method has been successfully examined for the sustainable energy transition of a chlorine production process (Ghannadzadeh and Tarighaleslami, 2019) and a petroleum refinery (Ghannadzadeh and Park, 2018).

To fill the gap in the literature regarding the energy transition period in the dairy processing industry, this paper deals with environmental LCA study of a cheese processing process to evaluate as a representative of the dairy processing industry. Natural gas is used as a second major fuel in the New Zealand dairy industry as well as in power plants where in public perspective natural gas is known as a clean fossil fuel. Therefore, in this paper, a transition stage from coal to biomass through natural will be studied.

This paper aims to analyse an LCA approach for the environmental impacts and energy balance derived from a cheese process. To do so, an exergy-aided LCA approach (Ghannadzadeh, 2018) will be applied to a dairy processing factory. To enhance the sustainability of a dairy processing factory in an energy transition period, assessment of power generation from alternative renewable energy sources such as biomass will be presented through step-wise scenarios supported by MCS. The standard framework of LCA will be followed an inventory data on databases applying into openLCA software (openLCA, 2018), and completed using the literature and the available databases.

2. Materials and methods

Prior to the assessment, the definition of the scope of the work including process constraints and technical conventions is required. This study deals with the energy transition pathway in New Zealand’s dairy processing industry starting from fossil fuels, moving through so-called green fossil fuels (i.e. natural gas) toward renewable energy.

2.1 Inventory databases

LCA is used to estimate the environmental impacts of a cheese processing process as a representative of different processes in New Zealand’s dairy processing industry. The inventory data are taken from an accessible database of United States Department of Agriculture, USDA, that contains worldwide dairy processing inventory data including the Pacific region (USDA, 2018) in line with the United States Life Cycle Inventory (US LCI) database (NREL, 2014). ReCiPe impact assessment method is also added to connect USDA and NREL flows to the impact assessment (ReCiPe, 2014). To estimate the environmental impacts of the case study openLCA 1.7.4 (openLCA, 2018) is used.

The functional unit is specified as 1 kg cheese processing. It means the plant aims to process 1 kg cheese using 0.123 MJ electricity from the grid, 0.025689 kg coal and 9.74598 kg coal boiler, as well as 7.309×10^{-6} m^3 natural gas proceed to plant. Moreover, the environmental impacts are evaluated with the impact method specified in ReCiPe 2014 endpoint method for the “Hierarchist” perspective by means of the physical allocation method and “World ReCiPe 2014 H/H [person/year]” normalization and weighting set (Ghannadzadeh, 2018a).

2.2 Scenario definition

A wide range of energy resources can be considered to mix in order to meet the final energy demand of the process. However, as the transition period is considered in this research, three fuels are chosen to define the energy transition pathway. In most New Zealand dairy processing plants coal and natural gas are the main fuel while in power plants coal, natural gas is used along with biomass and hydro-energy as the most available renewable energy sources. Geothermal, wind, and wave energies are the other available renewable energy sources. Therefore, in this research, to generate power an ideal energy mix can be considered moving from coal through natural gas to biomass. Three steps are chosen to introduce each alternative energy source into fuel mix that in each step one-third of the total energy mix is deduced from the base case and is added to the alternative energy source. Therefore, seven different scenarios can be defined as it is shown in Table 1. As it can be seen in the table, coal, natural gas, and biomass alone provide sufficient energy for the power in scenarios 1, 4, and 7 respectively.

Table 1: Energy mix scenario specification.

Fuel Type	Energy Mix (%)						
	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7
Coal	100	67	33	0	0	0	0
Natural Gas	0	33	67	100	67	33	0
Biomass	0	0	0	0	33	67	100

2.3 Cumulative exergy demand

Working with a number of impacts can lead scenarios to different routes, as it is the case in ReCiPe. Cumulative Exergy Demand is an aggregated criterion that indicates the sustainability of the whole system into only one figure. CExD is based on exergy as a global term in the system which is independent of the time and place. Exergy is known as a parameter to measure the quality of energy. It means exergy analysis is an effective tool that presents the maximum quantity of a resource that can be converted to work. Therefore, it is more suitable for the regions that environmental parameters are different from the parameters assumed in the ReCiPe characterization model. Exergetic methods can present the life cycle point of view of the cumulative exergy consumption for a product or a process from cradle-to-grave which means exergy can be part of an LCA by representing a method for life cycle impact analysis of resource consumption; this can be done by CExD.

2.4 Monte Carlo simulation

Monte Carlo simulation is a valuable tool to prove that the scenarios under consideration are statistically discernible (Ghannadzadeh, 2018a). In this study, the definition of scenarios is not by means of MCS; however, the analysis of scenarios through MCSs can be helpful when judging the significance of the variations in the comparison of scenarios. It means MCS is used to evaluate how much the entire life cycle of the production process is responsive to one-third change steps of energy mix. In this research, MCS can therefore be implemented to correlate the power input with the output parameters, e.g. CExD.

3. Results and discussions

The environmental impacts are reported in three categories based on the ReCiPe. These categories, which each have a number of subcategories are: Human Health with six subcategories; Ecosystem with six subcategories; and Resources with only one subcategory.

3.1 Human health category

Six subcategories present environmental impacts under human health. Comparison of these impacts for each category is shown in Figure 1. Climate change impacts represent GHGs (carbon dioxide emission equivalent) emissions (Figure 1a). In this impact, the worst scenario is Scenario 1 which represents coal with 5.98×10^{-7} DALY followed by Scenario 2 and Scenario 3 combinations of coal and natural gas. The lowest environmental impact in this category is for Scenario 7 which represents 100% biomass. Particulate matter formation, which is due to discharge of the formed nitrogen and sulfur oxides (sulfur dioxide), and particulates between 2.5 to 10 µm, results (Figure 1d) has a similar trend as climate change where the worst fuel chose is coal with 2.54×10^{-7} DALY while biomass is the best choice with 2.36×10^{-7} DALY.

Human toxicity which is caused by the emission of barium, mercury, and arsenic ions is presented in Figure 1b. Surprisingly for this impact, Scenario 4 (100 % natural gas) has the worst impact with 2.96×10^{-8} DALY and biomass shows the lowest impact of 1.28×10^{-8} DALY. Figure 1c presents ozone depletion where for natural gas and biomass there is an identical number of 8.49×10^{-14} DALY while for the scenarios with a higher percentage of coal the situation is worst, i.e. Scenario 3, 2, and 1. The reason for ozone depletion is due to the release of methane and Freon gases.

Photochemical oxidant formation impact is presented in Figure 1e. Biomass with 5.18×10^{-10} DALY causes the highest environmental damage whereas Scenario 4 shows the lowest environmental damage with only 1.44×10^{-11} DALY. It should be noted that photochemical oxidants are secondary air pollutants that are formed by sunlight action on nitrogen oxides and some reactive hydrocarbons. The most important phytotoxic components are ozone, and nitrogen and sulphur oxides. However, the summation of all human health impacts shows that scenarios with a combination of biomass, specifically Scenario 7, seem to be a better choice as opposed to the other scenarios (Figure 1f).

3.2 Ecosystem category

Six different subcategories represent environmental impacts under the ecosystem are presented in Figure 2. With respect to climate change, Scenario 7 has the lowest impact with 3.76x10^{-10} species.yr as opposed to Scenario 4 and Scenario 1 with 2.13x10^{-9} and 3.39x10^{-9} species.yr respectively (Figure 2a). Both biomass and coal have significantly lower freshwater ecotoxicity compared with natural gas with 4.86x10^{-13} species.yr as shown in Figure 2b. However, Scenario 7 (biomass) with 3.77x10^{-17} species.yr has a lower impact than Scenario 1. Freshwater ecotoxicity is caused by discharges of copper, barium, silver, nickel.

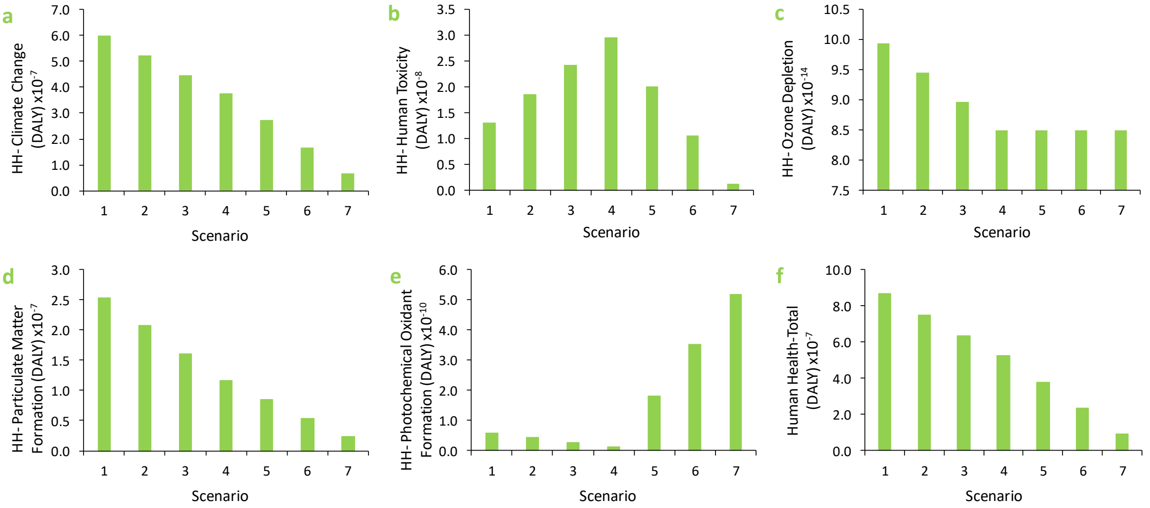

Figure 1: Impact categories of Human Health (HH) based on ReCiPe results.

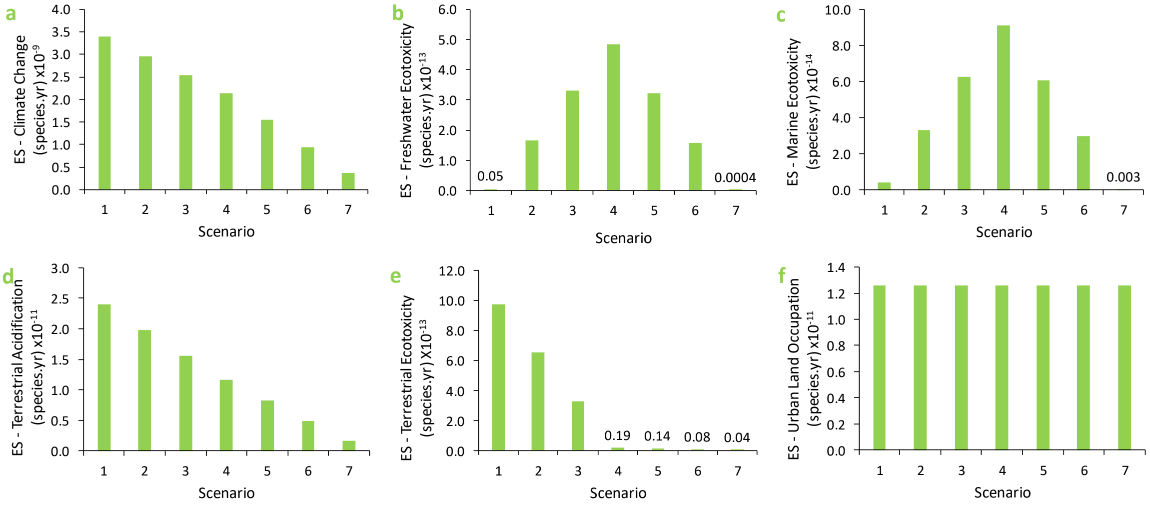

Figure 2: Impact categories of Ecosystem (ES) based on ReCiPe results

Marine ecotoxicity impact is presented in Figure 2c. Marine ecotoxicity has a similar trend to freshwater ecotoxicity where biomass has the lowest impact of 2.79x10^{-17} species.yr. The main reason for this impact is discharges of nickel, barium, silver, and mercury. Figure 2d presents terrestrial acidification impact where the worst impact is due to using coal as a fuel (Scenario 1). Biomass with 1.57x10^{-12} species.yr shows the lowest environmental damage where it has lowest release of sulphur and nitrogen oxides to the environment. As it can be seen in Figure 2e for terrestrial ecotoxicity impact Scenario 4 onward cause significantly lower environmental burden compared to the scenarios containing a portion of coal as fuel (Scenarios 1, 2, and 3). The urban land occupation impact is identical for all scenarios as it has been assumed all fuel types require the similar size of infrastructure (Figure 2f). However, in many cases natural gas supplied equipment have smaller sizes compared to coal and/or biomass supplied equipment, e.g. boiler. Considering the summation of the category, as expected, Scenario 7 with 3.90×10^{-10} species.yr has the lowest impact on ecosystem compared to fossil fuels such as natural gas 2.16×10^{-9} and coal with 3.43×10^{-9} species.yr.

3.3 Resources category

Figure 3a compares fossil depletion for seven different scenarios. As expected, the contribution of renewable energy sources can increase the sustainability of dairy product processing, e.g. cheese processing in this case study, especially in term of fossil resources depletion. Scenario 1 has the highest fossil depletion with $2.5x10^{-2}$ which means coal has 30 % more fossil resource depletion impact than natural gas (Scenario 4) with $1.47x10^{-2}$. By comparing the order of magnitude of biomass fossil depletion with scenarios containing a portion of fossil fuel it can be said that fossil depletion for biomass is nil.

3.4 Cumulative exergy demand results

Figure 3b presents CExD results of cheese production, including power generation. CExD has important implication in this study considering exergy destruction as a measure for production sustainability. Results show that using biomass for power generation is preferred as to oppose to the scenarios containing a portion of fossil fuel. However, by comparing the order of magnitude of each scenario, it can be seen that gas supplied electricity with CExD of 0.04 MJ-Eq is worse than coal supplied electricity with $5x10^{-5}$ MJ-Eq and biomass with10^{-6} MJ-Eq. In other words, considering CExD, the biomass based power is much more sustainable compared to natural gas and coal based power for New Zealand.

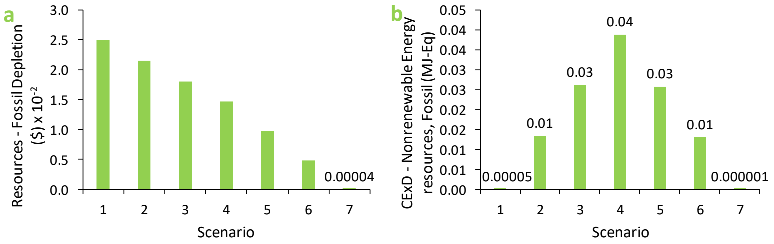

Figure 3: a) Impact category of Resources based on ReCiPe results; and b) CExD results for scenarios equivalent of non-renewable energy resources.

To enhance the robustness of results, MCS is used for further assessment of the scenarios limited to CExD where the CExD results are approximated and formed with uniform distribution. The probability distribution of MSC for 1 kW power demand is followed by the method presented in (Ghannadzadeh, 2018a). Figure 4 depicts an example of MCS uniform distribution results for each interval in Scenario 1 created by openLCA. Figure 3b presents the outcome of interval changes for results as the total prediction mean value range of CExD for each scenario. It exhibits that the complete trials do not possess identical value, revealing their relative independence, which basically paves the way for the definition of statistically-discernible scenarios. The carried-out MCSs suggest the defining scenario centred on the reported model is quite responsive to the 33.33% variation in the power generation source. In this case, the application of MCS is meaningful to prevent misleading conclusions in view of overestimations or underestimations.

Based on LCA that considers whole dairy processing at the production plant, $CO_{2\text{-e}}$ emission has the highest adverse impact on both human health and ecosystem. This means special attention to power and process heat generation of the dairy processing plant is worthy to be taken to avoid the burdens associated with the fossil fuels and quantify the impact of utilities. Although power generation system analysis can be performed on a standalone basis without considering the cheese production process, analysing both systems in a single study is helpful. This will allow the engineer to select the best option that meets minimum environmental requirements based on environmental regulations. For example, by increasing one-third of biomass as the contribution of renewable energies to the energy mix, the unsustainability of the cheese processing process is significantly reduced for Scenarios 5-7. It is especially interesting that the introduction of 33.33 % biomass to the energy mix in Scenario 5 can significantly reduce environmental impacts compared to Scenario 4.

LCA quantifies the environmental impacts of each energy mix scenario to allow the engineer to plan energy transition roadmap towards sustainable dairy processing production to help achieve New Zealand’s low emission targets by 2030. Considering LCA results that Scenario 7 (biomass) is the most environmentally sustainable option, it is recommended that the dairy industry should move towards utilising biomass as the main source of renewable energy. Finally, it should be noted that sustainability enhancement only deals with climate change (both human health and ecosystem), ozone depletion, and terrestrial ecotoxicity.

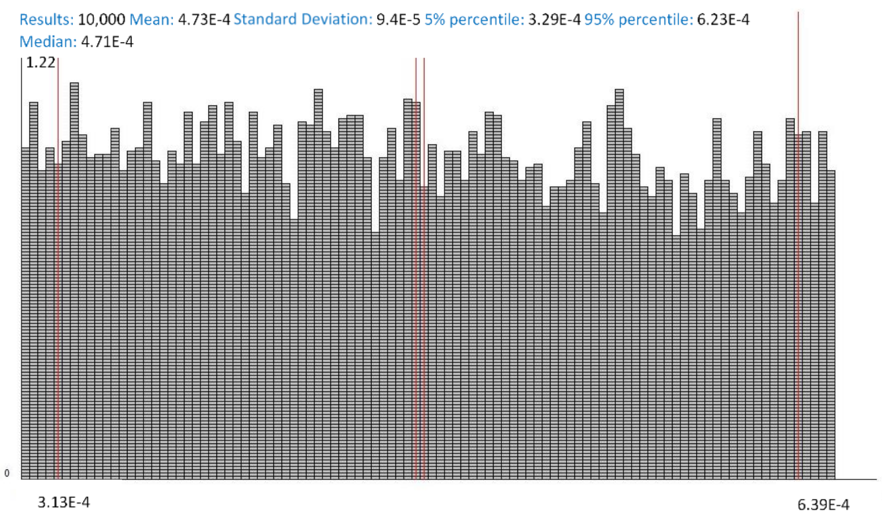

Figure 4: Monte Carlo simulation result for Scenario 1.

4. Conclusions

An environmentally sustainable pathway from fossil fuel sources towards renewable energy sources for cheese production in a dairy processing plant was studied in this paper. The study was performed using exergy assisted Life Cycle Assessment (LCA) supported by Monte Carlo simulation. LCA indicates that the proper choice of energy mix can increase the sustainability of the dairy production process. Introduction of one-third biomass as renewable energy to energy mix scenarios can significantly decrease the environmental burdens especially the impacts of CO_2 on the ecosystem and human health categories. The impact of the other renewable energy sources such as wind and geothermal energy in dairy processing plants will be studied in future work.

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