Final Consultants Report

Project 43: Natural Gas Hot Water Heating vs. Solar Thermal Hot Water Heating

MIE315 - Group 12
TA: [redacted]

Design for the Environment

<u>Group Members</u>:

Matilda Khoshaba	[redacted]
Yusuf [redacted]	[redacted]
Kerollos [redacted]	[redacted]
Kareem [redacted]	[redacted]

April 5th, 2020

Executive Summary

Our client, University of Toronto Co-op Residences, owns 24 residential homes near downtown Toronto. The Co-op Residences have been given a grant to replace their current water heating system. The two systems they are considering to implement are Solar Thermal Water Heating (ST) and Natural Gas Water Heating (NG) systems. The systems will be analyzed in terms of sustainability and their ability to maximize the benefit of the grant. The team aims to evaluate the two alternatives by conducting economic, hybrid, impact, societal, and sensitivity analysis on the life stages for both designs. Finally, a final recommendation will be made.

The goal of this project is to increase the sustainability of the U of T Campus Cooperative Residences through analysis of the NG and ST systems. The scope is to collect information on energy and material inputs/outputs for the life cycles of the systems, in order to determine their environmental impacts. A functional unit will be used, namely the amount of energy, in MJ input, required over 20 years, to heat 160 gallons of water per day to 60 ℃.

Economic analysis will be conducted to find the economic benefits of each system. The cash flows relevant to each life stage were converted to annual equivalent worth (AEW) as a common basis to compare, and it was found that ST cost $1937.01, while NG cost $2982.71 in total.

Using Hybrid LCA, it is found that the cost for ST was $25092.92 and for NG $64090.3. Process-based LCA was conducted on the performance use phases for both systems, and it was found that ST had less impact on environmental issues such as acidification and eutrophication. Finally, impact assessment quantified the effects of the two units as human health and biodiversity. Findings showed that ST has an effect of 7.6E-2 DALY on human health and 1.55E-4 species*year on biodiversity, while NG had 3.66 DALY and 6.17E-3 species*year.

Societal analysis focuses on the effects of the products not included in functional, environmental or economic analysis. NG received a score of 47% while ST recieved 75% implying that ST has a lower negative impact on the stakeholders selected with respect to their subcategories.

Sensitivity Analysis was conducted on the use phase to identify uncertainties in the data. NG was found to have uncertainties in the natural gas used per lifetime, and was determined that acidification increased linearly with natural gas consumed, with a maximum deviation of 28%. For ST, uncertainties in the number of days that electric backup operates resulted in a linear increase in the smog created, with a maximum deviation of 23% from the baseline.

The above results were looked at in conjunction with DfE strategies, and ST was recommended. Further improvements were mentioned to increase the sustainability of the ST design.

Table of Contents

1.0 Introduction

The University of Toronto Cooperative Residence received a grant and are looking to upgrade their home water heating systems. The purpose of upgrading is to combat the growing concerns about the environment since water heating consumes up to 25% of Canadian houses' energy, thus requiring an analysis of alternatives [1]. This is significant for the Cooperative Residence which owns 24 homes located in downtown Toronto; each has an average of 3 bathrooms and 8 students living together [2].

Water heating systems are a necessity in Toronto's freezing conditions. These systems provide hot water for washing clothes, showering, and other necessities. The heating systems are vital in ensuring the health and resident's safety by maintaining temperature levels.

Our team has been requested to determine whether a Natural Gas Water Heating system (NG) or a Solar Thermal Water Heating system (ST) should be installed. This study's goal is to increase sustainability of the residence by quantifiably comparing the two systems. Through a detailed study on the various energy consuming activities, the team will define conclusions on the environmental, economic, and societal benefits involved in each option to maximize the grant.

Regarding scope, both analyses will focus on five life cycle stages: premanufacturing, manufacturing, distribution, and use. The analysis will focus only on the impacts due to the inputs, outputs and direct energy consumption. A system boundary is defined in order to clarify what will be included/omitted in the analysis. The NG and ST analysis will not include common external features that are attached to either system such as any plumbing connections. Furthermore, if any by-products are formed during the main processes, their corresponding processes will not be included in the analysis, because they do not have a direct contribution to the production line. All emissions released to the atmosphere were recorded that have a direct effect on the environment and society.

From the PCR, the top three objectives were defined as the system that is more efficient, more environmentally friendly, and more economically viable. The analysis done throughout this report is based on finding how each water heating system satisfies these objectives. In the PCR, a detailed FOC and SLCA was done, using the amount of energy input required over 20 years to heat 160 gallons of water per day to 60 ℃ as the functional unit, in order to provide a preliminary recommendation to the client. The recommendation was that Solar Thermal Water Heating is the preferred design with a higher SLCA matrix score. The distribution and use stages impacted this result the most, where ST had a higher score due to possible leakages in the NG transmission lines discussed later in the report (Appendix A). Moreover, ST better met the above objectives further justifying our recommendation (Appendix B).

This report focuses on performing an Economic Analysis first to compare the economic viability of these systems across their life stages. Next, a Hybrid LCA is performed in line with an impact assessment that helps the team determine which system is more sustainable. Finally, societal and sensitivity analyses were performed to allow us further understand the effect on each system on the people and identify any uncertainties in the Hybrid LCA analysis. A recommendation is then made to the client by briefly describing the design for environment strategies used.

2.0 Economic Analysis

Economic analysis will be used to determine the economic benefits of each alternative through comparison of life costs. The lowest common multiple of the lifetimes, 20 years, will be used as the common lifetime [3][4]. The life cycle costs of NG and ST will be converted to Annual Equivalent Worth (AEW) as a basis for comparison and to account for the time value of money.

To analyze the economic effect of both water heating methods, the system costs are broken down into the five life stages to understand which contributed the most to the overall cost. Consequently, research was conducted on each life stage and as a result, the raw materials used, manufacturing process, and delivery were not included in the purchase cost of the systems.

Appendix S lists assumptions made on interest rate, maintenance costs, and disposal costs to ease the calculations.

2.1 Natural Gas Water Heating

The relevant life cycle costs of the NG is listed in Table 1 and illustrated in Figure 1.

Table 1: Life Cycle Costs of NG

Life Stage	Cash Flow	Metrics and Justification
Pre-Manufacturing	Raw Materials Cost	**Natural Gas** Well Drilling: *Cost:* $1652 (Appendix C) Inlet Gas Compression: *Cost:* $1752 (Appendix D) Well Casing: *Cost:* $0.40 (Appendix E) (Appendix F)

		Justification: Natural gas is the input fuel essential for this system to function. The extraction process consists of well drilling, inlet gas compression, and well casing. The calculations are based on the natural gas usage per year for water heaters with a capacity total of 160 gallons is 1032 therms. This cost will be regarded as a single initial cost at year 0.
		Tank *Cost:* $2198.35 (Appendix G) *Justification:* The tank consists of two steel layers, a polyurethane insulation layer, an inner glass layer, a magnesium rod, cardboard, and copper coil. These materials are essential to the lifetime of the tank, and are a single initial cost at year 0 and 10. All detailed calculations can be found in Appendix G.
Manufacturing	Manufacturing Costs	**Natural Gas Processing** Oil Condensate Removal: *Cost:* $0.2841 (Appendix H) Water Removal: *Cost:* $47.6 (Appendix I) Natural Gas Liquids Extraction: *Cost:* $6694.5 (Appendix J) Gas Sweetening: *Cost:* $1483.11 (Appendix K) *Justification:* Before natural gas can be used for domestic water heating, the gas must be processed to remove unwanted compounds. Natural gas processing consists of oil condensate removal, water removal, NGLs extraction, and gas sweetening. This step is essential to the functioning of the system, and the cost will be regarded as a single initial cost at year 0.
		Tank Manufacturing *Cost:* $689.12 [5] *Justification:* The cost of manufacturing one 40 gallon tank is $172.98, where for this system we are using 160 gallons. The cost to manufacture the natural gas tank is a single cost at year 0 and 10.

Distribution	Transportation of Materials/Product Costs	**<u>Natural Gas Distribution</u>** <u>Transmission Pipelines:</u> *Cost:* $142.544(Appendix L) <u>Metering Stations:</u> *Cost:* $10.212 (Appendix M) <u>Valves:</u> *Cost:* $4.6 (Appendix N) *Justification:* Distribution costs are attributed to the distribution lines, metering stations, and valves that are used to transport natural gas from the processing stations to domestic homes. This cost is a single cost at year 0, where the total cost of natural gas distribution was calculated for the system lifetime of 20 years.
		<u>Tank Transport</u> *Cost:* $50 [6] *Justification:* The cost of transporting the tank to UofT Cooperative Residences from a water tank vendor was calculated using the average cost of a rental truck per day in Toronto. This cost is a single cost at year 0 and 10.
Use	Initial Purchase Cost	<u>Natural Gas Water Heating System</u> *Cost:* $1500 [7] *Justification:* The average cost the buyer must pay to purchase and install the 2x 80 gallon water heating system, including exhaust vents. The cost is a single initial cost at year 0.
	Maintenance Costs	*Cost:*$105/yr [8] *Justification:* The maintenance costs for this system focused on maintenance specific to natural gas related features as well as the general water tank. The system was assumed to have all possible issues occur at maximum cost, one time during the lifetime of the system. This cost is an annual cost starting at year 1 and again at year 11.

	Operational Costs	*Cost:* $1511.49/yr [9] *Justification:* The operating cost is the average cost of the buyer's energy bill, in which both the cost of natural gas as well as the transportation of natural gas is included. This cost is an annual occuring cost throughout the lifetime of the system, starting year 1 and again at year 11.
	Replacement Costs	*Cost:* $1500 [7] *Justification:* Annual Equivalent Worth analysis will be undergone using a common lifetime of 20 years. The natural gas water heating system has a lifetime of 10 years, and therefore will be repurchased at year 10 with the same initial cost as year 0.
Disposal	Disposal Cost	*Cost:* $150 [10] *Justification:* It will cost approximately this much for the average disposal company in Toronto to recycle as much of the system as possible and dispose of the rest. This cost is a single final cost at year 10 and 20.
	Salvage Value	*Cost:*N/A *Justification:* The system will be disposed of at the end of its lifetime, and will therefore not have any salvage value.

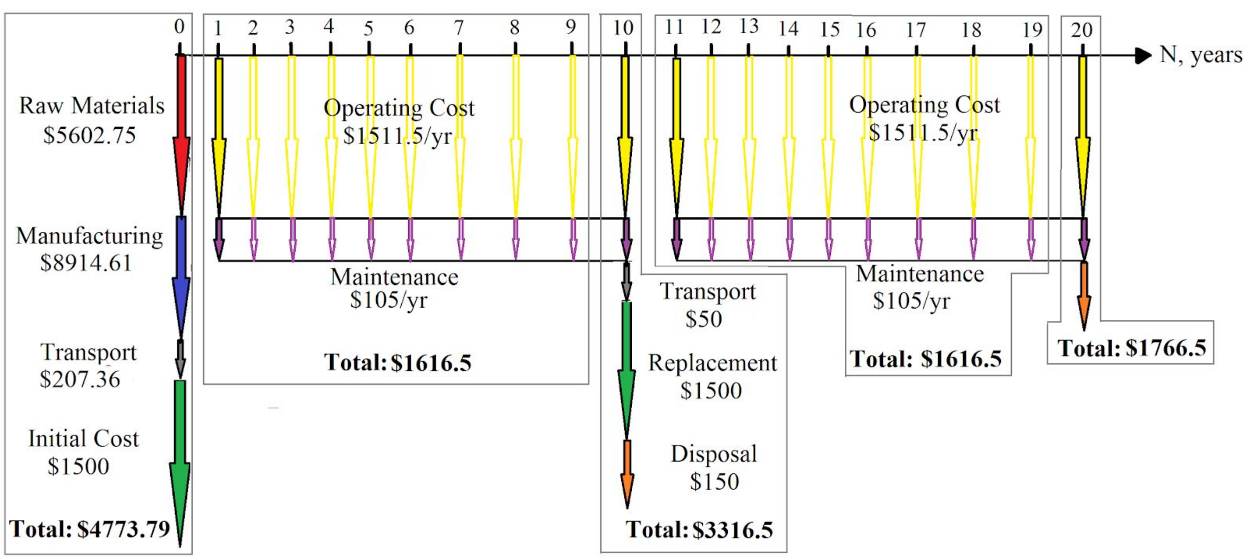

Figure 1. Cash Flow Diagram for NG

The cash flows listed in Table 1 will be converted to Net Present worth, added, and converted to AEW. The purpose of this conversion is to create a basis for comparison of the two systems with regards to the time value of money, using a common lifetime of 20 years. The equations for converting annual (A) and future (F) costs to present (P) costs, and present and future costs to annual costs can be found below (Equation 1-4). The interest *(i)* used was 5% (the general interest rate in the energy sector). The results can be found in Table 2, and all detailed calculations can be found in Appendix O [11].

Equation 1: $$P = A\frac{(1+i)^{-N}}{i(1+i)^{N}}$$

Equation 2: $$P = F(1+i)^{-N}$$

Equation 3: $$A = P\frac{i(1+i)^{N}}{(i+i)^{N}-1}$$

Equation 4: $$A = F\frac{i}{(i+i)^{N}-1}$$

Table 2: Annual Equivalent Worth for NG Life Stages

Life Stage	Annual Equivalent Worth
Premanufacturing	\$449.58
Manufacturing	\$715.33
Distribution	\$19.11
Use	\$1782.22
Disposal Cost (F)	\$16.47
Total AEW	**\$2982.71**

2.2 Solar Thermal Water Heating

The relevant life cycle costs of ST is listed in Table 3 and illustrated graphically in Figure 2.

Table 3: Life Cycle Costs of Solar Hot Water Heating System

Life Stage	Cash Flow	Metrics and Justification
Pre-Manufacturing	Raw Materials Cost	Solar Collector *Cost:* $174.16 (Appendix P) *Justification:* The collector is composed of an aluminum frame, glass cover, copper pipes, cardboard, and polyurethane insulation. The individual material costs and calculations can be found in Appendix P. This cost is a single initial cost at year 0.
		Tank *Cost:* $2215.5 (Appendix Q) *Justification:* The tank consists of two steel layers, a polyurethane insulation layer, an inner glass layer, a magnesium rod, cardboard, aluminum heat exchanger, and copper coil. These materials are essential to the lifetime of the tank, and are a single initial cost at year 0. All detailed calculations can be found in Appendix Q.
Manufacturing	Manufacturing Costs	Solar Collector *Cost:* $240 [12] *Justification:* The costs are welding, cutting and bending the aluminum frame. Also, coating and insulation is included. This cost is an annual cost starting year 1.
		Tank *Cost:* $689.12 [5] *Justification:* The cost of manufacturing one 40 gallon tank is $172.98, where for this system we are using 160 gallons. The cost to manufacture the water tank is a single cost at year 0.

Distribution	Transportation of Materials/Product Costs	Solar collector, Tank, and Electric Backup System *Cost:* $50 [6] *Justification:* The cost of transporting all of the components to UofT Cooperative Residences from a solar water heating provider was calculated using the average cost of a rental truck per day in Toronto. This cost is a single cost at year 0.
Use	Initial Purchase Cost	Solar Panel *Cost:* $10,000 [13] *Justification:* This is the average cost of buying solar collectors with a total surface area of 80 square feet and two 80 gallon water tanks. This is a single initial cost at year 0.
		Electric Backup *Cost:* $250 [8] *Justification:* A mandatory backup system is required when using solar water heating due it's variable function during colder/cloudy weather. The system will be electric. This cost is a single cost at year 0.
	Maintenance Costs	Solar Collector *Cost*: $121/yr [14] *Justification*: The required maintenance of solar water heating is concerned with the panels that compromise the solar collectors. This maintenance consists of removal of dust and vegetation as well as repairing cracks and damages. This is an annual cost starting at year 1.
		Tank *Cost*: $282.50/yr [15] *Justification*: The required maintenance of the tank is concerned with leak repairs, anode replacement, pressure valve replacement, and sediment flushing. This is an annual cost starting year 1.
		Electric Backup *Cost*: $240/yr [15] *Justification*: The required maintenance of the electric backup is concerned with the replacement of the heating element. This is an annual cost starting year 1.

	Operational Cost	*Cost:* $25/ yr [16] *Justification:* Operational costs consist of 6.19 kg of glycol replacement every 3 years . This is an annual cost starting year 1.
		<u>Electric Backup</u> *Cost:* $171.17/r [17] *Justification:* Electric backup heater operates around 3 hours per day for 80 days per year. This is an annual cost starting year 1.
	Replacement Costs	*Cost:* N/A *Justification:* The lifetime used in the analysis is the same as the lifetime of the product itself so a replacement cost is unnecessary.
Disposal	Disposal Cost	*Cost:* $150 [10] *Justification:* It will cost approximately this much for the average disposal company in Toronto to recycle as much of the system as possible and dispose of the rest. This cost is a single final cost at year 20.
	Salvage Value	*Cost:* N/A *Justification:* The lifetime used in the analysis is the same as the lifetime of the product itself so a salvage value is unnecessary

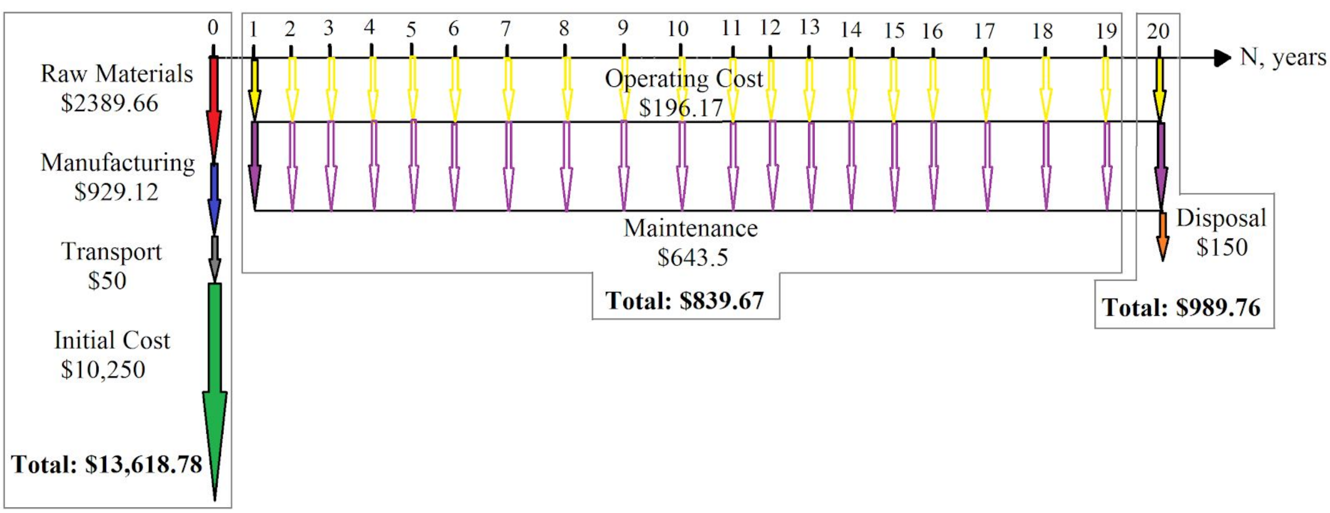

Figure 2. Cash Flow Diagram for ST

The cash flows listed in Table 3 will be converted to AEW as a basis for comparison using the common lifetime of 20 years. The purpose of this conversion is to create a basis for comparison of the two systems with regards to the time value of money, using a common lifetime of 20 years. Because ST has the same lifetime as the common lifetime, all cash flows can be converted to annual equivalent worth. Equations 1-4 will be used to convert annual (A) and future (F) costs to present (P) costs and present costs to annual costs. The interest *(i)* used will be 5% (the general interest rate in the energy sector). The results can be found in Table 4, and detailed calculations can be found in Appendix R [11].

Table 4: Annual Equivalent Worth for each Life Stage for ST

Life Stage	**Annual Equivalent Worth**
Premanufacturing	$191.75
Manufacturing	$74.55
Distribution	$4.01
Use	$1662.16
Disposal Cost (F)	$4.54
Total AEW	**$1937.01**

2.3 Economic Analysis Results

Economic analysis concludes with NG having an annual equivalent cost of $2982.71, and ST $1937.01.

Figures 3-4 depict the AEW life cycle costs for each system in percentile form. Although both systems have the greatest costs during the Use phase, it is evident that Use phase costs in ST contributes to a higher 82.8% compared to 58.5% for NG, due to ST not requiring constant operational activities (NG requires a supply of natural gas). The NG rather has greater costs in premanufacturing (16.5%) and manufacturing (23.6%).

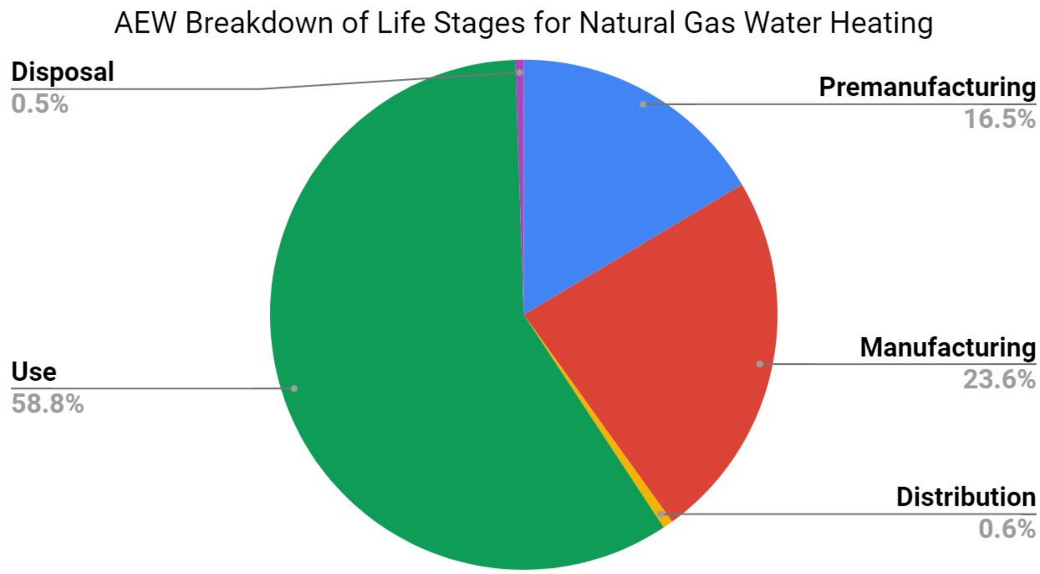

Figure 3. NG Life Stage Costs (Percentages)

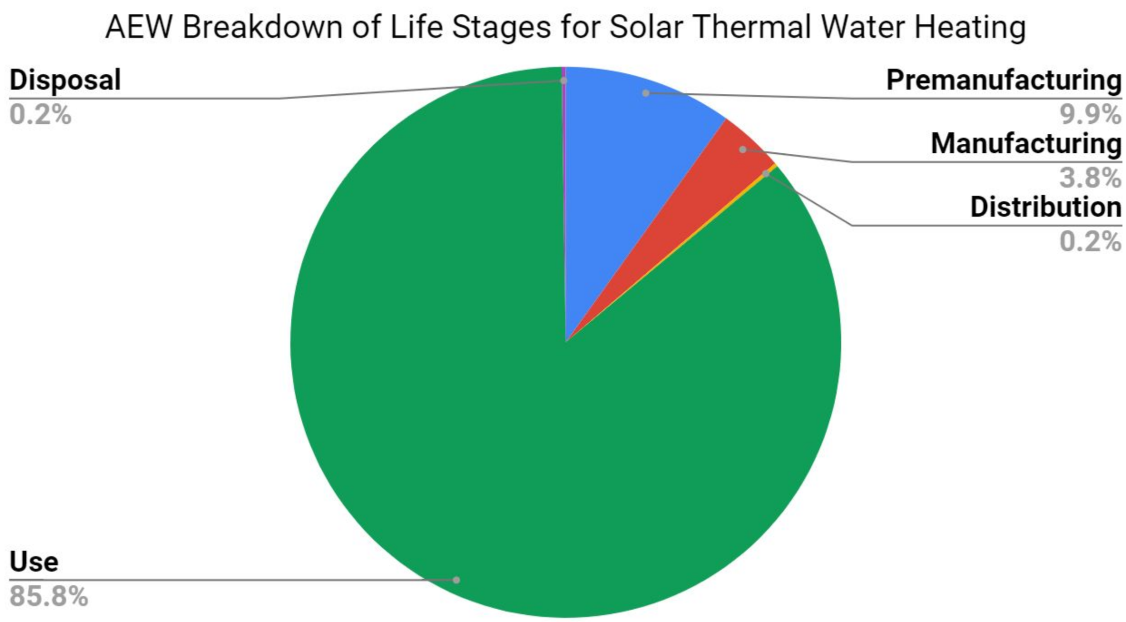

Figure 4. ST Life Stage Costs (Percentages)

Figure 5 illustrates the AEW life cycle costs for each system on a bar graph and shows that NG costs more than ST in every phase. This is significant when taking into consideration that ST's Use Phase contributes to a higher 82.8% compared to NG's 58.8%, meaning the NG use phase is more expensive even though it is 30% less dominant in the cost balance. This suggests that ST is more efficient and effective in converting its input energy to heat the water since it satisfies the functional unit in a more cost effective manner than NG during the operational phase. This is because of the quality of energy it uses. The solar radiation that ST uses is considered low energy quality and is high energy quality for NG. Since heating water requires low energy quality [18], it is more efficient to go from low energy to low energy than high to low. Furthermore, all of NG's costs are larger than ST, where premanufacturing is 1.67x greater and manufacturing is 6.21x greater. This suggests that NG is a cost intensive process to manufacture, implement and dispose because of the difficulties associated with NG.

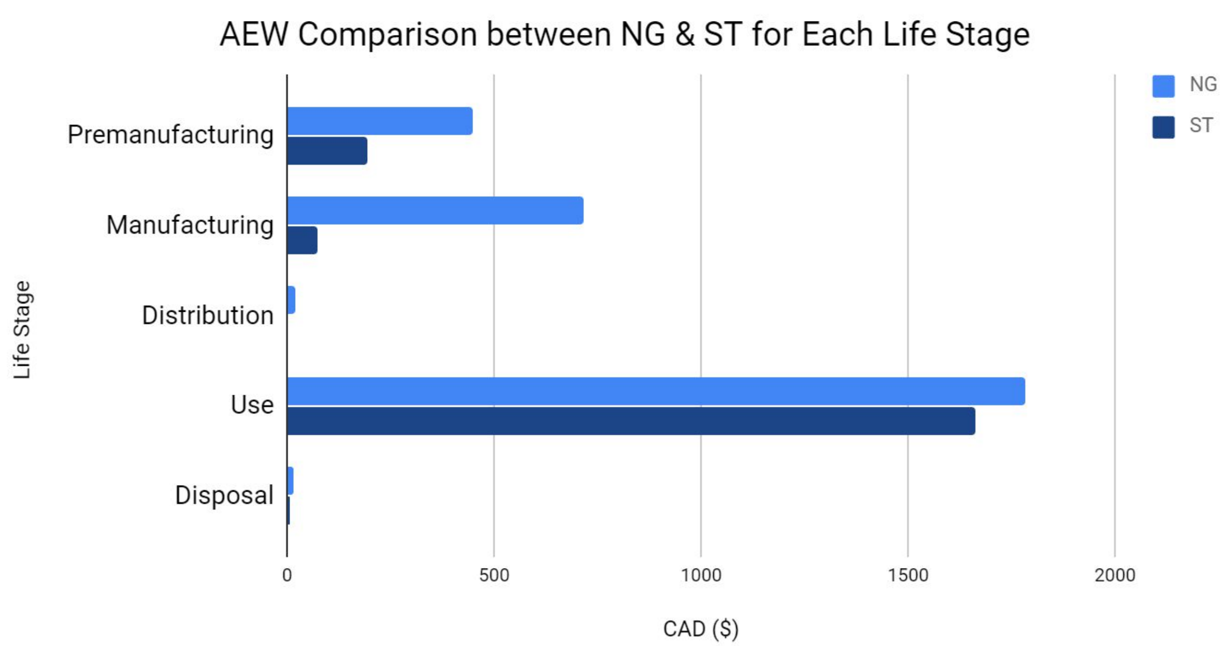

Figure 5. NG vs ST Life Stage Costs

Due to these reasons, it is evident why NG was determined to have greater costs than ST.

3.0 Hybrid LCA

Economic Input-Output LCA (EIO-LCA) will be utilized to compare monetary values based on the economic activity in industry-based processes. These monetary values will be used to identify major areas of cost in life-cycle stages as well as the overall cost differences of the systems. This will help the team make accurate recommendations of where cost could be reduced.

Process-based LCA (PLCA) focuses on quantifying the environmental impacts of unique life stages through data intensive analysis and detailed flows of processes. The resulting environmental impacts of NG and ST will be compared to determine which system contributes more to a given stressor.

Individually, EIO and PLCA are not sufficient to analyze the various life stages due to the differences in their ability to describe every life stage. Therefore, a hybrid of both analyses is required to comprehend each process. Flowcharts of the two systems and their respective system boundaries are located in each section (Figure 6 & 13).

Note: The sectors used in EIO-LCA hybrid analysis were selected such that they do not overlap, based on descriptions provided from models on the website.

3.1 Natural Gas Water Heating

Figure 6 illustrates the flow chart consisting of every life stage. The inputs and outputs of premanufacturing, manufacturing, distribution, use, and disposal are outlined.

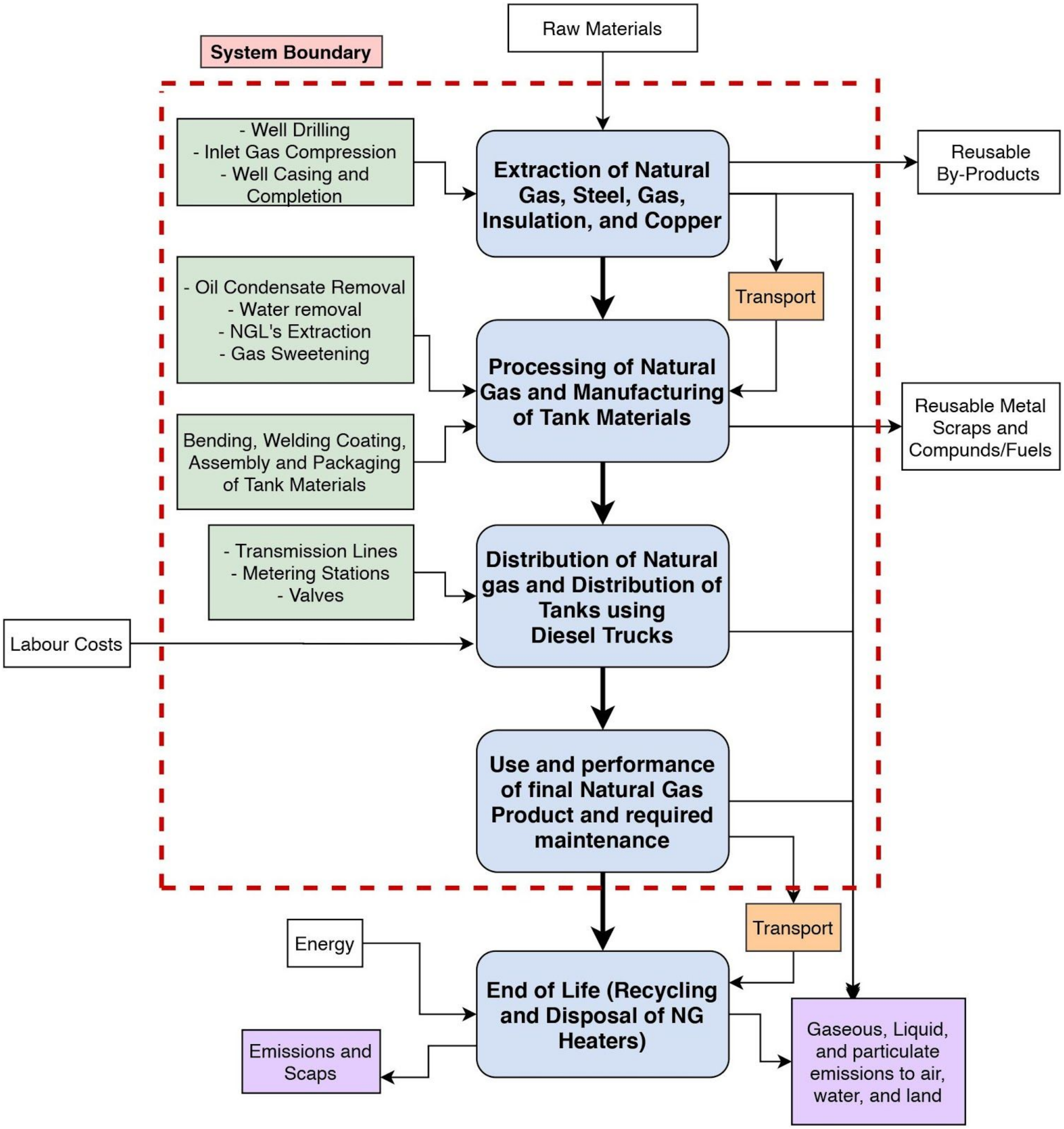

Figure 6. Flow Chart of Overall NG Life Cycle

Pre-manufacturing

The pre-manufacturing process of Natural Gas involves three main processes: Well Drilling, Inlet Gas Compression, and Well Completion (Figure 8). See Appendix T for all the inputs, outputs, air emissions, and waste/hazards of pre-manufacturing.

Well Drilling:

Conventional drilling methods of NG is the main focus of this report. This is based on the fact that conventional wells are the traditional wells drilled in modern day [19]. The team's main focus in this section will be the raw material used for running this system. The production of the equipment involved is outside the scope of this project. The prime mover shown above supplies the power to the rig, and is run on diesel engines [20]. See Appendix C for cost calculations.

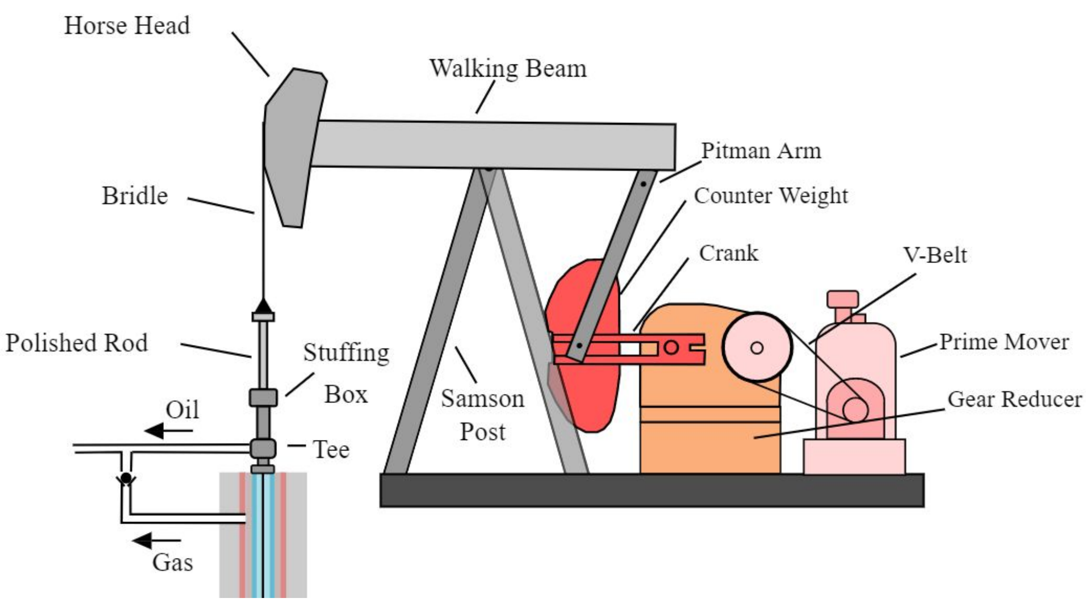

Figure 7. Equipment Used in Drilling Process [19]

EIO-LCA

Raw Material: Natural Gas [21]

Sector: Drilling oil and gas wells

Justification: Use of EIO-LCA in NG drilling is done to avoid setting the boundary for the system shown in Figure 7, which would otherwise require conducting a life-cycle assessment of different rigs used in the industry to capture the diesel oil and fuel gas consumption according to their size, drilling capacity, etc. [22]. Since natural gas extraction is a standard process, EIO-LCA captures the industrial average of fuel and diesel consumption for this process [23].

Cost: \$1652 dollars for a 20 year life cycle [9] → \$3453 *(after conversion of economic activity)*

Inlet Gas Compression:

Inlet gas compression is a process by which the pressure of natural gas is increased for local NG pipeline system transport. This is to achieve a delivery from the wellhead to end-use locations [24]. The main components involved in this process are two-stage / three-stage compressors and gathering pipelines [24][25].

Compressors utilized at the NG wellhead to boost up the pressure for natural gas transport. Assuming a two stage compressor is used, this sets a compression energy intensity requirement of 1.76 x 10^-4 MWh per kg of natural gas [26].

EIO-LCA
Raw Material: Energy Intensity
Sector: Air and Gas Compressor Manufacturing
Justification: Compressed air is essential in the well drilling phase, and the use of inlet gas compression to produce this air is a standard use in the oil and gas industry, thus must be considered in this analysis [27]. Since this process is often used in the industry, an EIO-LCA analysis is conducted. See Appendix D for cost calculations.
Cost: 2.894815 million Canadian Dollars per well → $1,752 per product → $4117.2 *(after conversion of economic activity)*

Well Casing and Completion:

Well Casing refers to the process by which a number of carbon steel pipes are positioned in a drilled hole, in order to serve as a protection for the well stream from external impurities [28][29].

EIO - LCA
Raw Material: Carbon Steel
Sector: Support activities for oil and gas operations
Justification: The pre-manufacturing section is focused on the materials of which the products are made. Carbon steel is utilized in various mining applications across the industry such as heat exchangers and pipes [30]. Hence, an industry average is taken using EIO-LCA. See Appendix E for cost calculations.
Cost: 6.065 x 10^-5 USD → $5.88 x 10^-5 *(after conversion of economic activity)*

After the Well Casing procedure, cement is placed between the casing and the walls of the drilled well [28]. This is done to ensure no fluid enters the groundwater resources of the drilling process.

EIO-LCA

Raw Material: Cement (119.1 bbl [31])

Sector: Cement Manufacturing

Justification: Since cementing is an industry-wide process used to position the casing to avoid mixing of non-hydrocarbons with NG stream, the emissions of cement manufacturing must be considered using EIO-LCA [32]. See Appendix F for cost calculations.

Cost: $661 per well → $0.40012 per product → $0.408 *(after conversion of economic activity)*

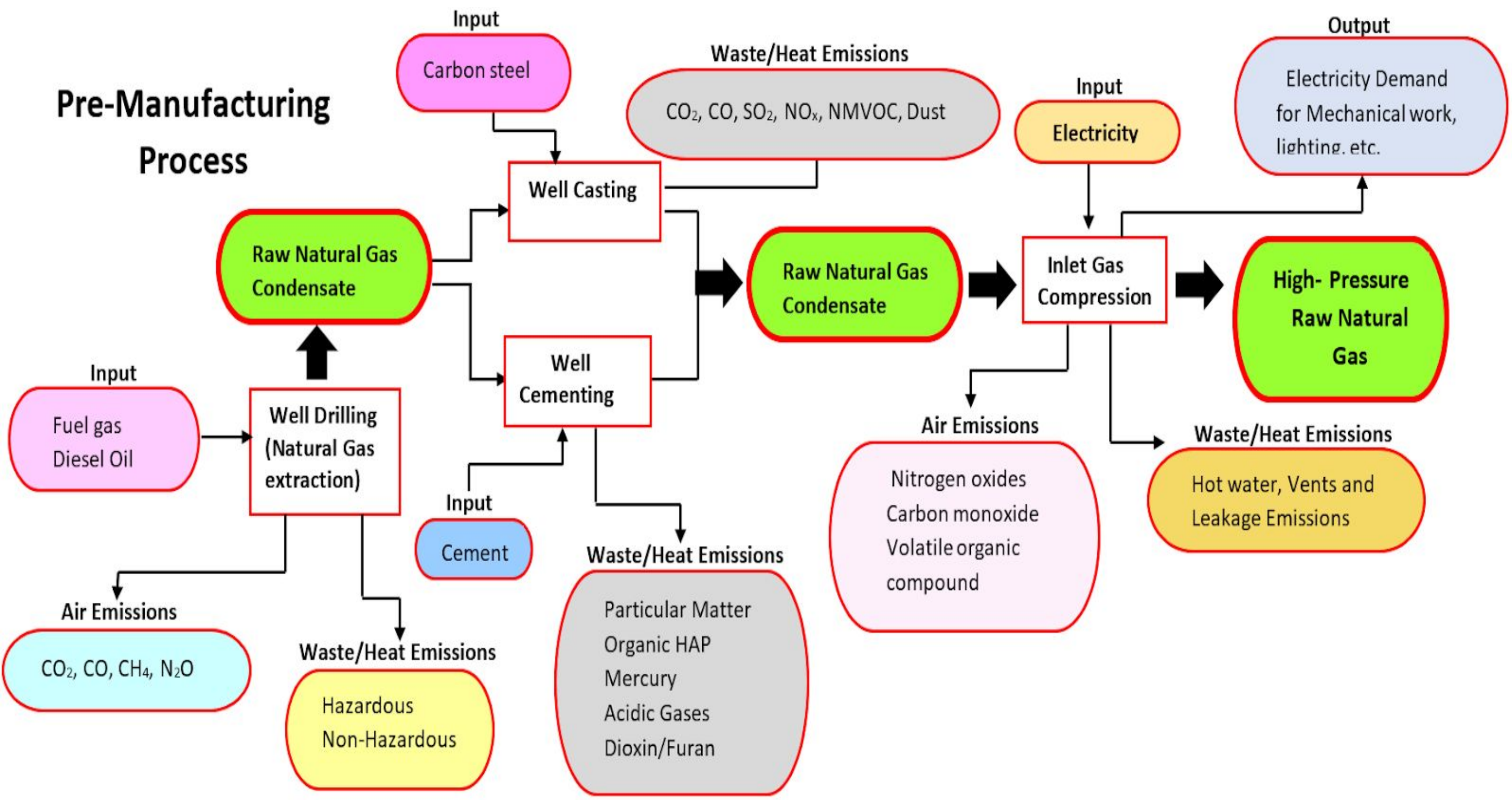

Figure 8: Flow Chart for Pre-Manufacturing Stage for NG

Manufacturing

The first step of the manufacturing process of natural gas is the separation of the natural gas from the extracted oil-gas mixture[33] (Figure 9). This process occurs by utilizing a closed tank This uses a gravitational force to separate denser fluids from the gas stream [34]. See Appendix U for the inputs, outputs, air emissions, and waste/hazards.

EIO-LCA

Manufacturing Process: Oil Condensate Removal

Sector: Other basic organic chemical manufacturing
Justification: This sector comprises manufacturing basic organic chemicals which aligns with the by-products of oil condensate removal, oil and gas, which are both hydrocarbons [34]. Hence, this sector is chosen in EIO-LCA analysis. See Appendix H for the cost calculations.
Cost: \$0.2841 per product → \$0.268 *(after conversion of economic activity)*

Following the separation of the oil from the Natural Gas stream, there remains water in the mixture that must be extracted to ensure the stream satisfies the standards of the transport pipelines [34].

EIO-LCA
Manufacturing Process: Water Removal
Sector: Petroleum lubricating oil and grease manufacturing
Justification: Lubricating oil is dehydrated in a process similar to that of NG, thus the sector above is chosen in the EIO-LCA analysis [35]. The use of PLCA means conducting a life cycle assessment of all the possible water removal processes, Glycol Dehydration and Solid-Desiccant Dehydration [34][36]. The EIO-LCA rather calculates an average of all the possible processes. See Appendix I for the cost calculations.
Cost: \$47.6 per product → \$35.98 *(after conversion of economic activity)*

The following step is the removal of Natural Gas Liquids, which is required for the natural gas stream to satisfy the standard associated with the pipeline it is to be transported through [37].

EIO-LCA
Manufacturing Process: Natural Gas Liquids (NGLs) Extraction
Sector: Petrochemical manufacturing
Justification: Petrochemical manufacturing produces hydrocarbons similar to that of NGLs composition, thus the sector above is chosen in the EIO-LCA analysis [38][39]. PCLA omits the use of publicly based data, contradicting the purpose of NGLs. NGLs are used in various sectors of the economy such as cooking and vehicle fuel, hence the emissions should represent NGL volume production for the public [40]. See Appendix J for cost calculations.
Cost: \$6694.5 → \$2871.94 *(after conversion of economic activity)*

Next, boilers are used to sweeten the gas by removing H2S and CO2, producing heat in the process. They account for the major amount of heat used in the process [41].

EIO-LCA
Manufacturing Process: Gas Sweetening
Sector: Industrial gas manufacturing

Justification: The gas sweetening process could involve different scenario planning and sensitivity analyses. Thus, EIO-LCA is used due to its consideration of Sensitivity analyses and Scenario planning. See Appendix K for cost calculations.
Cost: \$1483.11 → \$1321.45 *(after conversion of economic activity)*

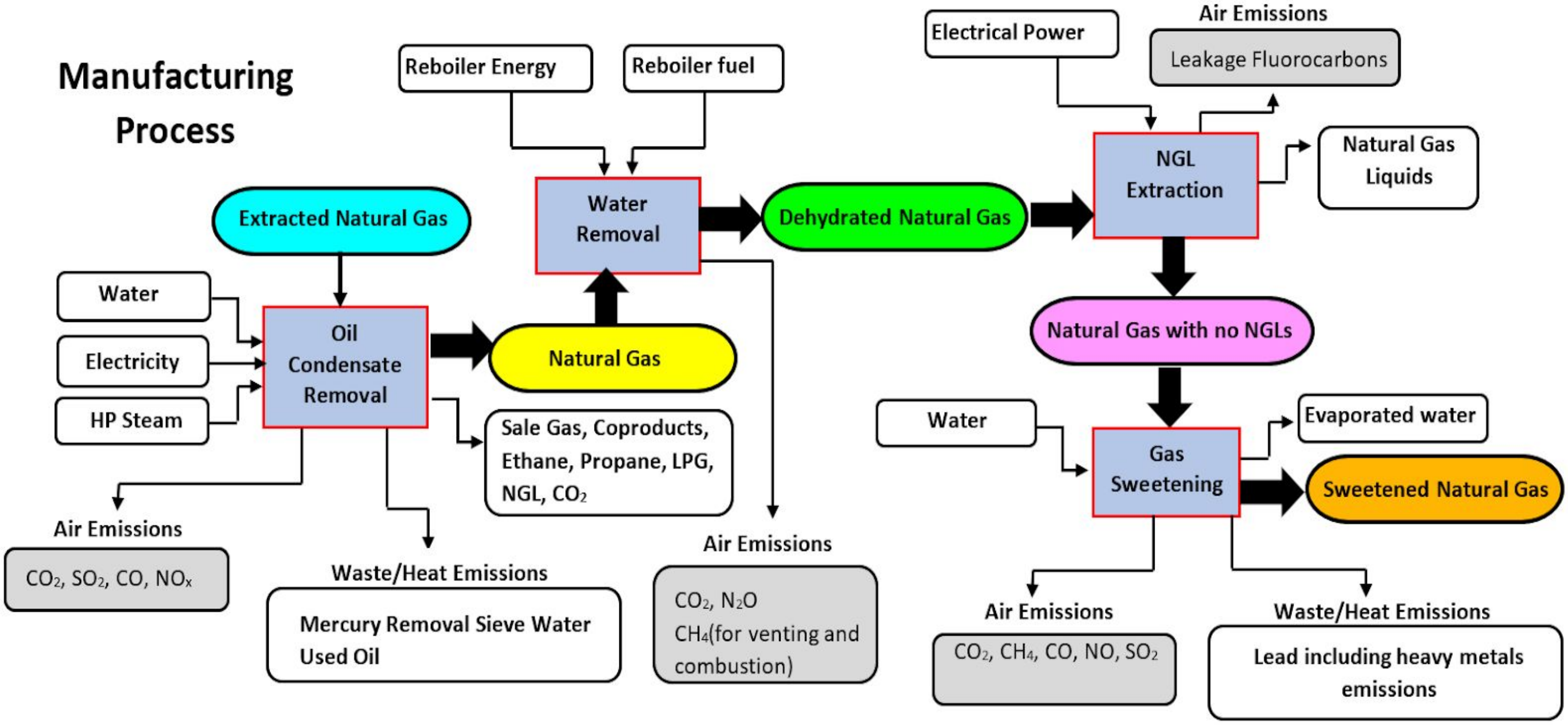

Figure 9. Flow Chart for Manufacturing Stage for NG

Transport

The following section will focus on the components which make up the pipeline system of natural gas (Figure 10). See Appendix V for all the inputs, outputs, air emissions, and waste/hazards of transport.

Transmission pipelines are responsible for carrying the processed natural gas products to the corresponding consumer for use [43]. See Appendix L for the cost calculations.

EIO-LCA
Transport Process: Transmission Pipelines
Raw Material: Carbon Steel [44]
Sector: Pipeline Transportation
Justification: Transmission pipelines have both direct and indirect economic impact on GDP, full-time jobs related to functioning these pipelines, as well as labour income [45]. Thus, due to its effect on the different sectors of an economy, EIO-LCA is used.
Cost: $142.544 → $143.969 *(after conversion of economic activity)*

Metering stations are placed along the length of the pipeline with two main goals: lower the volume of gas and distribute it to different consumers to lower the volume of the natural gas passing through, to transmit it along the pipe, and meter the natural gas to different consumers [44][46]. See Appendix M for cost calculations.

EIO-LCA
Transport Process: Metering Stations
Raw Material: N/A
Sector: Natural Gas Distribution
Justification: Metering Stations warrant companies responsible for pipeline distribution to manage volumes of NG to different users by calculating the flowrate of the gas stream [47]. This forms a major step in the Natural Gas Distribution and must be accounted for. EIO-LCA is utilized due to the fact that this is a service. See Appendix M for cost calculations.
Cost: $10.212 per product → $8.7414 *(after conversion of economic activity)*

EIO-LCA
Transport Process: Valves
Raw Material: N/A
Sector: Natural Gas Distribution
Justification:Valves are included in huge numbers along the pipelines. These are placed to avoid blockages, ensure smooth flow, and serve as safety measures [44]. The number of control valves in the processing plant could reach up to 300 units [48]. See Appendix N for cost calculations.
Cost: $4.6 → $3.94 *(after conversion of economic activity)*

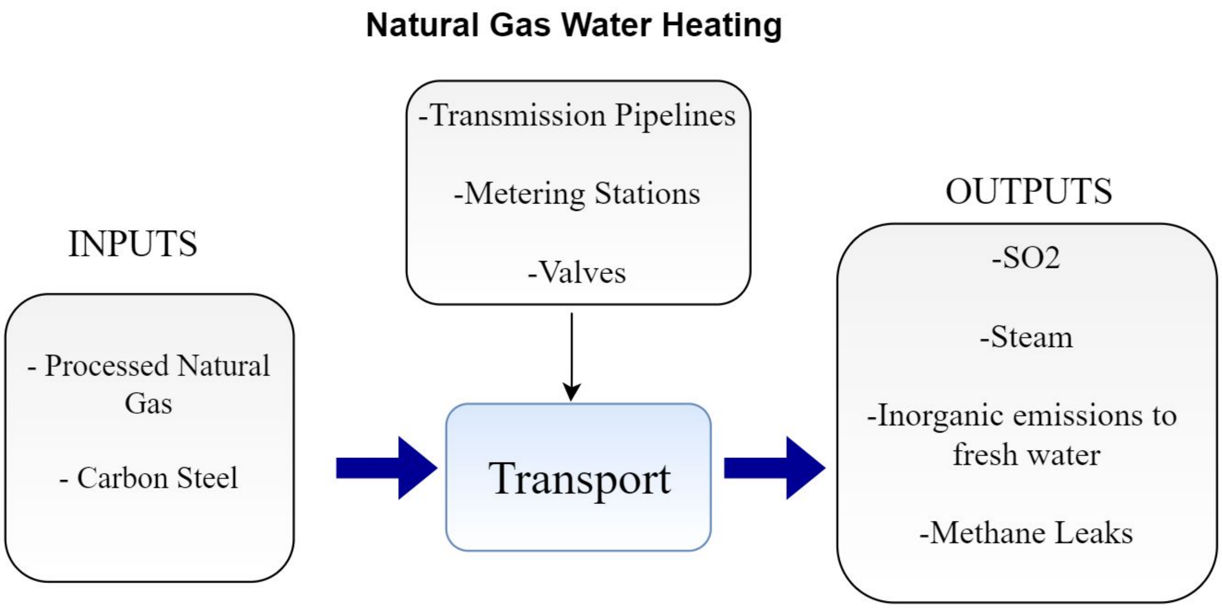

Figure 10. Flow Chart for Transport Stage for NG

Maintenance (Use)

This section focuses on maintenance and operational costs for NG during its use (Figure 11).

EIO -LCA
Maintenance Process: Tank Repairs (Table 1)
Sector: Residential Maintenance and Repairs
Justification: Throughout the lifetime of the natural gas water tank, maintenance and repairs may be required. The repairs could be related to general tank issues such as the replacing of the pressure release valve, or more concerned with gas related features such as a malfunctioning gas control valve [8]. Because maintenance of the water heating tank is considered a standard residential expense common to every household, EIO-LCA was used
Cost: $3328.7 (Table 1)

EIO -LCA
Maintenance Process: Natural Gas Constant Supply [9]
Sector: Natural Gas Distribution
Justification: The NG requires a constant supply of natural gas to achieve its function. Natural gas distribution and supply is a common sector in many industries, and because EIO-LCA focuses on economy wide assessments this was determined to be the most effective choice for analysis.
Cost: $48,804.75 (Table 1)

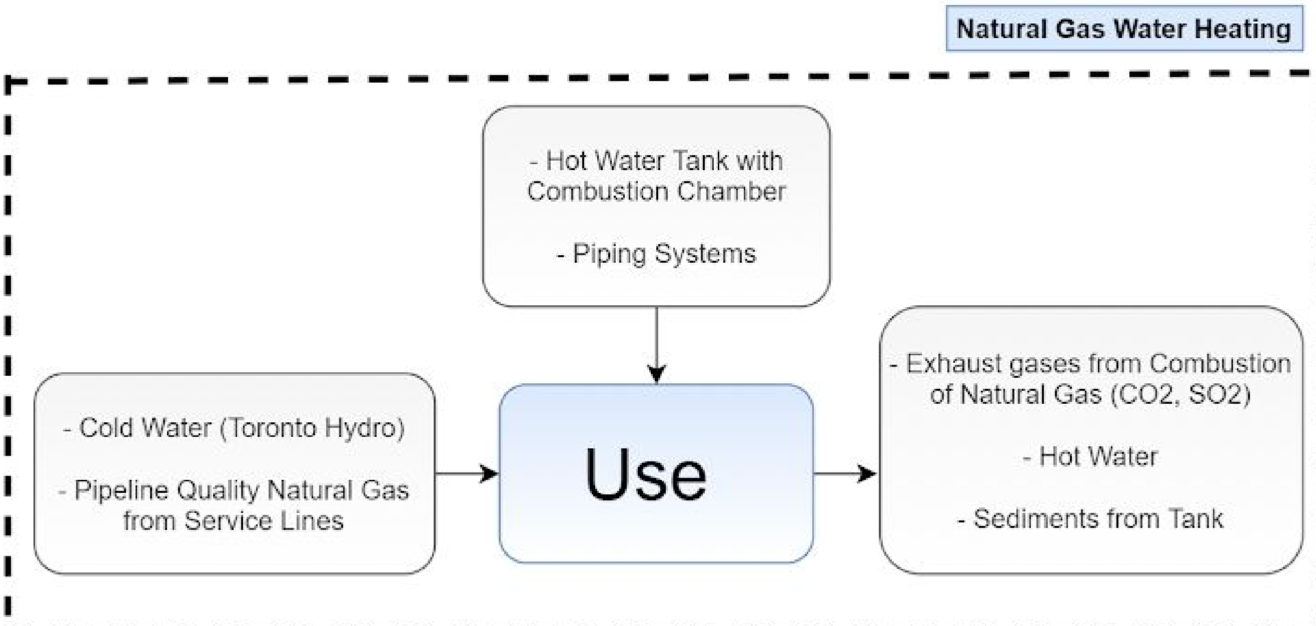

Figure 11. Flow Chart for Use Maintenance Phase of NG

Performance (Use)

PLCA

Description: The performance of NG is a unique process for this system. The limited sectors found in EIO-LCA provide a general average of economic and environmental data from the past. This can cause inaccuracy when trying to use this data to describe a unique system. PLCA provides the benefits of catering to the specific process by analyzing its inputs/outputs and their effects on the environment, and will therefore be used as our choice for analysis. Table 5 lists the environmental effects of the natural gas water heating system performance use phase, and Figure 12 illustrates the corresponding input and output flow diagram.

Table 5: Inputs and Outputs of NG Use Phase [49]

Name	Impact Result	Unit
Human Health - Carcinogens	0.00012	CTuh
Human Health - Non - Carcinogens	0.00075	CTuh
Ecotoxicity	3.82609E4	CTue
Respiratory effects	966.98773	Kg PM2.5eq
Acidification	2.20211E4	Kg SO2 eq
Resource Depletion - Fossil Fuels	2.04169E7	MJ Surplus
Ozone Depletion	0.22204	Kg CFC-11 eq
Eutrophication	849.13006	Kg N eq
Global Warming	4.04195E6	Kg CO2 eq
Photochemical Ozone Formation	1.95720E5	Kg O3 eq

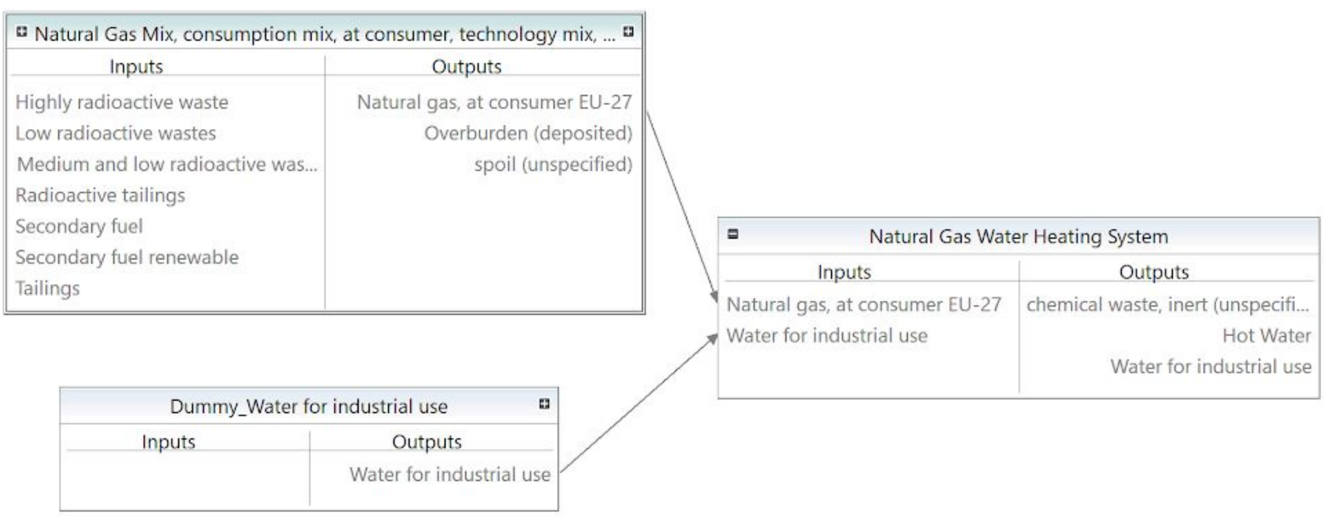

Figure 12: Flow Diagram for NG Use Life stage [49]

End of Life

Not included in analysis.

3.2 Solar Thermal Water Heating

Figure 13 illustrates the flow chart consisting of every life stage. The inputs and outputs of premanufacturing, manufacturing, distribution, use, and disposal are outlined.

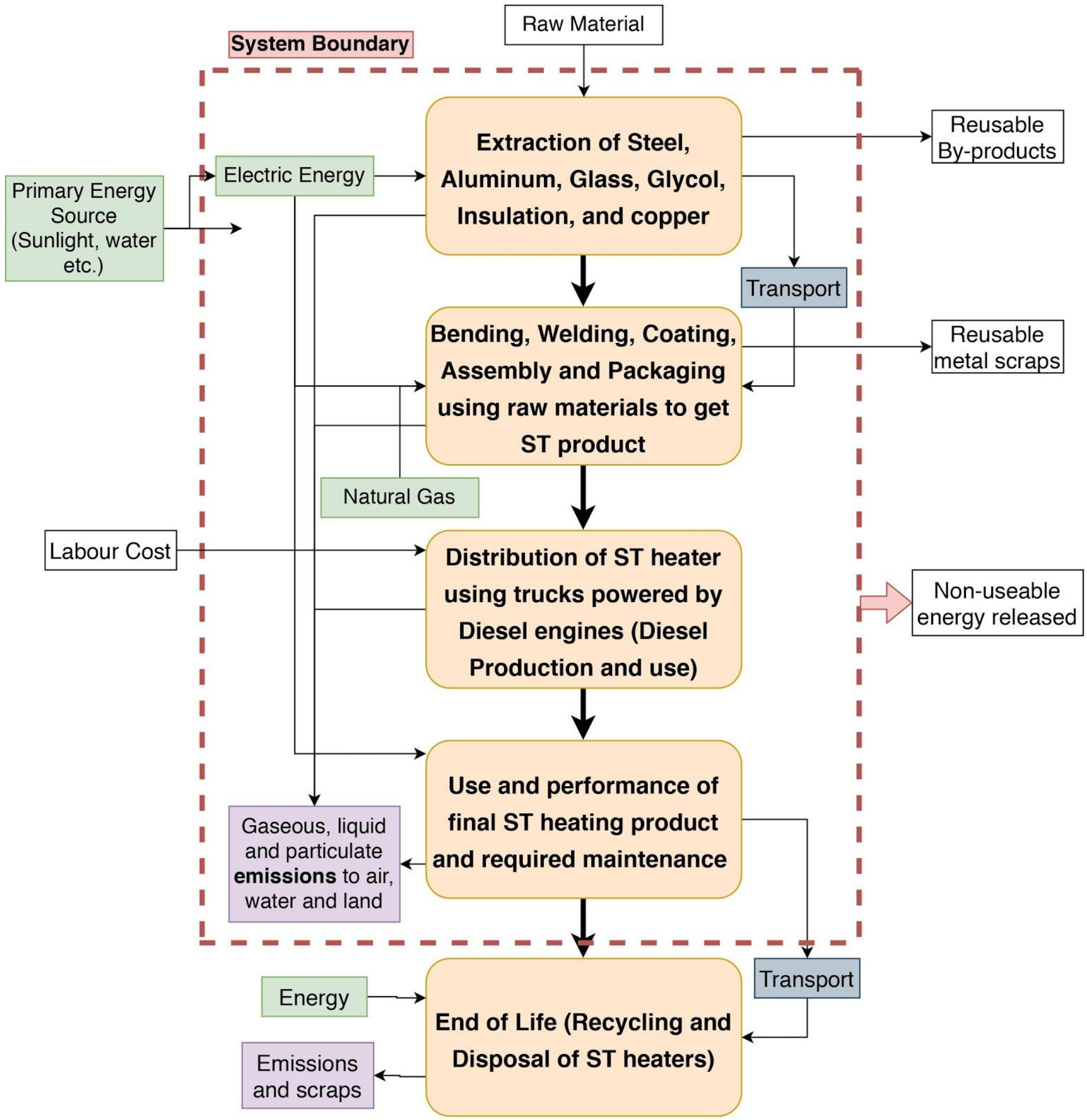

Figure 13. Final flowchart of life stages for ST

Pre-manufacturing

Analysis method for this life stage is using EIO-LCA for both the solar collector and tank (Figure 14). Specifically, the economic activity is displayed and used for calculation to find the value of each material below [50].

Raw Material: Aluminum found in the collector's framework and the heat exchanger in the tank
Sector: Alumina refining and primary aluminum production
Justification: The manufacturing of aluminum involves several machines that are involved in extraction and refinement during the Bayer and Hall-Heroult process [51]. Also, this process is used in the industry and data can be found [52]. Hence, EIO-LCA is chosen as the analysis method due to the commonality of the process, meaning it is not unique enough for a PLCA analysis.
Cost: $104.4/ST

Raw Material: Stainless Steel found in the tank's framework
Sector: Iron ore mining
Justification: Steel pre-manufacture involves iron extraction which includes several machinery that can help form the required material (Steel) [53]. As a result, EIO-LCA is the appropriate type of analysis here due to the industry wide application of this process and all indirect or direct data can be found for this process to evaluate the environmental and economic impact.
Cost: $264.8/ST

Raw Material: Copper for the solar collector's pipes and in the tank's coil
Sector: Primary smelting and refining of copper
Justification: Copper is manufactured through well implemented processes in the industry and information about it's available [54]. Since copper is used in the heating coil and the piping for the collector it must be considered in our emissions evaluation.
Cost: $505.5/ST

Raw Material: Magnesium found in the anode rod of the tank
Sector: Gold, silver, and other metal ore mining
Justification: Although a direct sector involving magnesium extraction is not mentioned, magnesium extraction is known in the industry with a similar process to other metal extractions like gold and silver [55]. Hence, EIO-LCA analysis is ideal
Cost: $12.9/ST

Raw Material: Glass container-like internal surface of the tank
Sector: Glass container manufacturing

Justification: For the internal surface of the tank that is made of glass, the sector can be found on the EIO website which indicates the public availability of the data and the commonality of the process in the industry [56].
Cost: $163.1/ST

Raw Material: Cover Glass for the collector's surface
Sector: Flat glass manufacturing
Justification: Cover glass and its manufacture process is a world-wide industry [57]. Hence, EIO-LCA is used.
Cost: $30.4/ST

Raw Material: Glycol found in both the solar collector
Sector: All other chemical product and preparation manufacturing
Justification: Glycol is a major component that is required for the heat exchange process in the system. The extraction process involves several chemicals that are passed to processes like hydrolysis [58]. These processes can be found to be prevalent in the industry implying that EIO-LCA is perfect.
Cost: $15.7/ST

Raw Material: Polyurethane Insulation found in both the solar collector and tank
Sector: Mineral wool manufacturing
Justification: This material is trickier since its manufacture is also known in the industry but finding an exact sector was an issue [59]. Hence, a similar process was found in the above sector and was used for direct and indirect output values for EIO-LCA.
Cost: $78.7/ST

Raw Material: Cardboard found in the packaging for the product
Sector: Paperboard container manufacturing
Justification: Cardboard which is used for our packaging is used world-wide [60]. Hence, EIO-LCA can be used.
Cost: $0.86/ST

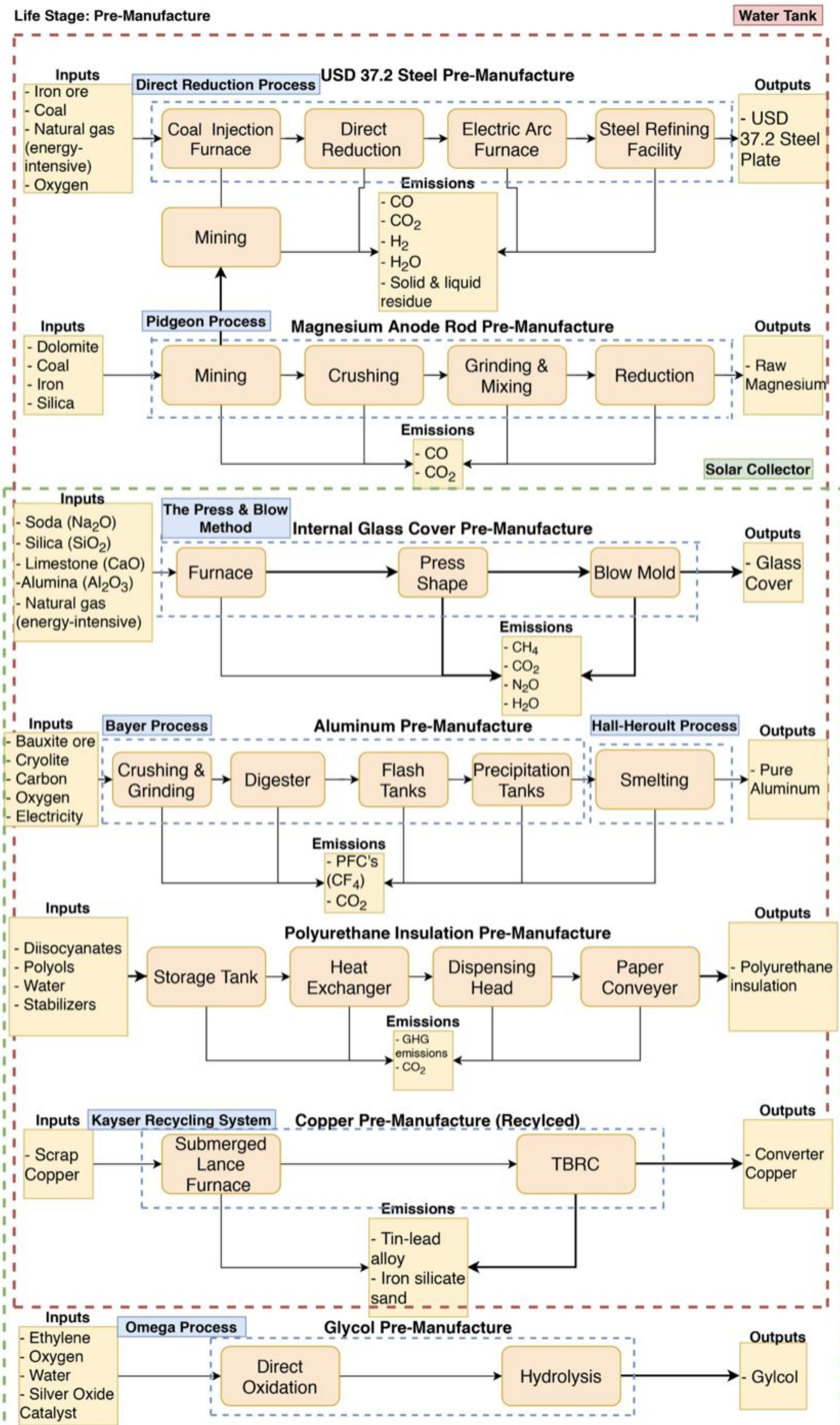

Figure 14. Premanufacturing Flow Chart for ST

Manufacturing
Analysis method for this life stage is using EIO-LCA for both the solar collector and tank (Figure 15). Specifically, the economic activity is displayed and used for calculation to find the value of each material below [50].

Manufacturing Process: Cutting and Bending different metals
Sector: Metal cutting and forming machine tool manufacturing
Justification: These machining processes are very common, therefore we can use EIO-LCA to get impact values (direct and indirect) [61].
Cost: $5.20 per ST

Manufacturing Process: Welding separate metals together
Sector: Fluid power process machinery
Justification: Welding is common practice and can be quantified using the sector above [62]. After understanding the process, information can be used and stretched for our purpose knowing some uncertainty and some aggregate data assumptions are taken.
Cost: $758.60 per ST

Manufacturing Process: Gluing materials together
Sector: Adhesive manufacturing
Justification: The process of gluing and adhesive manufacturing is very common, hence, EIO-LCA is used knowing the advantages of such analysis outweigh the drawbacks [63].
Cost: $2.37 per ST

Manufacturing Process: Coating
Sector: Coating, engraving, heat treating and allied activities
Justification: Coating is a wide-spread process that is used in the manufacturing industry to protect materials [64]. As a result, EIO-LCA can be used to analyze this specific process and help give values to the required outputs from past assessments of the sector. Note: there are irregularities in the data but this is preferred over using PLCA.
Cost: $5.45 per ST

Manufacturing Process: Assembly and Packaging
Sector: Packaging machinery manufacturing
Justification: The product is assembled which is not a major process that requires a separate sector. However, packaging is a final and major process that is used in the manufacturing industry to prepare products for shipping [65]. Hence, EIO-LCA is used for analysis by applying past product assessment on this product.
Cost: $9.9 per ST

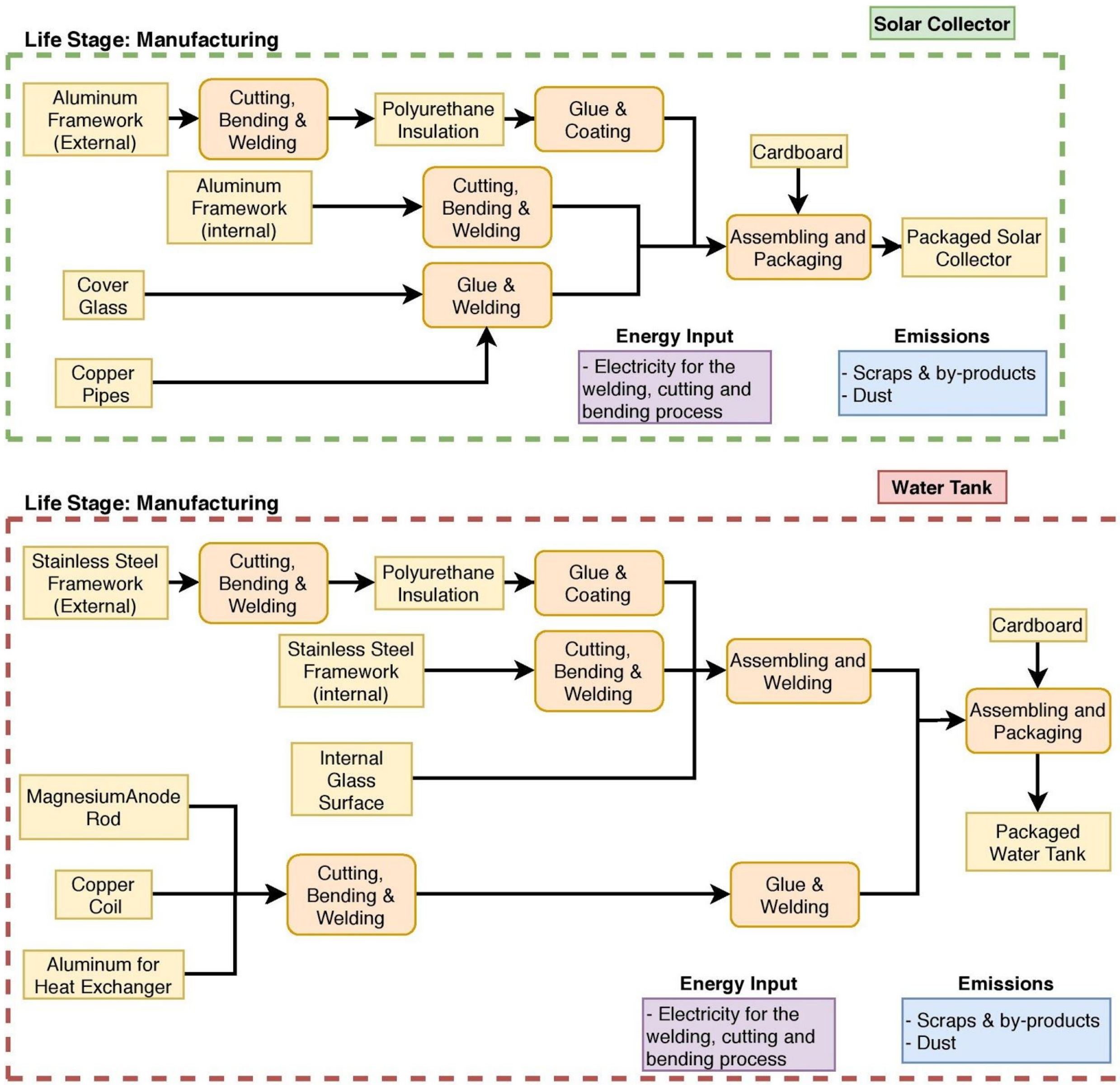

Figure 15.Flow Chart for Manufacturing ST

Transport

Analysis method for this life stage is using EIO-LCA for both the solar collector and tank (Figure 16). Specifically, the economic activity is displayed and used for calculation to find the value of each material below [50].

Energy Input: Diesel used by delivery trucks

Sector: Petrochemical manufacturing
Justification: The emissions (direct or indirect) can be found using the EIO-LCA due to its existence in the industry in the above sector [66].
Cost: $9.78 per ST

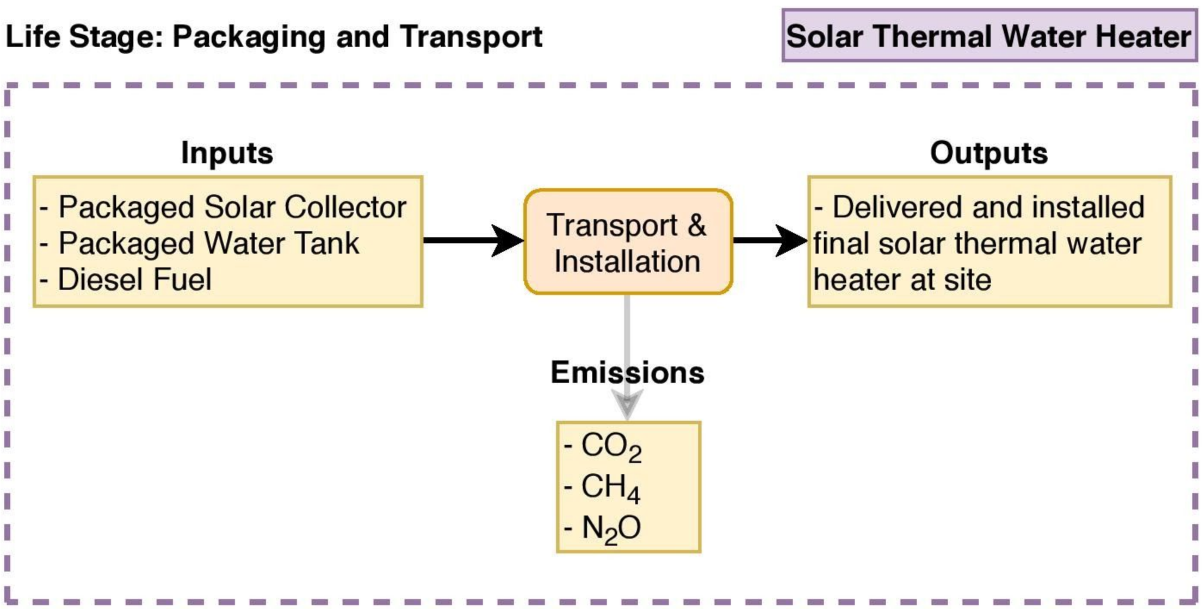

Figure 16. Flowchart for ST transport phase

Maintenance (Use)
The following section involves using EIO-LCA on maintenance specific Processes of the ST (Figure 17).

Solar Collector Cleaning
Sector: Soap and Cleaning Compound Manufacturing
Justification: To maintain optimal performance, solar collectors are washed with soap and water [67]. Since soap is the product of an independent industry and is not unique to the solar collectors, EIO-LCA is used.
Cost: $134.92/ST

Tank Maintenance
Sector: Residential Maintenance and Repair
Justification: The maintenance of the tank consists of repairing leaks among many other things. This repair is done by the residential custodial staff [68] which is a sector that is not specified to ST, therefore EIO-LCA is used.
Cost: $12,204/ST
Electric Backup Maintenance

Sector: Residential Maintenance and Repair
Justification: The maintenance of the electric backup consists of replacing the heating element to (Table 3) ensure sufficient heating of the water. This repair is done by the residential custodial staff which is a sector that is not specified to ST, therefore EIO-LCA is used.
Cost: $10,368/ST

Glycol Replacement
Sector: All other chemical product and preparation manufacturing
Justification: Glycol, the working fluid of the ST, is an essential part of the product that transfers heat from the sun to the water. To ensure that the heater is working, the glycol is replaced every 2-5 years [16] as its thermal properties deteriorate over time. Since glycol is a used chemical and not specific to ST, EIO-LCA is used.
Cost: $418.34/ST

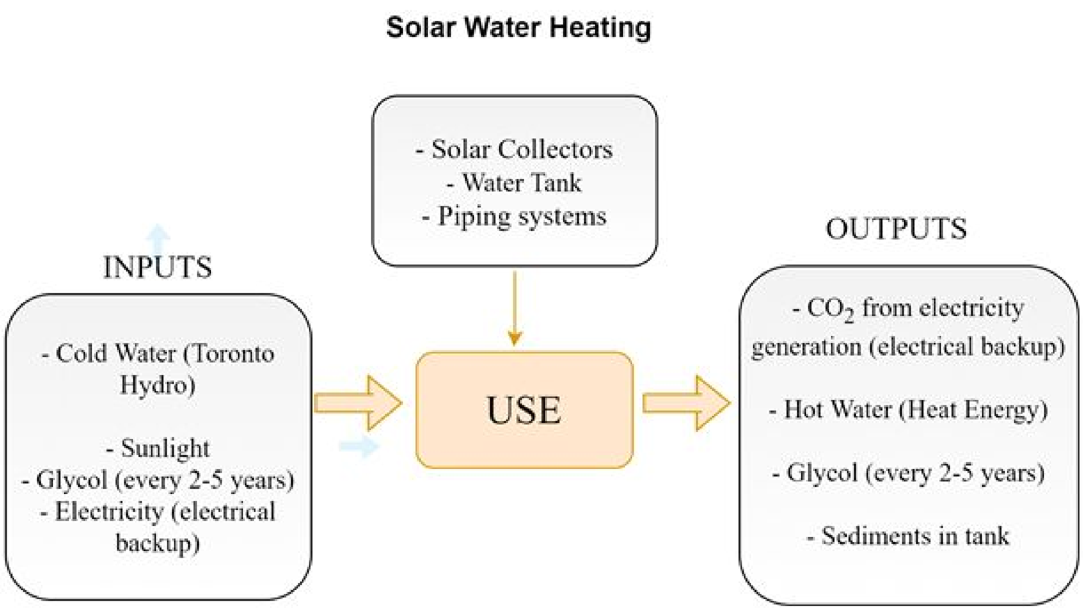

Figure 17. Flowchart for ST

Performance (Use)
(Analysis method for this life stage is using the PLCA)

Description: The performance of ST is dependent on the solar radiation it receives. The solar radiation that Toronto receives varies throughout the year, ranging from 3.19 to 6 kWh/m^2/day [69]. This translates to around 16.59 to 31.21 kWh/day of heat produced by the two 40 sq-ft solar collectors assuming 70% efficiency [70]. An electric water heater that uses around 3700W is also used between 50 to 80 days of the year when the solar collectors don't receive sufficient sunlight [14]. Since this analysis is process specific because of how the ST operates, no relevant sectors were found using EIO-LCA and PLCA was used instead. Table 6 lists the environmental effects of the ST performance use phase, and Figure 18 illustrates the corresponding inputs and outputs with a flow diagram.

Table 6: Environmental Impacts of ST during Use Phase [49]

Name	**Impact Result**	**Unit**
Human Health - Carcinogens	6.2154E-6	CTuh
Human Health - Non - Carcinogens	7.59189E-6	CTuh
Ecotoxicity	2255.295	CTue
Respiratory effects	52.0193	Kg PM2.5eq
Acidification	1239.063	Kg SO2 eq
Resource Depletion - Fossil Fuels	2.8418E5	MJ Surplus
Ozone Depletion	0.01375	Kg CFC-11 eq
Eutrophication	51.507	Kg N eq
Global Warming	1.99558E5	Kg CO2 eq
Photochemical Ozone Formation	1.1402E4	Kg O3 eq

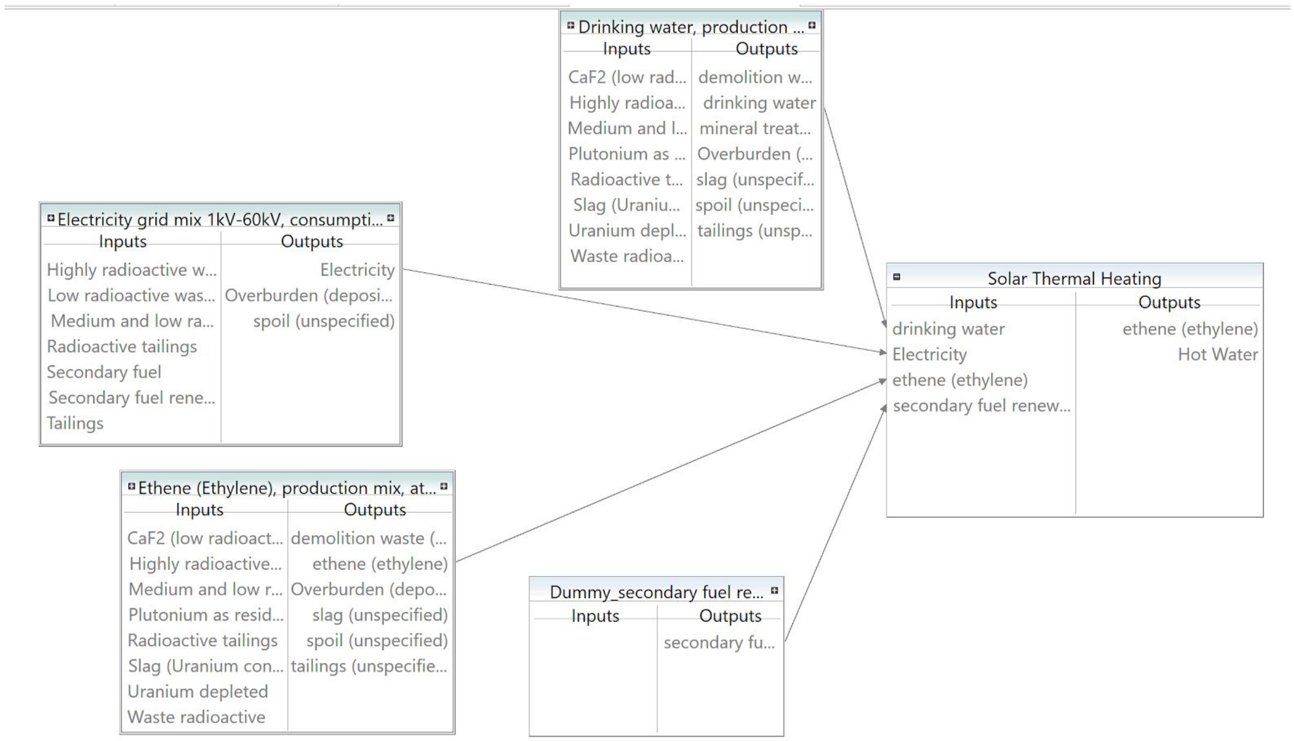

Figure 18. Flow chart of Use phase for ST [49]

End of Life
Not included in analysis.

3.3 Hybrid LCA Results

The total dollars per heating system for NG is $64,090.35 and for ST is $25,092.92. Note that the tanks are not compared; they are identical in both designs.

During premanufacturing, the main cost contributors in NG is the energy required in Well drilling and Inlet gas compression (Figure 19). The main contributors for cost for ST are the materials, Aluminum, Stainless Steel, copper, and glass. A direct comparison of NG vs ST depicts that cost is lower in ST because its materials have a lower cost as compared to the energy required in NG (Figure 20). ST has a product-based focus while NG has a process and energy based focus, resulting in a challenge to find a common ground for system comparison.

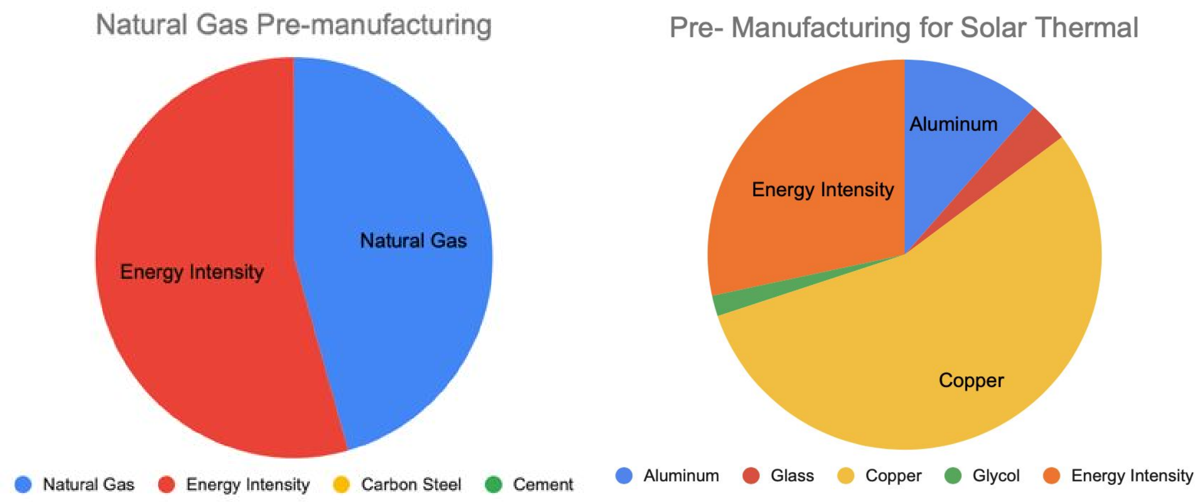

Figure 19. Major Cost Contributors in ST and NG

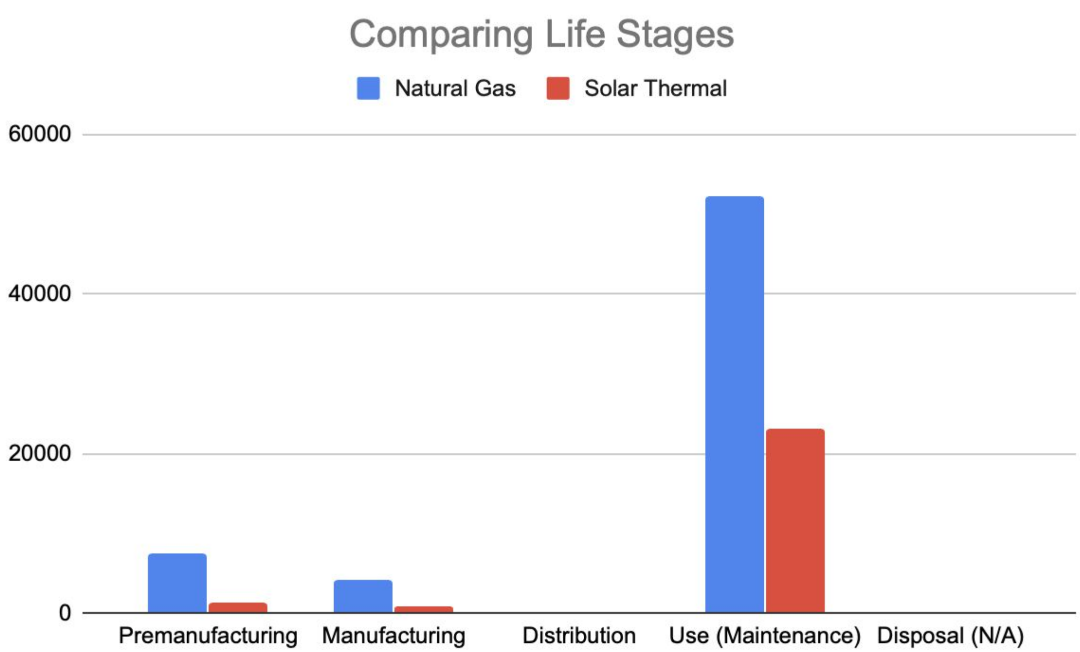

Figure 20. EIO Cost analysis of ST and NG

During manufacturing, the processes that utilize natural gas contribute to most of the cost (Figure 21). However, the amount of natural gas used is larger than the amount used in ST, resulting in NG having an overall higher cost (Figure 20). Despite that, different technologies could exist in Gas sweetening of NG, with lower consumption of natural gas inferring a lower overall cost.

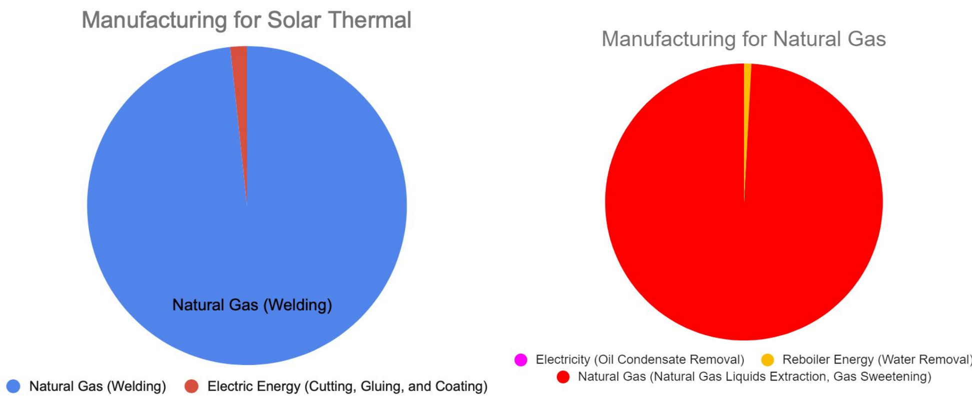

Figure 21. Manufacturing of ST vs NG

During Distribution, ST requires trucks powered by diesel engines which cost less compared to the transmission line in NG. Both systems require labour costs which increases the cost of transportation and introduces uncertainty. Distribution in both systems has an overall less cost than the other life stages (Figure 20).

As shown in Table 5 - 6, resource depletion is most impacted due to the natural gas in NG and the electric backup in ST, where NG has a larger impact. The electric backup operates 50-80 days annually since ST is efficient at converting sunlight to heat water [69]. NG resource consumption is higher due to NG requiring a constant supply of natural gas. Solar radiation in Toronto varies from 3.19-6 kWh/m^2/day, affecting the ability of ST to heat water to the required temperatures [70]. In terms of the maintenance phase, which utilizes EIO-LCA, NG costs more than ST due to the constant supply of natural gas (Figure 20).

Disposal is not included in the system boundary as both EIO-LCA and PLCA do not provide relevant sectors for analysis for this life stage. However, a discussion of the disposal effects can still be explored. All the metals, like aluminum, steel, and glass used are recyclable [14]. However, the insulation used is not recyclable and needs to be disposed of by professionals [14]. For ST, glycol is also recycled using chemical reactions in order to retain thermal properties.

4.0 Impact Assessment

Impact assessment consists of four sections: Selection of impact categories, quantified Classification, Characterization and Valuation of the results. The assessment is performed to quantify the effect of the processes in each life stage on the environment by analyzing the inputs, outputs, and energy consumption. This helps the team understand the results from the Hybrid LCA to make a stronger recommendation to the client.

4.1 Natural Gas Heating System

1. Selection

The following impact categories were chosen for the analysis and the reasoning for each selection is discussed: (See Appendix W for details)

- Global Warming
- Acidification
- Photochemical Smog
- Eutrophication
- Ozone Depletion

The categories chosen were selected based on the collected data of the emissions produced within each life stage.

2. Classification

Table 7 lists the inputs, outputs, and energy consumption for the life stages in NG and their corresponding environmental impacts.

Table 7: The inputs and outputs for certain sectors, found in PCR, for use during EIO-LCA

Product	**Life Stage**	**Inputs**	**Total Output Sectors** (TRACI) [50]				
			Global Warming (kg CO2 eq)	Acidification Air (kg SO2 eq)	HH Particulate Air (kg PM2.5)	Eutrophication Air (kg N eq)	Ozone Depletion (kg CFC-11 eq)
Natural Gas	Pre-manufacturing	Diesel Oil:62.25 x 10^3 kg Fuel Gas: 1.1 x 10^10 kg Energy Intensity:40.15 x 10^6 KWh Carbon Steel: 0.0236 Kg Cement: 28425 kg	Diesel Oil: 0.00528 Fuel Gas: 0.696 Energy Intensity: 37.832 Carbon Steel: N/A Cement: 4.99875	Diesel Oil: 0.2874 Fuel Gas: 27,797.36 Energy Intensity: 0.109 Carbon Steel: N/A Cement: 0.0211598	Diesel Oil: 0.0587 Fuel Gas: 5682.82 Energy Intensity: N/A Carbon Steel: N/A Cement: 0.00505	Diesel Oil: 0.01344 Fuel Gas: 1300 Energy Intensity: 0.0050 Carbon Steel: N/A Cement: N/A	Diesel Oil: N/A Fuel Gas: N/A Energy Intensity: N/A Carbon Steel: N/A Cement: 4.1643×10^{-5}
	Manufacturing	Oil Condensate Removal: Water	Oil Condensate Removal: 0.3097 Water	Oil Condensate Removal: 0.00139 Water	Oil Condensate Removal: 0.000235 Water	Oil Condensate Removal: 0.0000324 Water	Oil Condensate Removal: N/A Water

		Removal: Natural Gas Liquids Extraction: Gas Sweetening:	Removal: 5.1887 Natural Gas Liquids Extraction: 3856.1 Gas Sweetening: 5383.7	Removal: 0.0193 Natural Gas Liquids Extraction: 3.046 Gas Sweetening: 1.6759	Removal: 0.00404552 Natural Gas Liquids Extraction: 0.864 Gas Sweetening: 0.174	Removal: 0.0003499 Natural Gas Liquids Extraction: 0.088399 Gas Sweetening: 0.08424	Removal: N/A Natural Gas Liquids Extraction: N/A Gas Sweetening: 0.0001661
	Transport	Transmission Lines: Metering Station Valves:	Transmission Lines: 513.2 Metering Station 3.21 Valves: 1.443	Transmission Lines: 0.1166 Metering Station 0.0047797 Valves: 0.00215	Transmission Lines: 0.006344 Metering Station 0.000786 Valves: 0.000354	Transmission Lines: 0.006512 Metering Station 0.000191 Valves: 0.000086	Transmission Lines: N/A Metering Station N/A Valves: N/A
	Use	Natural Gas Supply	53907.1	408.28	36.16	0.00658	Negligible
	End of Life	N/A	0	0	0	0	0
Tank	Pre-manufacturing	Stainless Steel: 485.8 kg (Framework) Magnesium: 1.4 kg Copper: 40 kg Glass: 61 kg Polyurethane Insulation: 4.88 kg Cardboard: 2.5 kg Electric Energy: 3.5 GJ [72]	Steel: 348.6 Mg: 12.15 Glass: 127.6 Copper: 113.4 Insulation: 37.3 Cardboard: 0.25 [71]	Steel: 2.00 Mg: 0.069 Glass: 0.931 Copper: 1.55 Insulation: 0.233 Cardboard: 0.00168	Steel: 0.72 Mg: 0.029 Glass: 0.306 Copper: 0.43 Insulation: 0.125 Cardboard: 0.00052	Steel: 0.055 Mg: 0.002 Glass: 0.028 Copper: 0.015 Insulation: 0.00717 Cardboard: 0.000043	Negligible
	Manufacturing	**Cutting** is composed of milling, turning, facing, etc.	Cutting & Bending: 1.34 [73] Welding: 210.9 [74]	Cutting & Bending: 0.00576 Welding: 0.97	Cutting & Bending: 0.00194 Welding: 0.29	Cutting & Bending: 0.00014 Welding: 0.023	Negligible

		[61]. It requires machining tools and results in dust and heat. **Bending** which involves roll forming, spinning, deep drawing, etc. [78]. (Requires machinery) **Welding** is the act of joining separate pieces of metal together using heating [62]. (Requires heat for either electricity or gas) **Gluing** is used to fasten and bond two components that are non-metals [63]. **Coating** is a certain material that is deposited on surfaces [64]. **Assembling** involves cell and modular assembly which put together the final product [79]. **Packaging** is	Gluing: 1.12 [75] Coating: 2.88 [76] Assembling & Packaging: 2.05 [77]	Gluing: 0.0047 Coating: 0.011 Assembling & Packaging: 0.0097	Gluing: 0.0017 Coating: 0.0030 Assembling & Packaging: 0.003	Gluing: 0.00012 Coating: 0.00027 Assembling & Packaging: 0.000234	

		the final step that prepares the product for shipping [65]. (Requires manual labour)					
	Transport	Fuel (Diesel): 1.49 gallons [81]	Diesel: 9.91 [80]	Diesel: 0.0263	Diesel: 0.00697	Diesel: 0.000754	Negligible
	Use	<u>Tank Repairs:</u> \$2100 per lifetime <u>Cold Water Supply:</u> cold water from Toronto Hydro to be heated	1472.1	6.363	4.41	0.2142	Negligible
	End of Life	Energy needed to recycle[14]: • Copper - 10MJ/kg • Steel - 11.7MJ/kg • Glass - 12.1kJ/kg • Magnesium - 14.4MJ/kg [82] [83] Stainless Steel: 485.8 kg	4521.74	4.667	1.42	0.1244	Negligible

		Magnesium: 1.4 kg Copper: 40 kg Glass: 61 kg Polyurethane Insulation: 4.88 kg Cardboard: 2.5 kg					
TOTAL			65191.32 Kg CO2eq	28227 Kg SO2 eq	5727 Kg PM2.5 eq	1300.67 Kg N eq	Negligible

3. Characterization

Final values were found with the appropriate metrics in Table 8. These values were calculated using the 2002 TRACI database on the EIO website taking the CPI conversion into account. The required final values are:

- Global Warming - 65191.32 Kg CO2eq
- Acidification - 28227 Kg SO2 eq
- Photochemical Smog - 5727 Kg PM2.5 eq
- Eutrophication - 1300.67 Kg N eq
- Ozone Depletion - Negligible

4. Valuation

Focusing on the main three effects that can be found in the ReCiPe midpoint to endpoint document provided by the instructor can minimize the four above metrics to just three.

- Human Health: 3.66 DALY
- Biodiversity (Ecosystem): 6.17E-3 Species*yr
- Resource Consumption: 48517.02 USD2013

4.2 Solar Thermal Heating System

Life Cycle Impact Analysis Steps

1. Selection

The selection step for ST is the same as NG, and can be found in section 4.1.1.

2. Classification

Table 8 lists the inputs, outputs, and energy consumption for the ST system and their corresponding environmental impacts.

Table 8: The inputs and outputs for certain sectors, found in PCR, for use during EIO-LCA

Product	**Life Stage**	**Inputs**	**Total Output Sectors** (TRACI) [50]				
			Global Warming (kg CO2 eq)	Acidification Air (kg SO2 eq)	HH Particulate Air (kg PM2.5)	Eutrophication Air (kg N eq)	Ozone Depletion (kg CFC-11 eq)
Solar Collector	Pre-manufacturing	Aluminum: 20 kg (Framework) Glass: 11.3 kg Copper: 22.6 kg Polyurethane Insulation: 2 kg Cardboard: 1.8 kg Glycol: 6.72 L Electric Energy: 2.02 GJ [84]	Al: 112.2 Glass: 31.3 Copper: 64.1 Insulation: 15.3 Cardboard: 0.18 [71]	Al: 0.8434 Glass: 0.276 Copper: 0.875 Insulation: 0.096 Cardboard: 0.00121	Al: 0.218 Glass: 0.075 Copper: 0.243 Insulation: 0.051 Cardboard: 0.000377	Al: 0.009 Glass: 0.0115 Copper: 0.0085 Insulation: 0.0029 Cardboard: 0.000031	Negligible
	Manufacturing	**Cutting** is composed of milling, turning, facing, etc. [61]. It requires machining tools and results in dust and heat. **Bending** which involves roll forming, spinning, deep drawing, etc. [78]. (Requires machinery)	Cutting & Bending: 1.34 [73] Welding: 210.9 [74] Gluing: 1.12 [75] Coating: 2.88 [76] Assembling & Packaging: 2.05 [77]	Cutting & Bending: 0.00576 Welding: 0.97 Gluing: 0.0047 Coating: 0.011 Assembling & Packaging: 0.0097	Cutting & Bending: 0.00194 Welding: 0.29 Gluing: 0.0017 Coating: 0.0030 Assembling & Packaging: 0.003	Cutting & Bending: 0.00014 Welding: 0.023 Gluing: 0.00012 Coating: 0.00027 Assembling & Packaging: 0.000234	Negligible

		Welding is the act of joining separate pieces of metal together using heating [62]. (Requires heat for either electricity or gas) **Gluing** is used to fasten and bond two components that are non-metals [63]. **Coating** is a certain material that is deposited on surfaces [64]. **Assembling** involves cell and modular assembly which put together the final product [79]. **Packaging** is the final step that prepares the product for shipping [65]. (Requires manual labour)					
	Transport	Fuel (Diesel): 1.49 gallons [81]	Diesel: 9.91 [80]	Diesel: 0.0263	Diesel: 0.00697	Diesel: 0.000754	Negligible
	Use	Sunlight: ~37.05 kWh/day Electricity: backup requires 3700W and operates 3 hours per day, 80 days per year Cold water: Water supply from Toronto Hydro	Electricity: 32077.26 Glycol: 15.9 Solar Collector Cleaning: 166.50	Electricity: 173 Glycol: 0.26 Solar Collector Cleaning: 1.52	Electricity: 34.2 Glycol: 0.09 Solar Collector Cleaning: 0.64	Electricity: 2.52 Glycol: Negligible Solar Collector Cleaning: Negligible	Electricity: Negligible Glycol: Negligible Solar Collector Cleaning: Negligible

		Glycol: required approximately every 3 years Solar Collector Cleaning: soap and water are used to clean the collectors					
	End of Life	Energy[16]: ● Copper - 10MJ/kg to recycle ● Aluminum - 55.44MJ/kg to recycle ● Glass - 12.1kJ/kg to recycle Aluminum: 20 kg Glass: 11.3 kg Copper: 22.6 kg Polyurethane Insulation: 2 kg Cardboard: 1.8 kg	447.59	0.43	0.14	0.02	Negligible
Tank	Pre-manufacturing	Aluminum: 7.5 kg Stainless Steel: 485.8 kg (Framework) Magnesium: 1.4 kg Copper: 40 kg Glass: 61 kg Polyurethane Insulation: 4.88 kg Cardboard: 2.5 kg Electric Energy: 3.5 GJ [72]	Al: 42.1 Steel: 348.6 Mg: 12.15 Glass: 127.6 Copper: 113.4 Insulation: 37.3 Cardboard: 0.25 [71]	Al: 0.316 Steel: 2.00 Mg: 0.069 Glass: 0.931 Copper: 1.55 Insulation: 0.233 Cardboard: 0.00168	Al: 0.082 Steel: 0.72 Mg: 0.029 Glass: 0.306 Copper: 0.43 Insulation: 0.125 Cardboard: 0.00052	Al: 0.004 Steel: 0.055 Mg: 0.002 Glass: 0.028 Copper: 0.015 Insulation: 0.00717 Cardboard: 0.000043	Negligible
	Manufacturing	**Cutting** is composed of	Cutting & Bending:	Cutting & Bending:	Cutting & Bending:	Cutting & Bending:	Negligible

		milling, turning, facing, etc. [61]. It requires machining tools and results in dust and heat. **Bending** which involves roll forming, spinning, deep drawing, etc. [78]. (Requires machinery) **Welding** is the act of joining separate pieces of metal together using heating [62]. (Requires heat for either electricity or gas) **Gluing** is used to fasten and bond two components that are non-metals [63]. **Coating** is a certain material that is deposited on surfaces [64]. **Assembling** involves cell and modular assembly which put together the final product [79]. **Packaging** is the final step that prepares the product for shipping [65]. (Requires manual labour)	1.34 [73] Welding: 210.9 [74] Gluing: 1.12 [75] Coating: 2.88 [76] Assembling & Packaging: 2.05 [77]	0.00576 Welding: 0.97 Gluing: 0.0047 Coating: 0.011 Assembling & Packaging: 0.0097	0.00194 Welding: 0.29 Gluing: 0.0017 Coating: 0.0030 Assembling & Packaging: 0.003	0.00014 Welding: 0.023 Gluing: 0.00012 Coating: 0.00027 Assembling & Packaging: 0.000234	
	Transport	Fuel (Diesel): 1.49 gallons [81]	Diesel: 9.91 [80]	Diesel: 0.0263	Diesel: 0.00697	Diesel: 0.000754	Negligible
	Use		1553.07	6.71	4.65	0.23	Negligible

	End of Life 2215.5	Energy needed to recycle[16]: ● Copper - 10MJ/kg ● Steel - 11.7MJ/kg ● Aluminum - 55.44MJ/kg ● Glass - 12.1kJ/kg ● Magnesium - 14.4MJ/kg [82][83] Aluminum: 7.5 kg Stainless Steel: 485.8 kg Magnesium: 1.4 kg Copper: 40 kg Glass: 61 kg Polyurethane Insulation: 4.88 kg Cardboard: 2.5 kg	5693.84	5.45	1.76	0.21	Negligible
Total			39402.18 Kg CO_2 eq	196.65 kg SO_2 eq	6.42 kg PM2.5 eq	3.19 kg N eq	Negligible

3. Characterization

Final values were found with the appropriate metrics in Table 9. These values were calculated using the 2002 TRACI database on the EIO website taking the CPI conversion into account. The required final values are:

- Global Warming - 39402.18 Kg CO_2 eq
- Acidification - 196.65 kg SO_2 eq
- Photochemical Smog - 6.42 kg PM2.5 eq
- Eutrophication - 3.19 kg N eq
- Ozone Depletion - Negligible

4. Valuation

Focusing on the main three effects found in the ReCiPe midpoint to endpoint document provided by the instructor can minimize the four above metrics to just three.

- Human Health: 7.6E-2 DALY
- Biodiversity (Ecosystem): 1.55E-4 Species.year
- Resource Consumption: 14.5 USD 2013

4.3 Impact Assessment Results

Following the impact analysis, the final valuation results are compiled into bar charts, as shown in Figures 22 - 24. The goal of these charts is to illustrate visual context for direct comparison between the results of the two systems. This allows the team to draw accurate claims.

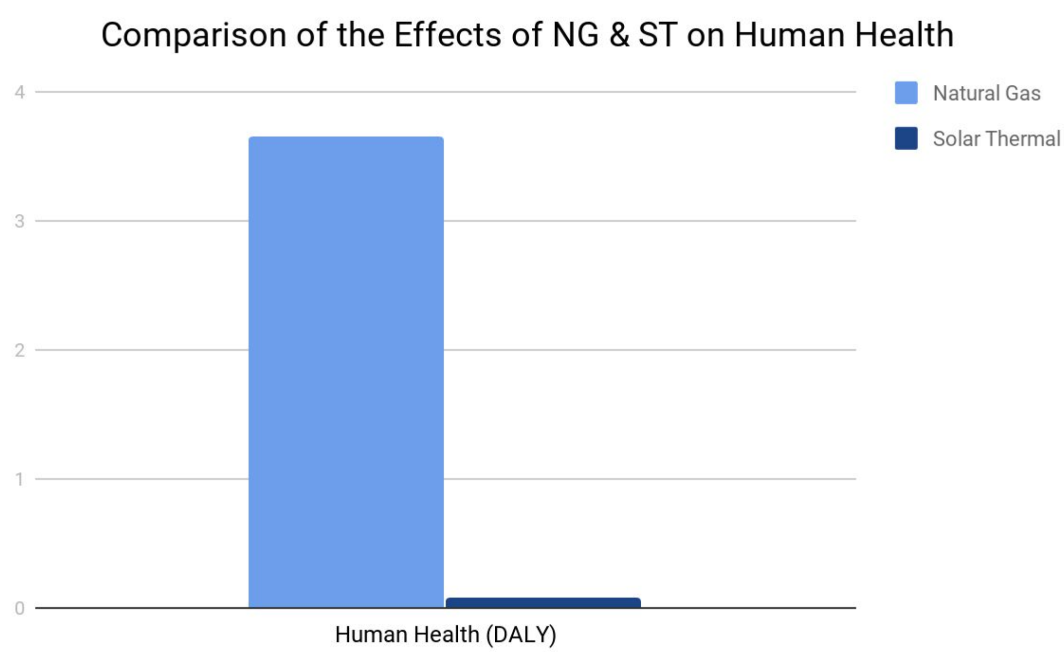

Figure 22. Human Health ST and NG comparison

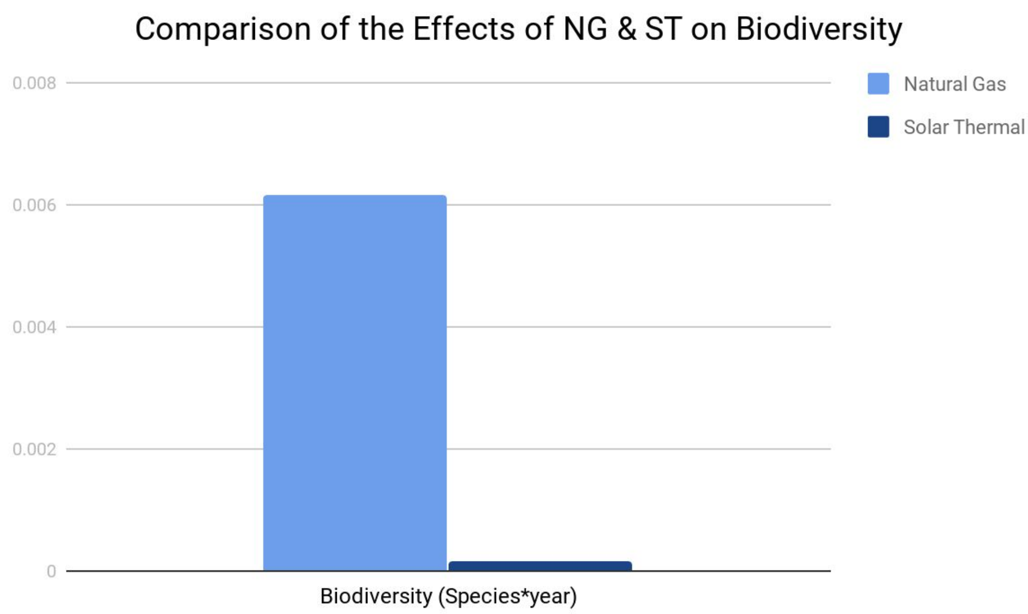

Figure 23. Biodiversity ST and NG comparison

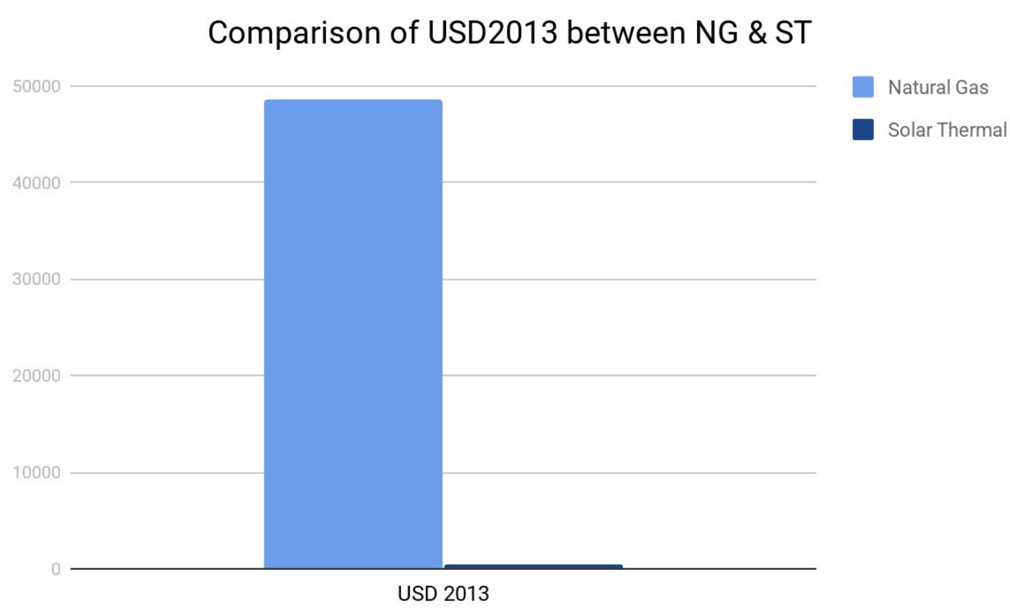

Figure 24. Resource Consumption of ST and NG

The Human Health factor, DALY, includes damages done to human health ranging from climate change to toxic chemical exposure [85] by quantifying the gap between the ideal healthy living and the current health status [86]. The high DALY value found in NG due to the large amounts of CO2eq, resulting from the gas sweetening stage, suggests that the manufacturing processes used for NG reduce the quality of life due to illnesses (Figure 22). Furthermore, the large CO2eq in the transport of NG suggests leakages exist throughout the transmission lines, which could be the result of Carbon Steel corrosion.

Biodiversity reflects the effect on the environment and its species. Hence, the higher the value, the worse off the environment is. This implies that NG has a direct effect on the Earth's species due to its higher value (Figure 23). This is expected as NG utilizes high energy intensity found natural gas which produces emissions during the use stage unlike the ST's clean energy.

The NG requires a constant input of natural gas during the use phase for the system to function, while ST requires replacement of glycol, a fluid that is more environmentally friendly than natural gas. Analyzing Figure 24, it is evident that NG's reliance on natural gas to function translates to why NG's Resource Consumption is more than 3000x greater than ST.

5.0 Societal Analysis

Starting by identifying the stakeholders involved throughout the life stages of the systems, their location, interests, and needs. The first stakeholder is the local community since the (Pre-)production of these systems can impact their health, safety and cultural heritage. This includes aboriginal communities living in forests, where their need is access to clean water [87][88]. The workers, during (Pre-)production, may face discrimination, poor working conditions and an absence of a contract. Finally, the consumers and the society itself are concerned about their health, safety, corruption and economic development during the use and disposal phases.

5.1 Natural Gas Water Heating

Table 9 lists the stakeholders and the effect of the NG.

Table 9 : A breakdown of the different stakeholder groups and the life stages involved to provide a justified score that can be used for comparison

Stakeholder Group	**Subcategory** (Life Stage)	**Status** (i.e. score justification)	**Score** (0-4)
Local Communities	Cultural Heritage (Pre-manufacturing) N/A for other life stages	Arising of subcultural conflict within domestic local communities and the labor force involved in the operation of the project [89]. Utilizing industrial camps as a substitute to regular housing could potentially result in the risk intensification of forest fires and demolition of sacred places [90].	2
	Health and Safety (Manufacturing) N/A for other life stages	During the production phase of a well, a significant percentage of the drilling fluid uses sediments in underground water reserves, which ultimately results in the pollution of groundwater. This directly affects nearby communities which depend on drinking water pumped from wells. Solutions include pumping the groundwater into surrounding ponds; however, it could potentially leak into groundwater in the vicinity of the pond, which could ultimately have a negative impact on wildlife animals health [91].	1

Worker	Presence of Legal Contract (Manufacturing) N/A for other life stages	With the increase and decrease of the work demand and supply in the oil and gas industry, there could exist several renegotiations. The effect of this is an increase in the risk of layoffs and lower insurance protection given to a worker [92].	2
	Discrimination (Manufacturing) N/A for other life stages	The main form of discrimination within the oil and gas industry is in the form of age discrimination. This is shown through [93]: 1. HRs set certain criteria that does not admit job applicants of over a certain age. 2. Legally change the criteria which could affect the age at which employees should leave work.	2
	Health and Safety (Pre-manufacturing) N/A for other life stages	High fatality rate in the operations within the raw gas extraction procedures. This is due to the contact with on-site equipment as well as the exposure to toxic environmental emissions [94].	1
Society	Contribution to Economic Development (Use and Disposal) N/A for other life stages	In the drilling sector of raw gas extraction, there will be an increase in the total jobs by 12,000 over a span of 10 years, amounting to a total of 30,100 jobs by 2027 [95].	4
	Corruption (All Life Stages)	Bribery (Premanufacturing): Due to government policies, companies of the Oil and Gas industry must adhere to providing contracts to local vendors. Fraud as well as other abuses could result from the supplier's end to win these profitable deals [96]. Bribery (Transport and Storage) Due to government policies, the	1

		transport of goods includes detailed inspection at the border, which is carried by government personnel such as officials and agents. This is to avoid the transport of illegal products, even through pipelines. Bribery occurs in the event where it could accelerate the customs clearance through an import or export permit [97]. Corruption at the border could have severe impacts in the long run on investment as well as public expenditures. According to the World Bank, this could lower the confidence the public places in governmental bodies, and could result in an overall decrease in the agreement to other customs laws by the business sector [98].	
Consumer	Health and Safety (Use and Disposal) N/A for other life stages	Natural gas is odorless; however, it has an added scent on the consumers' side to give a unique smell that can be recognized by the consumer in the case of an unexpected leakage. Natural gas has safety measures and safety results which exceed other energy forms. In the case of a leakage, risks include explosion due to a fire ignition with air [99].	3
Total (Out of 32)			15 Or 47%

Strategies to mitigate issue:

1) To detect illegal payments, strict controls are applied. For instance, reviewing transactions, detecting payment that led to increased supplier satisfaction, and direct control of the company's cash [96].
2) Apply anti-corruption measures in the form of good controllership. These include the application of rules on travel expenses, as well as reporting of the business purpose of any particular trip [96]

5.2 Solar Thermal Water Heating

Table 10 lists the stakeholders and the effects of ST.

Table 10: A breakdown of the different stakeholder groups and the life stages involved to provide a justified score that can be used for comparison

Stakeholder Group	**Subcategory** (Life Stage)	**Status** (i.e. score justification)	**Score** (0-4)
Local Communities	Cultural Heritage (Pre-manufacturing) N/A for other life stages	When making steel, natural gas is used as a heat source at the furnace. Natural gas requires a pipeline which does harm to Canada's cultural lands [100]. Note that this is the only part of the process that does harm.	2
	Health and Safety (Use) N/A for other life stages	When the system is implemented and is being utilized by the user, it does no harm to the community's health since solar energy is clean without emissions the degrade health [101].	4
Worker	Presence of Legal Contract (Manufacturing) N/A for other life stages	Steel workers and metal workers in general in Canada are required to have labour contracts [102]. Although the regulations are strict ensuring contracts are fair, some may be pressured to accept harsher contracts (more working hours) and they lack power to fight back.	3
	Discrimination (Manufacturing) N/A for other life stages	Canada is known for its diversity and that applies to the metal workers as well. The industry is open to all races with regulation protecting against discrimination [103]. Unfortunately, discrimination is embeded in our society and eliminating it completely is challegening. We can only regulate it on a high level.	3
	Health and Safety (Manufacturing) N/A for other life stages	Although the regulation in Canada (on a federal level) help create a safer work environment (i.e. hardhats, steel toe	

		boots, etc.), the nature of the work is dangerous and put the workers at risk that can only be avoided if a large sum of additional money is spent [104].	2
Society	Contribution to Economic Development (Use and Disposal) N/A for other life stages	Solar thermal water heaters actually positively affect the economic development of a home that installs it. Electric bills are lower and the overall home resale value increases [105].	4
	Corruption (All Life Stages)	Again, the product is entirely manufactured and used in Canada (from raw materials to disposal). Since Canada placed 12th between countries that are least corrupt, we can safely consider corruption is not a main factor [106]. However, some internal company corruption may still exist which slightly lowers its score.	3
Consumer	Health and Safety (Use and Disposal) N/A for other life stages	Similar to local communities, solar is clean and won't result in emissions that put the consumer at risk. Some materials may contain slight toxins but not significant enough to cause concern [107].	3
Total (Out of 32)			24 Or 75%

Strategies to mitigate issues:

1) One of the main weaknesses is the safety of workers which is due to employers minimizing expenditure on safety during the steel manufacture. Hence, utilizing a different material would mitigate this issue (e.g. aluminum since lighter and easier to deal with).

5.3 Societal Analysis Results

ST had a final score of 75% which was higher than NG score, 47%. NG extraction in the pre-manufacturing phase introduces negative impacts on health/safety of local communities by polluting groundwater reserves, and affecting surrounding wildlife as well. Meanwhile, ST is considered a clean source of energy which mitigates all the issues faced by NG.

6.0 Sensitivity Analysis For Hybrid LCA and Impact Assessment

Sensitivity analysis will be conducted on the use (performance) life stage, analyzed using PLCA, to identify how uncertainties in the literature values for the inputs will affect the categories selected in the impact assessment.

Assumption:

Intensity of usage was taken to be 20 gallons of water per person in the residence. Knowing that there are 7-9 persons in the residence, two 80 gallon tanks were used to fulfill the required capacity.

6.1 Natural Gas Water Heating

Significant Uncertainty: NG

The parameter used in performing the sensitivity analysis is NG. NG was used as an input in PLCA in the use stage. The input varied over a range of 100,000 m^3 to 180,000 m^3, as shown in Figure 25. This input was chosen due to its dependence on variables such as the amount of hot water used on the residences and the efficiency of the tank. This results in a large window of possible natural gas volumes per lifetime. Because of this, natural gas will be examined using sensitivity analysis to determine whether a difference in the natural gas volume per lifetime will increase any environmental impacts.

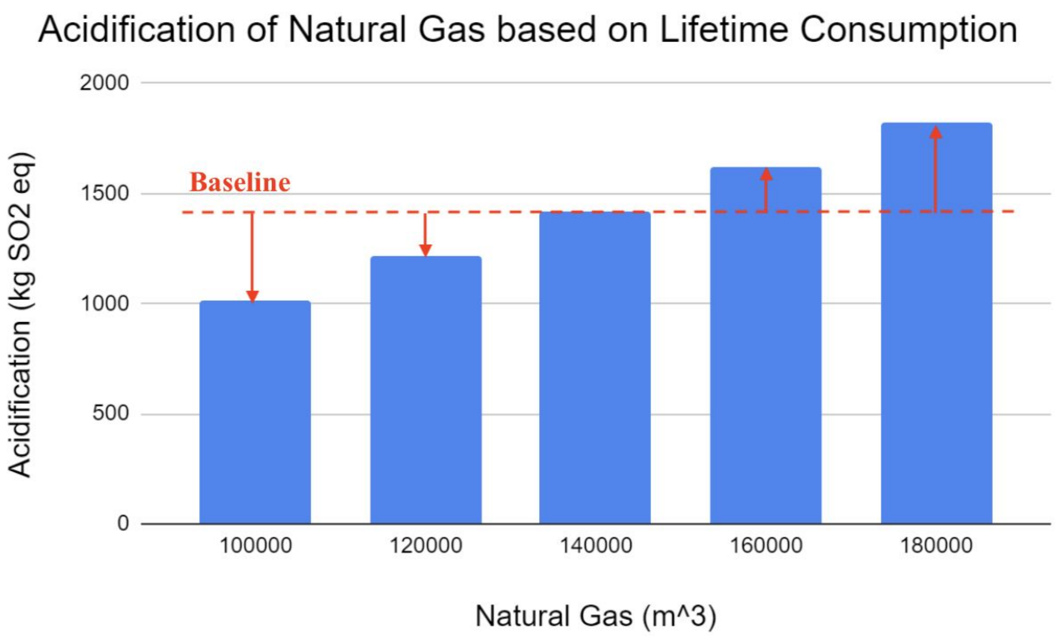

Figure 25. Acidification (kg SO2eq) vs Natural Gas (m^3) with a baseline for comparison [49]

Sensitivity Analysis:

The outputs of the process were selected to be the five categories used in the impact assessment. The collected data from the outputs were compiled over the entire range, and the most significant output change was found, Acidification. The baseline was selected to be the average of the input range, 100,000 - 180,000, and the average of the Acidification data collected over the entire range, as shown on Figure 25. According to Figure 25, the trend shown is a direct proportionality in the change of the inputs to the change of the outputs and was confirmed using the OpenLCA software.

Conclusion:

This shows that natural gas has a direct effect on the emissions of SO_2 to the environment through a linear relationship. The greatest variance away from the baseline was 28.53% from the baseline which suggests that second hand calculations are valid for this analysis.

6.2 Solar Thermal Water Heating

Significant Uncertainty: (ST)

The main uncertainty that was encountered during the performance phase of the ST heater was the number of days that the electric backup is required to operate. This is due to the variation of the solar radiation that ST receives throughout the year, ranging from 3.19 to 6 kWh/m^2/day, which affects how much of the water it is able to heat. Literature values suggested that the backup operates between 50 to 80 days of the year (Figure 26).

Sensitivity Analysis:

Compared to the four impact categories, photochemical smog formation was found to have the largest variance as the input varied from 50 to 80 days. The resulting baseline was calculated as the average of the kg CO3eq. Input varies by 7.5 days and the resulting change in smog formation was found to be linear (Figure 26) using OpenLCA software. A baseline is then found based on the average of these results. The aim is to find the error variation of these results from the baseline and draw a conclusion about the PLCA accuracy.

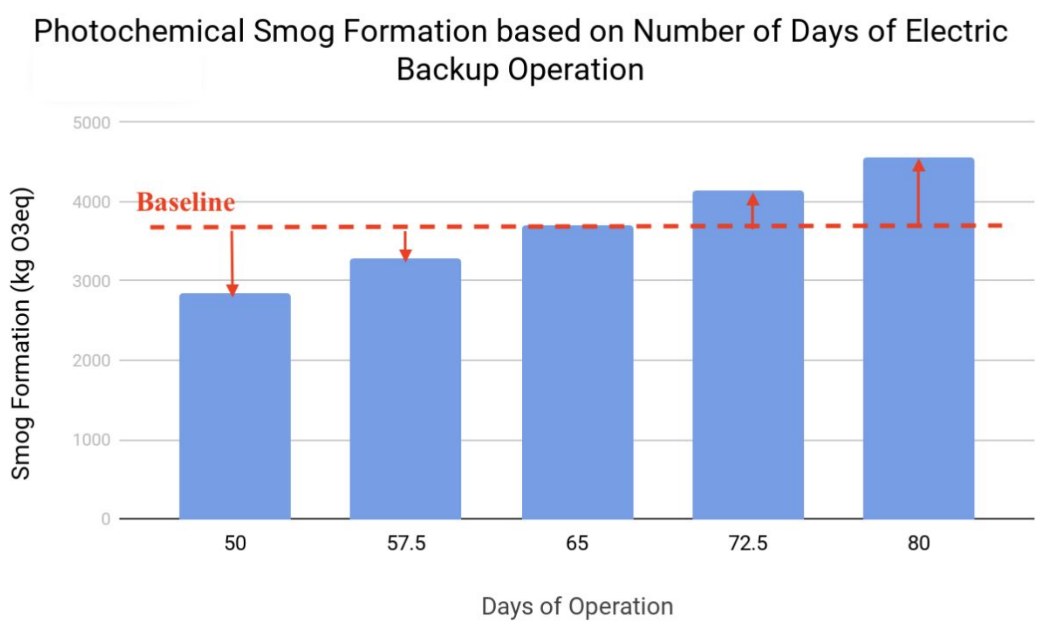

Figure 26. Smog Formation (kg O3eq) vs Operation Days with baseline [49]

Conclusion:

Smog formation is linearly dependent on the number of electric backup operation days. The greatest variance away from the baseline was 23.08% from the baseline which suggests that second hand calculations are valid for this analysis.

7.0 Summary and Recommendations

Economic, Hybrid, Societal, and Sensitivity analysis were conducted on NG and ST to determine the final recommendation. The results of the analyses will be incorporated with design for environment strategies to determine how well the systems incorporate the strategies, and the final recommendation for the client will be determined.

The first design for environment (DfE) strategy discussed is the minimizing of resource consumption. Although the main energy consuming process for ST is virgin material extraction, it is still lower than NG that uses high energy at the inlet gas compressor. Using the results of Hybrid LCA, NG has an energy intensive process in comparison with ST in the pre-manufacturing stages. Also, ST employs passive energy in the use phase by converting solar radiation to heat water using glycol as a medium for heat transfer, while NG uses active energy to pump a supply of natural gas. This can be seen through the results of Economic analysis on the Use phase, where the NG use costs are higher than ST uses costs, even though NG use accounts for 30% less of the overall cost.

The next DfE strategy is to use low impact resources. Regarding the energy cascade, ST uses solar radiation, low energy quality, and NG uses natural gas, high energy quality. Since heating water requires low quality, ST is more efficient as it converts from low to low. Using economic analysis, AEW of ST ($1662.16) is less than that of NG ($1782.22) which suggests that ST is more efficient. Regarding renewable energy and toxicity, ST uses solar radiation as its main form of energy input, a renewable energy source that produces no emissions. NG uses fossil fuels that are non-renewable and emit harmful substances when burned. This can be seen in the Use performance phase Impact Assessment, where the midpoint-to-endpoint ReCiPe category results for NG range from 70 -3000x larger than ST.

Optimizing the product lifetime is the third DfE strategy considered. In terms of facilitating maintenance, repairs, cleaning, and remanufacturing, ST requires dust and vegetation removal as they block sunlight from the solar collectors. In contrast, NG requires maintenance to ensure toxic gas leaks are avoided, which is shown in its maintenance cost. Both systems require periodic tank maintenance to ensure efficiency and extended lifetime. This can be seen in the use maintenance phase EIO-LCA where there are large costs

The following DfE strategy is to extend the material lifetime. A comparison between NG and ST depicts that NG combustion in the heating tank combustor has irreversible effects on the materials involved, reducing recycling opportunities. In contrast, ST uses a heat exchanger to heat the water. This increases the materials' lifetime used and allows for recycling opportunities.

From the above analyses, the team recommends the Solar Thermal Water Heating System as the design that is most sustainable and will maximise the grant. Also, it is less energy intensive, uses low impact resources, optimizes the product lifetime, extends material life and designs for disassembly. In addition, it can be further improved in certain aspects that can help strengthen the recommendation.

There are a few recommendations based on the DfE strategies that can be implemented into the ST to increase its sustainability. Firstly, to minimize ST energy consumption, it is recommended to use more recycled materials instead of virgin materials since it can minimize energy consumption by 90-95% [14]. Furthermore, to improve ST as a passive system, a fluid that has better thermal properties than glycol can be used to increase efficiency. For the solar energy quality, not much improvement can be made as it is already optimized. To further optimize the lifetime and facilitate maintenance, automated solar collector cleaning should be added and a tankless alternative should be used.

8.0 References

[1]Energyeducation.ca. 2020. *Domestic Water Heating - Energy Education*. [online] Available at: <https://energyeducation.ca/encyclopedia/Domestic_water_heating> [Accessed 19 March 2020].

[2]"Our Homes," Campus Cooperative Residences. [Online]. Available: https://campus.coop/houses/. [Accessed: 19-Mar-2020].

[3]2020. [Online]. Available: https://www.lowes.com/n/how-to/when-to-replace-a-water-heater. [Accessed: 16- Mar- 2020]

[4]"Save Money and More with ENERGY STAR Qualified Solar Water Heaters", *Energystar.gov*, 2020. [Online]. Available: https://www.energystar.gov/products/water_heaters/water_heater_solar/benefits_savings. [Accessed: 16- Mar- 2020]

[5]*Aceee.org*, 2020. [Online]. Available: https://www.aceee.org/files/proceedings/2000/data/papers/SS00_Panel1_Paper14.pdf. [Accessed: 16- Mar- 2020]

[6]"5 Moving Truck Rental Alternatives to U-Haul in Toronto | MovingWaldo", *Movingwaldo.ca*, 2020. [Online]. Available: https://www.movingwaldo.ca/moving-truck-rental/5-truck-rental-alternatives-to-u-haul-in-toronto/. [Accessed: 16- Mar- 2020]

[7]"2020 Water Heater Installation Cost | New Water Heater Cost", *Fixr.com*, 2020. [Online]. Available: https://www.fixr.com/costs/install-water-heater. [Accessed: 16- Mar- 2020]

[8]"Water Heater Repair Service Costs In 2018 [Quick Guide]", *Carroll Plumbing & Heating, Inc.*, 2020. [Online]. Available: https://www.carrollplumbingva.com/water-heater-repair-service-costs-guide/. [Accessed: 16- Mar- 2020]

[9]"How Much Natural Gas Do These Appliances Use? | Oasis Energy", Oasis Energy, 2020. [Online]. Available: https://oasisenergy.com/appliances-natural-gas-usage/. [Accessed: 16- Mar- 2020]

[10]"Pricing2 - JUST JUNK®", *JUST JUNK®*, 2020. [Online]. Available: https://justjunk.com/book2?section=pricing. [Accessed: 16- Mar- 2020]

[11]"Energy stocks perform well when interest rates rise", *TheStreet*, 2020. [Online]. Available: https://www.thestreet.com/investing/stocks/energy-stocks-perform-well-when-interest-rates-rise-13852756. [Accessed: 16- Mar- 2020]

[12]Table 10.6 Solar Thermal Collector Shipments by Type, Price, and Trade, 1974-2009 (Thousand Square Feet, Except as Noted)", *Eia.gov*, 2020. [Online]. Available: https://www.eia.gov/totalenergy/data/annual/showtext.php?t=ptb1006. [Accessed: 17- Mar- 2020]

[13]"Solar Water Heaters: Solar-Powered Water Heating Systems," Fast Water Heater. [Online]. Available: https://www.fastwaterheater.com/water-heaters/solar/. [Accessed: 15-Mar-2020].

[14]M. Khoshaba, Y. Elgharib, K. Guirgus and K. Maarouf, "Preliminary Consultants Report: Natural Gas vs Solar Water Heating", 2020.

[15] "How Much Does it Cost to Repair a Hot Water Tank in Vancouver?: Ashton Plumbing Heating & Air Conditioning® British Columbia, Canada," Ashton Plumbing Heating & Air Conditioning, 20-Sep-2018. [Online]. Available: https://ashtonservicegroup.com/2018/09/20/how-much-does-it-cost-to-repair-a-hot-water-tank-in-vancouver/. [Accessed: 16-Mar-2020].

[16] "BoilerandCoolingWater.com," Propylene Glycol Application Uses. [Online]. Available: https://www.boilerandcoolingwater.com/Propylene-Glycol-s/1321.htm. [Accessed: 15-Mar-2020].

[17]J. Lietz, "How Much Does the Hot Water Heater Affect an Electric Bill?," Home Guides | SF Gate, 15-Dec-2018. [Online]. Available: https://homeguides.sfgate.com/much-hot-water-heater-affect-electric-bill-88704.html. [Accessed: 15-Mar-2020].

[18]Y. Kazemi, "Design for Environment Lecture Slides", 2020.

[19] "Oil well," *Oil well - Energy Education*. [Online]. Available: https://energyeducation.ca/encyclopedia/Oil_well. [Accessed: 19-Mar-2020].

[20] “prime mover,” prime mover - Schlumberger Oilfield Glossary. [Online]. Available: https://www.glossary.oilfield.slb.com/en/Terms/p/prime_mover.aspx. [Accessed: 19-Mar-2020].

[21] "Unit Process Library", netl.doe.gov, 2020. [Online]. Available: https://netl.doe.gov/node/2573. [Accessed: 21- Mar- 2020].

[22] “Junex,” *Drilling equipments : drilling rig, field office and more[Junex, Quebec]*. [Online]. Available: http://www.junex.ca/our-equipment. [Accessed: 19-Mar-2020].

[23] “How is Natural Gas Extracted: Hydraulic Fracturing in Canada,” CAPP. [Online]. Available: https://www.capp.ca/natural-gas/drilling-and-fracturing/. [Accessed: 20-Mar-2020]

[24] W. L. Interactive, “Gas Compression,” *USA Compression Partners LLC*. [Online]. Available: https://www.usacompression.com/compression-applications/gas-compression/. [Accessed: 19-Mar-2020].

[25] “Stage Compressor,” *Stage Compressor - an overview | ScienceDirect Topics*. [Online]. Available: https://www.sciencedirect.com/topics/engineering/stage-compressor. [Accessed: 25-Feb-2020].

[26] "Unit Process Library", netl.doe.gov, 2020. [Online]. Available: https://netl.doe.gov/node/2573. [Accessed: 20- Mar- 2020].

[27] Q. Compressor, "Chapter 4: Natural Gas Industry and Compressed Air", Quincy Compressor, 2020. [Online]. Available: https://www.quincycompressor.com/evolution-compressed-air/chapter-4-natural-gas-industry-compressed-air/. [Accessed: 20- Mar- 2020].

[28] “How Does Casing Work?,” *RIGZONE Empowering People in Oil and Gas*. [Online]. Available: https://www.rigzone.com/training/insight.asp?insight_id=333&c_id=. [Accessed: 20-Mar-2020].

[29] C. Burnett, T. Evans, and T. Evans, “Oil Well Construction: Casing and Tubing,” *Analyzing Metals*, 22-Apr-2016. [Online]. Available:https://www.thermofisher.com/blog/metals/oil-well-construction-casing-and-tubing/. [Accessed: 19-Mar-2020].

[30] I. Robinson, “Steels Used in Down the Hole Mining Equipment,” *AZoMining.com*, 03-Sep-2019. [Online]. Available: https://www.azomining.com/Article.aspx?ArticleID=1439. [Accessed: 20-Mar-2020].

[31] *drillingformulas.com*. [Online]. Available: http://www.drillingformulas.com/calculate-cement-oil-well-cement-volume-required/. [Accessed: 19-Mar-2020].

[32] L. Brenner, “How Deep Should Casing Go Into a Water Well?,” Home Guides | SF Gate, 07-Oct-2016. [Online]. Available: https://homeguides.sfgate.com/deep-should-casing-water-well-86491.html. [Accessed: 19-Mar-2020].

[33] G. Elert, “Density of Steel,” *Density of Steel - The Physics Factbook*. [Online]. Available: https://hypertextbook.com/facts/2004/KarenSutherland.shtml. [Accessed: 20-Mar-2020].

[34] “NaturalGas.org,” *NaturalGasorg*. [Online]. Available: http://naturalgas.org/naturalgas/processing-ng/. [Accessed: 19-Mar-2020].

[35] “Lubricating Oil,” *How Products Are Made*. [Online]. Available: http://www.madehow.com/Volume-1/Lubricating-Oil.html. [Accessed: 19-Mar-2020].

[36] Carnegie Mellon University,” *Approaches to LCA - Economic Input-Output Life Cycle Assessment - Carnegie Mellon University*. [Online]. Available: http://www.eiolca.net/Method/LCAapproaches.html. [Accessed: 20-Mar-2020].

[37] “The Role of Natural Gas Liquids (NGLs) in the American Petrochemical Boom,” *Kinder Morgan White Paper*, Mar. 2018.

[38] *Free Life Cycle Assessment on the Internet*. [Online]. Available: http://www.eiolca.net/cgi-bin/dft/use.pl?newmatrix=US430CIDOC2002. [Accessed: 19-Mar-2020].

[39] F. D. I. C. Services, “Home,” *Maverick Engineering*. [Online]. Available: https://www.maveng.com/index.php/business-streams/oil-gas/natural-gas-processing/ngl-extraction-fractionation. [Accessed: 19-Mar-2020].

[40] "Density of Cement, Portland in 285 units and reference information," *Density of Cement, Portland in 285 units and reference information*. [Online]. Available: https://www.aqua-calc.com/page/density-table/substance/cement-coma-and-blank-portland. [Accessed: 20-Mar-2020].

[41] "Unit Process Library," netl.doe.gov. [Online]. Available: https://netl.doe.gov/node/2573. [Accessed: 20-Mar-2020].

[42] M. R. Eden, M. G. IERAPETRITOU, and G. P. Towler, Eds., 13th International Symposium on Process Systems Engineering.

[43] "Pipeline Safety Stakeholder Communications," *PHMSA*. [Online]. Available: https://primis.phmsa.dot.gov/comm/FactSheets/FSTransmissionPipelines.htm?nocache=5866. [Accessed: 20-Mar-2020].

[44] "NaturalGas.org," NaturalGasorg. [Online]. Available: http://naturalgas.org/naturalgas/transport/. [Accessed: 19-Mar-2020].

[45] "Economic Impacts from Operation of Canada's Energy Transmission Pipelines ," Apr. 2016.

[46] "Fundamentals Of Gas Pipeline Metering Stations," *Pipeline & Gas Journal*. [Online]. Available: https://pgjonline.com/magazine/2009/january-2009-vol-236-no-1/features/fundamentals-of-gas-pipeline-metering-stations. [Accessed: 19-Mar-2020].

[47] "Gas Metering Stations," *Haamavaran*. [Online]. Available: http://www.hep-co.com/gas-metering-stations/. [Accessed: 19-Mar-2020].

[48] Emerson Process Management, "Natural Gas Processing", 2013.

[49][1]Openlca.org, 2020. [Online]. Available: http://www.openlca.org/openlca/. [Accessed: 04-Apr- 2020]

[50] Carnegie Mellon University, "CMU - Economic Input-Output Life Cycle Assessment - Carnegie Mellon University," CMU - Economic Input-Output Life Cycle Assessment - Carnegie Mellon University. [Online]. Available: http://www.eiolca.net/. [Accessed: 17-Mar-2020].

[51] “Mitigating Emissions from Aluminum.” [Online]. Available: http://climate.columbia.edu/files/2012/04/GNCS-Aluminum-Factsheet.pdf. [Accessed: 17-Mar-2020].

[52] Yasamin Kazemi, Lecture Slides, Topic: "MIE315 – Design for Environment.” MIE315, Faculty of Applied Science and Engineering, University of Toronto, Toronto, Mar. 2020.

[53] H. Tanaka, “Potential for CO2 emissions reduction in MIDREX direct reduction process .” [Online]. Available: https://ieaghg.org/docs/General_Docs/Iron and Steel 2 Secured presentations/2_1400 Hidetoshi Tanaka.pdf. [Accessed: 17-Mar-2020].

[54] Recycling Technology. [Online]. Available: https://www.aurubis.com/en/products/recycling/technology. [Accessed:23-Feb-2020].

[55] T. Bell, “How Pure Magnesium Is Produced,” The Balance, 24-Nov-2019. [Online]. Available: https://www.thebalance.com/magnesium-production-2339718. [Accessed: 17-Mar-2020].

[56] “Technical Support Document for the Glass Manufacturing Sector.” [Online]. Available: https://www.epa.gov/sites/production/files/2015-02/documents/tsd_glass_epa_1-22-09.pdf. [Accessed: 17-Mar-2020].

[57] Glass Making. [Online]. Available: https://www.believersinglass.com/GlassMaking.php. [Accessed: 17-Mar-2020].

[58] “Ethylene Glycol (EG) Production and Manufacturing Process,” Icis. [Online]. Available: https://www.icis.com/explore/resources/news/2007 /11/05/9075767 /ethylene-g lycol-eg-production-and-manufacturing-process/. [Accessed: 17-Mar-2020].

[59] “Polyurethane,” How Products Are Made. [Online]. Available: http://www.madehow.com/Volume-6/Polyurethane.html. [Accessed: 17-Mar-2020].

[60] F. Ardente and G. Beccali, [Online]. “Life Cycle Assessment of a Solar Thermal Collector.” [Accessed: 17-Mar-2020].

[61] “Definition of Machining or Metal Cutting - Examples of Machining Processes,” Minaprem.com. [Online]. Available: http://www.minaprem.com/machining/introduction/definition-of-machining-or-metal-cutting-examples-of-machining-processes/. [Accessed: 17-Mar-2020].

[62] “What is Welding? - Definition, Processes and Types of Welds,” TWI. [Online]. Available: https://www.twi-global.com/technical-knowledge/faqs/what-is-welding#EnergySources. [Accessed: 17-Mar-2020].

[63] “Sealants - Adhesion - Bonding - Fastening,” Adhesives. [Online]. Available: https://www.adhesives.org/adhesives-sealants. [Accessed: 17-Mar-2020].

[64] “What is a coating?,” TWI. [Online]. Available: https://www.twi-global.com/technical-knowledge/faqs/faq-what-is-a-coating. [Accessed: 17-Mar-2020].

[65] “Packaging,” Vault. [Online]. Available: https://www.vault.com/industries-professions/industries/packaging/background. [Accessed: 17-Mar-2020].

[66] “Trucking: Diesel Technology Forum,” https://www.dieselforum.org. [Online]. Available: https://www.dieselforum.org/about-clean-diesel/trucking. [Accessed: 18-Mar-2020].

[67] “Cleaning Your Solar Panels,” Evergreen Solar. [Online]. Available: https://evergreensolar.com/how/cleaning/. [Accessed: 17-Mar-2020].

[68] Jackie, “Search Results for: maintenance,” Co. [Online]. Available: https://co-ophousingtoronto.coop/?s=maintenance. [Accessed: 20-Mar-2020].

[69] B. Palmer, “Solar water heaters: Are they better than solar electric panels?,” Slate Magazine, 01-Feb-2011. [Online]. Available: https://slate.com/technology/2011/02/solar-water-heaters-are-they-better-than-solar-electric-panels.html. [Accessed: 16-Mar-2020].

[70] “Solar Resource Data, Tools, and Maps,” NREL.gov. [Online]. Available: https://www.nrel.gov/gis/solar.html. [Accessed: 16-Mar-2020].

[71] “Material Prices,” 05-Mar-2019. [Online]. Available: http://web.mit.edu/course/3/3.11/www/modules/props.pdf. [Accessed: 17-Mar-2020].

[72] Brighterstrings, “Stainless Steel Energy Use,” Brighter Strings, 13-May-2018. [Online]. Available: https://brighterstrings.wordpress.com/2016/03/27/stainless-steel-energy-use/. [Accessed: 17-Mar-2020].

[73] “Sheet metal products: how to calculate production cost: Dallan SpA,” Dallan, 01-Jul-2019. [Online]. Available: https://www.dallan.com/en/news/four-steps-to-calculate-the-manufacturing-cost-of-sheet-metal-products/. [Accessed: 17-Mar-2020].

[74] “How Much Does Metal Welding Cost?,” 2020 Welding Metal Cost | Sheet Metal Welding Prices | Welders. [Online]. Available: https://www.improvenet.com/r/costs-and-prices/metal-welding-cost. [Accessed: 17-Mar-2020].

[75] M. Ceschan, “How much does glue cost?,” Industrial Glue Blog - LD Davis. [Online]. Available: https://blog.lddavis.com/glue-cost. [Accessed: 17-Mar-2020].

[76] C. Hren, “How Much Do Industrial Coatings Cost?,” Industrial Traffic Marking Paints & Coatings, 06-Jan-2020. [Online]. Available: https://www.aexcelcorp.com/blog/how-much-do-industrial-coatings-cost. [Accessed: 17-Mar-2020].

[77] EETimes, “Packaging is becoming the biggest cost in assembly, passing capital equipment -,” EETimes, 26-Aug-1999. [Online]. Available: https://www.eetimes.com/packaging-is-becoming-biggest-cost-in-assembly-passing-capital-equipment/. [Accessed: 17-Mar-2020].

[78] “Overviews,” Sheet Metal Forming. [Online]. Available: https://www.custompartnet.com/wu/sheet-metal-forming. [Accessed: 17-Mar-2020].

[79] “Assembly Line Methods,” Inc.com, 30-Nov--1. [Online]. Available: https://www.inc.com/encyclopedia/assembly-line-methods.html. [Accessed: 17-Mar-2020].

[80] “Gasoline and Diesel Fuel Update - U.S. Energy Information Administration (EIA),” Gasoline and Diesel Fuel Update - U.S. Energy Information Administration (EIA), 10-Mar-2020. [Online]. Available: https://www.eia.gov/petroleum/gasdiesel/. [Accessed: 17-Mar-2020].

[81] “Fuel Efficiency Benchmarking in Canada's Trucking Industry,” Natural Resources Canada, 03-Jul-2019. [Online]. Available:

https://www.nrcan.gc.ca/energy/efficiency/transportation/commercial-vehicles/reports/7607. [Accessed: 17-Mar-2020].

[82] “New magnesium process cuts energy use by 60%,” The Chemical Engineer, 12-Oct-2017. [Online]. Available: https://www.thechemicalengineer.com/news/new-magnesium-process-cuts-energy-use-by-60/. [Accessed: 18-Mar-2020].

[83] Recycling Magnesium - International Magnesium Association. [Online]. Available: https://www.intlmag.org/page/sustain_recycle_ima. [Accessed: 18-Mar-2020].

[84] “Aluminum Production,” Aluminum Production - an overview | ScienceDirect Topics. [Online]. Available: https://www.sciencedirect.com/topics/engineering/aluminum-production. [Accessed: 17-Mar-2020].

[85]"Interpretation of metrics: DALY and damage to human health | PRé Sustainability", *Pre-sustainability.com*, 2020. [Online]. Available: https://www.pre-sustainability.com/news/metrics-interpretation-daly-and-damage-to-human-health. [Accessed: 04- Apr- 2020]

[86]"WHO | Metrics: Disability-Adjusted Life Year (DALY)", *Who.int*, 2020. [Online]. Available: https://www.who.int/healthinfo/global_burden_disease/metrics_daly/en/. [Accessed: 04- Apr- 2020]

[87] “Forest Management Guide for Cultural Heritage Values.” [Online]. Available: https://dr6j45jk9xcmk.cloudfront.net/documents/2784/guide-culturalheritage-aoda.pdf. [Accessed: 04-Apr-2020].

[88] “JavaScript is required to view this site,” ontario.ca. [Online]. Available: https://www.ontario.ca/page/working-first-nations-improve-drinking-water. [Accessed: 04-Apr-2020].

[89] Banktrack.org, 2020. [Online]. Available: https://www.banktrack.org/download/160620_oil_and_gas_guidance_note_pdf/160620_oilandgasguidancenote.pdf. [Accessed: 20- Mar- 2020].

[90] C. A. P. & M. G. Lipsett, “The Canadian oil sands: environmental, economic, social, health, and other impacts.”
Link: https://www.witpress.com/Secure/elibrary/papers/SDP13/SDP13048FU1.pdf

[91] “Hydraulic Fracturing and its Impact on Water Resources,” Water Footprint Calculator. [Online]. Available: https://www.watercalculator.org/footprint/fracking-water/. [Accessed: 18-Mar-2020].

[92] T. R. Control, “Managing Oil and Gas Risk with Contractual Risk Transfer,” *Travelers Insurance*. [Online]. Available: https://www.travelers.com/resources/business-industries/oil-gas/managing-oil-and-gas-risk-with-contractual-risk-transfer. [Accessed: 19-Mar-2020].

[93] “Rigzone Poll: Age Discrimination a Concern in Oil and Gas,” *RIGZONE Empowering People in Oil and Gas*. [Online]. Available: https://www.rigzone.com/news/rigzone_poll_age_discrimination_a_concern_in_oil_and_gas-12-dec-2017-152773-article/. [Accessed: 19-Mar-2020].

[94] “Search Geoscience Currents,” American Geosciences Institute, 17-Jan-2020. [Online]. Available: https://www.americangeosciences.org/geoscience-currents/health-and-safety-oil-and-gas-extraction [Accessed: 20-Mar-2020].

[95] G. Doluweera, P. Kralovic and D. Millington, "ECONOMIC IMPACTS OF CANADIAN OIL AND GAS SUPPLY IN CANADA AND THE US", Calgary, 2017.
Link:
https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/energy/energy-resources/CERI_Study_166_Full_Report.pdf

[96] Ernst & Young, "Managing bribery and corruption risks in the oil and gas industry", 2014. Link:https://www.ey.com/Publication/vwLUAssets/EY-Managing-bribery-and-corruption-risk-in-the-oil-and-gas-industry/$FILE/EY-Managing-bribery-and-corruption-risk-in-the-oil-and-gas-industry.pdf

[97] A. Beattie, “Why These Industries Are Prone to Corruption,” *Investopedia*, 08-Feb-2020. [Online]. Available: https://www.investopedia.com/articles/investing/072115/why-these-industries-are-prone-corruption.asp. [Accessed: 20-Mar-2020].

[98] “Corruption at borders,” U4 Anti-Corruption Resource Centre. [Online]. Available: https://www.u4.no/publications/corruption-at-borders. [Accessed: 20-Mar-2020].

[99] H. Gas, "Hazards of Natural Gas", Pinedalegas.com, 2020. [Online]. Available: https://www.pinedalegas.com/natural-gas/hazards-of-natural-gas. [Accessed: 21- Mar- 2020].

[100] L. Cecco, “Pipeline battle puts focus on Canada's disputed right to use indigenous land,” The Guardian, 11-Jan-2019. [Online]. Available: https://www.theguardian.com/world/2019/jan/11/canada-pipeline-indigenous-trudeau-treaty. [Accessed: 20-Mar-2020].

[101] S. Matasci, “2020 Health & Environmental Benefits of Solar: EnergySage,” Solar News, 03-Jan-2020. [Online]. Available: https://news.energysage.com/health-environmental-benefits-of-solar-energy/. [Accessed: 20-Mar-2020].

[102] “Collective Agreements,” USW Canada. [Online]. Available: https://www.usw.ca/act/campaigns/d6hcc/resources/collective-agreements. [Accessed: 20-Mar-2020].

[103] “Human Rights & Equity,” USW Canada. [Online]. Available: https://www.usw.ca/act/activism/human-rights. [Accessed: 20-Mar-2020].

[104] “Health and Safety,” USW Canada. [Online]. Available: https://www.usw.ca/districts/3/health-and-safety. [Accessed: 20-Mar-2020].

[105] “Economic Benefits: Renewable Energy Corporation: Timonium, MD,” Renewable Energy Solar. [Online]. Available: https://www.renewableenergysolar.net/benefits/economic-benefits/. [Accessed: 20-Mar-2020].

[106] Staff, “Canada slips in global corruption ranking in aftermath of SNC-Lavalin scandal,” Montreal, 24-Jan-2020. [Online]. Available: https://montreal.ctvnews.ca/canada-slips-in-global-corruption-ranking-in-aftermath-of-snc-lavalin-scandal-1.4782290. [Accessed: 20-Mar-2020].

[107] “Solar Thermal Recycling of Hazardous Waste Materials,” Solar Thermal Recycling of Hazardous Waste Materials – Professorship of Renewable Energy Carriers | ETH Zurich. [Online]. Available: https://prec.ethz.ch/research/solar-materials-processing/recycle.html. [Accessed: 20-Mar-2020].

[108] K. Phumpradab, S. H. Gheewala, and M. Sagisaka, "Life cycle assessment of natural gas power plants in Thailand," *The International Journal of Life Cycle Assessment*, vol. 14, no. 4, pp. 354–363, 2009.

[109] E. Dossat, Termodinámica básica y aplicada. 1992. Link:http://webserver.dmt.upm.es/~isidoro/bk3/c15/Fuel%20properties.pdf

[110] "Fuels - Densities and Specific Volume," Engineering ToolBox. [Online]. Available: https://www.engineeringtoolbox.com/fuels-densities-specific-volumes-d_166.html. [Accessed: 20-Mar-2020].

[111] Starling, Savidge, and Iso, "Natural gas - Calculation of compression factor - Part 2: Calculation using molar-composition analysis," *Unitrove*, 01-Jan-1970. [Online]. Available: https://www.unitrove.com/engineering/tools/gas/natural-gas-density. [Accessed: 20-Mar-2020].

[112] "Javascript Required!," *Heat values of various fuels - World Nuclear Association*. [Online]. Available: https://www.world-nuclear.org/information-library/facts-and-figures/heat-values-of-various-fuels.aspx. [Accessed: 18-Mar-2020].

[113] L. Brenner, "How Deep Should Casing Go Into a Water Well?," *Home Guides | SF Gate*, 07-Oct-2016. [Online]. Available: https://homeguides.sfgate.com/deep-should-casing-water-well-86491.html. [Accessed: 19-Mar-2020].

[114] G. Elert, "Density of Steel," Density of Steel - The Physics Factbook. [Online]. Available: https://hypertextbook.com/facts/2004/KarenSutherland.shtml. [Accessed: 20-Mar-2020].

[115] FocusEconomics, "Steel Price (USA): Historical Charts, Forecasts, & News," *FocusEconomics | Economic Forecasts from the World's Leading Economists*. [Online]. Available: https://www.focus-economics.com/commodities/base-metals/steel-usa. [Accessed: 19-Mar-2020].

[116] "94 lb. Portland Cement-112494," The Home Depot. [Online]. Available: https://www.homedepot.com/p/94-lb-Portland-Cement-112494/100570364. [Accessed: 18-Mar-2020].

[117] “Cubic Meters to US Barrels (Oil),” *Metric Conversion*. [Online]. Available: https://www.metric-conversions.org/volume/cubic-meters-to-us-oil-barrels.htm. [Accessed: 19-Mar-2020].

[118] “Density of Cement, Portland in 285 units and reference information,” *Density of Cement, Portland in 285 units and reference information*. [Online]. Available: https://www.aqua-calc.com/page/density-table/substance/cement-coma-and-blank-portland. [Accessed: 20-Mar-2020].

[119] "Scrap Metal Prices | Canada – All of the latest scrap metal prices in Canada.", Scrapmetalpricer.ca, 2020. [Online]. Available: https://www.scrapmetalpricer.ca/. [Accessed: 16- Mar- 2020]

[120] Network, "Magnesium Price Steady Beyond China’s Dominance | INN", Investing News Network, 2020. [Online]. Available: https://investingnews.com/daily/resource-investing/critical-metals-investing/magnesium-investing/magnesium-price-steady-beyond-chinas-dominance/. [Accessed: 16- Mar- 2020]

[121]f. GmbH, "Copper PRICE Today | Copper Spot Price Chart | Live Price of Copper per Ounce | Markets Insider", markets.businessinsider.com, 2020. [Online]. Available: https://markets.businessinsider.com/commodities/copper-price. [Accessed: 16- Mar- 2020]

[122]Web.mit.edu, 2020. [Online]. Available: http://web.mit.edu/course/3/3.11/www/modules/props.pdf. [Accessed: 16- Mar- 2020]

[123]“POLYURETHANE: Price: per kg: USD,” PharmaCompass.com. [Online]. Available: https://www.pharmacompass.com/price/polyurethane. [Accessed: 16-Mar-2020].

[124] T. DiChristopher, "Why trash is no longer cash for recycling biz", CNBC, 2020. [Online]. Available: https://www.cnbc.com/2015/05/28/why-trash-is-no-longer-cash-for-recycling-biz.html. [Accessed: 16- Mar- 2020]

[125] Natural Gas STAR, "Natural Gas Dehydration", 2006.
Link: https://www.epa.gov/sites/production/files/2017-08/documents/robinson_ftworth_2006.pdf

[126]C. Jin and Y. Lim, "Economic evaluation of NGL recovery process schemes for lean feed compositions", *Chemical Engineering Research and Design*, vol. 129, pp. 297-305, 2018. Available: 10.1016/j.cherd.2017.11.027 [Accessed 19 March 2020].

[127] K. Mearkeltor, "Natural Gas Sweetening Process Design," School of Doctoral Studies (European Union) Journal.
Link: https://www.dioneoil.com/uploads/6/8/7/4/6874938/gas_sweetening_cost.pdf

[128] A. Bahadori, "Detailed Engineering and Design for Natural Gas Processing Projects," Natural Gas Processing, pp. 723–802, 2014.

[129] "Pipelines Across Canada," *Natural Resources Canada*, 25-Jul-2016. [Online]. Available: https://www.nrcan.gc.ca/our-natural-resources/energy-sources-distribution/clean-fossil-fuels/pipelines/pipelines-across-canada/18856. [Accessed: 20-Mar-2020].

[130] *Manufacturers, Suppliers, Exporters & Importers from the world's largest online B2B marketplace-Alibaba.com*. [Online]. Available: https://www.alibaba.com/product-detail/Mini-lpg-Cooking-Gas-Plant-Cooking_62139686578.html?spm=a2700.7724857.normalList.2.739f35326uF3AH&s=p. [Accessed: 19-Mar-2020].

[131] "Inflation Rate between 2020-2002: Inflation Calculator," *$20,000 in 2020 → 2002 | Inflation Calculator*. [Online]. Available: https://www.in2013dollars.com/us/inflation/2020?endYear=2002&amount=20000. [Accessed: 19-Mar-2020].

[132] "InvestmentMine," InvestmentMine, 12-Mar-2020. [Online]. Available: http://www.infomine.com/investment/metal-prices/aluminum/. [Accessed: 14-Mar-2020].

[133] "Unit Process Library", netl.doe.gov, 2020. [Online]. Available: https://netl.doe.gov/node/2573. [Accessed: 21- Mar- 2020].

[134] W. J. Kostowski, J. Kalina, P. Bargiel, and P. Szufleński, "Energy and exergy recovery in a natural gas compressor station – A technical and economic analysis," Energy Conversion and Management, vol. 104, pp. 17–31, 2015.

[135] Energy.gov, 2020. [Online]. Available: https://www.energy.gov/sites/prod/files/2016/09/f33/CHP-Recip%20Engines.pdf. [Accessed: 21-Mar- 2020]

[136] “Portland Cement Manufacturing Industry: National Emission Standards for Hazardous Air Pollutants (NESHAP),” EPA, 15-Oct-2019. [Online]. Available: https://www.epa.gov/stationary-sources-air-pollution/portland-cement-manufacturing-industry-national-emission-standards. [Accessed: 20-Mar-2020]. Link:https://www.epa.gov/stationary-sources-air-pollution/portland-cement-manufacturing-industry-national-emission-standards

[137] R. T. Elworthy, “Natural gas in Alberta,” 1924. Linkhttps://www.alberta.ca/assets/documents/cci-natural-gas-processing-modules-definitions.pdf

[138] “Welcome to my.access -- please choose how you will connect,” *my.access - University of Toronto Libraries Portal*. [Online]. Available: https://journals-scholarsportal-info.myaccess.library.utoronto.ca/pdf/18755100/v38icomplete/187_ergeaicingsp.xml. [Accessed: 20-Mar-2020].

[139] *Iifiir.org*, 2020. [Online]. Available: http://www.iifiir.org/userfiles/file/publications/notes/NoteTech_29_EN.pdf. [Accessed: 21- Mar-2020]

[140] "Unit Process Library", netl.doe.gov, 2020. [Online]. Available: https://netl.doe.gov/node/2573. [Accessed: 21- Mar- 2020].

[141] “Natural gas liquids recovery,” Handbook of Natural Gas Transmission and Processing, pp. 365–400, 2006.
Link:
http://www.carbonlab.eu/wp-content/uploads/2017/06/07_Acid_gas_removal_dehydration_and_NGL_recovery.pdf

[142][B. G. Goar, “Sulfur Recovery from Sour Natural Gas: A Review of Gas Treating/Claus Plant Design and Operations,” *SPE Symposium on Sour Gas and Crude*, 1974. Link: https://www.researchgate.net/publication/229783018_Recovery_of_sulfur_from_sour_acid_gas_A_review_of_the_technology

[143] J. Thompson, “A map of $1.1 billion in natural gas pipeline leaks,” *High Country News*, 29-Nov-2017. [Online]. Available: https://www.hcn.org/issues/49.22/infographic-a-map-of-leaking-natural-gas-pipelines-across-the-nation. [Accessed: 20-Mar-2020].

[144] J. P. Gutierrez, E. L. Ale Ruiz, and E. Erdmann, Energy requirements, GHG emissions and investment costs in natural gas sweetening processes, Dec. 2016.
Link:https://www.researchgate.net/publicati`on/311959742_Energy_requirements_GHG_emissions_and_investment_costs_in_natural_gas_sweetening_processes/link/5cf33c22a6fdcc8475fceec2/download

9.0 Appendices

Appendix A: SLCA Matrices [14]

Tables 11-12 are the SLCA matrices for Natural Gas Water heating and Solar Thermal water heating.

Table 11: SLCA Matrix for Natural Gas Water Heating

SLCA Matrix	Material Choice	Energy Use	Solid Residue	Liquid Residue	Gaseous Residue
Pre-Manufacturing	4	0	0	1	0
Manufacturing	4	0	4	4	2
Packaging and Transport	0	2	0	1	1
Use	0	2	3	4	0
Disposal	3	1	2	4	1
Total	43				

Table 12: SLCA Matrix for Natural Gas Water Heating

SLCA Matrix	Material Choice	Energy Use	Solid Residue	Liquid Residue	Gaseous Residue
Pre-Manufacturing	2	0	1	2	0
Manufacturing	3	2	4	4	4
Packaging and Transport	4	3	4	4	3
Use	3	3	4	3	3
Disposal	3	3	2	3	1
Total	68				

Appendix B: Weighted Decision Matrix [14]

Table 13 is the weighted decision matrix for the Natural Gas Water heating and Solar Thermal water heating systems.

Table 13: Weighted Decision Matrix for Systems

	Solar Thermal Heating	**Natural Gas Heating**
Objective 1 *(9.5%)*	69%	100%
Objective 2 *(23.8%)*	45%	20%
Objective 3 *(23.8%)*	100%	40%
Objective 4 *(19.0%)*	87.27%	100%
Objective 5 *(4.8%)*	100%	87%
Objective 6 *(4.8%)*	100%	70%
Objective 7 *(14.3%)*	99.6%	100%
Total (100%)	81.5%	64.6%

Appendix C: Cost calculations for Pre-manufacturing: Well Drilling

Table 14 lists the input fuels required for well drilling, and the final price of natural gas well drilling per lifecycle.

Table 14: Cost Calculations for Well Drilling

Material	**Natural Gas Output Baseline**	**Diesel Oil (per 100 m3 output of Natural Gas) L**	**Fuel Gas (per 100m3 output of Natural Gas) m3**	**Price**
Conventional Natural Gas	100 m^3	0.0234 [108]	4.24 [108]	$1652 per life cycle [9]

→ From below, the total volume of Natural Gas extracted is 320.4043 x 10^6 m^3 of natural gas

- For Diesel Oil:
  - (0.0234L/100 m^3 of NG) * (320.4043 x 10^6 m^3 of NG) = 75 x 10^3 L
  - Density of Diesel oil = 0.830 Kg/L [109]

- Total Mass of Diesel Oil Used = (75 x 10^3 L)*(0.830 Kg/L) = 62.25 x 10^3 kg of Diesel Oil
- Price of Diesel Oil : 1.09 $ / Litre in 2015 [115]
- Using a CPI conversion: $\frac{1.09 \frac{\$}{Litre} \text{ in } 2015 \; x \; 179.880 \; (CPI \text{ in } 2002)}{237.017 \; (CPI \text{ in } 2015)}$ = 0.827 $ / L
- Total Price of Diesel Oil: (0.827 $ / L) * (75x 10^3 L) = 62,025 $
- Total Price of Diesel Oil per product: (62,025$ per well)/(1362) = 45.54$ needed per product

- For Fuel Gas:
  - (4.24 m^3/100 m^3 of NG) * (320.4043 x 10^6 m^3 of NG) = 13.59 x 10^6 m^3 of Fuel Gas
  - Density of Fuel Gas = 800 kg/m^3 [110]
  - Total Mass of Fuel Gas Used = (13.59 x 10^6 m^3 of Fuel Gas) * 800 kg/m^3 = 1.1 x 10^10 kg of Fuel Gas
  - Price of Fuel Gas: 0.585 $ / Litre in 2015 [110]
  - Using a CPI conversion: $\frac{0.585 \frac{\$}{Litre} \text{ in } 2015 \; x \; 179.880 \; (CPI \text{ in } 2002)}{237.017 \; (CPI \text{ in } 2015)}$ = 0.444 $ / L
  - Total Price of Fuel Gas: 0.444 $ / L * 13.59 x 10^9 L = 6 billion dollars per well
  - Total Price of Fuel Gas per product: (6 billion dollars per well)/(1652) = 3.632 million dollars needed per product

- Calculations:
  - ➔ Well Capacity: Max capacity of 1.55 million $(ft^3)\,/\,day$ which is equivalent to 43891 m^3 /day of natural gas
  - ➔ Density of Natural Gas is 0.712 kg/ m^3 [111]
  - ➔ In 20 years (analysis period of the hybrid LCA), there is 7300 days
  - ➔ Total volume of natural gas extracted per day = (43891 m^3 /day) * (7300 days) = 320.4043 x 10^6 m^3 of natural gas
  - ➔ Total mass of Natural Gas extracted = (320.4043 x 10^6 m^3) * (0.712 kg/ m^3) = 228.13 x 10^6 kg of natural gas

Apply the conversion factor from per well to per product:

- ➔ Amount of Natural Gas needed in the life cycle is 167,501.5 kg [112]
- ➔ The factor to be used to divide by is: 228.13 x 10^6 kg of natural gas / 167,501.5 kg of natural gas = 1362

Appendix D: Cost calculations for Pre-manufacturing: Inlet Gas Compression

Calculation: [1.76 x 10^{-4} $\frac{MWh}{kg\ of\ natural\ gas}$] * (228.13 x 10^6 kg of natural gas) = 40151 MWh

Cost of 9.5 $\frac{cents}{kwh}$ (2015 average)

→ Convert by the CPI model to 2002 (Table from [52]):

$$\frac{9.5\ \frac{cents}{kwh}\ in\ 2015\ x\ 179.880\ (CPI\ in\ 2002)}{237.017\ (CPI\ in\ 2015)} = 7.21\ cents\ /\ kwh$$

Consumer Price Index in the United States

Year	CPI	Year	CPI
2017	245.120	2008	215.303
2016	240.008	2007	207.342
2015	237.017	2006	201.600
2014	236.736	2005	195.300
2013	232.957	2004	188.900
2012	229.594	2003	183.960
2011	224.939	2002	179.880
2010	218.056	2001	177.100
2009	214.537	2000	172.200

→ We need 1.76 x 10^-1 KWh per kg of natural gas;

Total amount of KWh needed:

1.76 x 10^-1 $\frac{KWh}{kg\ of\ natural\ gas}$ * 228.13 x 10^6 kg of natural gas = 40.15 x 10^6 KWh over the span of 20 years

Total cost of Energy Consumption of Air Compressor Per Well:

→ 40.15 x 10^6 KWh * 7.21 cents / kwh = 289.4815 x 10^6 cents

→ 289.4815 x 10^6 cents = 2.894815 million Canadian Dollars per well

Apply the conversion factor from per well to per product:

Method: **From Well Drilling**, the conversion from per well to per product is 1362

- ➔ The total cost of Energy Consumption of the Air compressor per product is equal to:
    - ◆ (Total cost of Energy Consumption of Air Compressor Per Well) / (Factor) = 2,125 $

Appendix E: Cost calculations for Pre-manufacturing: Well Casing and Completion

Calculation:

→ A typical well requires a casing to extend 5.5 m below the Earth's Surface [113]

→ The average Well Casing thickness per well is equal to 0.248 inches = 0.0062992 [114]

→ The average outside diameter of the well casing is equal to 9.2545 inches = 0.235 m [114]

→ The price of Carbon Steel in 2015 was 461.14 USD / tonne [115]

→ Using a CPI conversion, the price of Carbon Steel in 2002 is: $\frac{461\ \frac{USD}{tonne}\ in\ 2015\ x\ 179.880\ (CPI\ in\ 2002)}{237.017\ (CPI\ in\ 2015)}$

= 350 USD/tonne in 2002

→ **Calculate the Total mass of Carbon Steel Used**:

Step #1: *Find the area of the outer diameter of the casing*

- $2*pi*r^2*L = 2*pi*(\frac{0.235}{2})^2 * 5.5 = 0.47711\ m^2$

Step#2: Find the volume of well casing used

- Total Volume = Total Surface Area x Thickness of the well casing
  *= 0.47711 m^2 * 0.0062992 m = 3.005409733 x 10^-3 m^3*

Step #3: Find the total mass of carbon steel

- Density of Carbon Steel = 7.85 g/cm^3 [114]
- Mass of Carbon Steel Used = (7.85 g/cm^3) * (*3.005409733 x 10^-3 m^3) * (10^3* $\frac{cm^3}{m^3}$)
  = 23.5925 g of carbon steel = 0.0236 Kg of Carbon Steel

Total Cost of Carbon Steel Casing Per Well:

→ 0.0236 Kg of Carbon Steel * 350 USD/tonne = 8.26 x 10^-3 USD

Apply the conversion factor from per well to per product:

Method: **From Well Drilling**, the conversion from per well to per product is 1362

- ➔ The total cost of Carbon Steel needed per product is equal to:
  - ◆ (Total cost of carbon steel per well) / (Factor) = 6.065 x 10^-5 $

Appendix F: Cost calculations for Pre - manufacturing: Cementing

Calculation:

- Price of 43 Kg of cement is 15$ [116]
- 1 m3 is equal to 6.29 US bbl [117]
- Density of cement is 1500 kg/m^3 [118]
  - Thus, 119.1 bbl of cement is equivalent to 18.95 m3
  - The total mass of cement needed per well is thus equal to (1500 kg/m^3) * (18.95 m^3) = 28425 kg
  - Hence, the total cost of cement is 28425/43 = 661.05$ per well

Apply the conversion factor from per well to per product:

Method: **From Well Drilling**, the conversion from per well to per product is 1362

- The total cost of cement per product is equal to:
  - (Total cost of cement Per Well) / (Factor) = $0.40012 per product

Appendix G: Costs of Individual materials for Natural Gas Water Tank

Table 15 depicts the specific costs for the natural gas tank materials.

Table 15: Costs of Individual tank materials for Natural Gas Water Heating

Tank Materials	**Cost**
Stainless Steel	$3.20/kg [119] $485.5 kg Total Cost: $1553.6
Magnesium	$2.10 USD / pound or $1.32 CAD/kg [120] 1.4 kg Total Cost: $1.85
Copper	$7.46/kg [121] 40 kg Total Cost: $298.4

Glass	$5.42/kg [122] 61 kg Total Cost: $330.62
Polyurethane Insulation	$2.78/kg [123] 4.88 kg Total Cost: $13.57
Cardboard	$0.14/kg [124] 2.5 kg Total Cost: $0.35
TOTAL	$2198.39

Appendix H: Cost calculations for Manufacturing: Oil Condensate Removal

Calculation:

- ➔ Cost of Natural Gas Separation based on the required environmental flows:
    - ◆ Electricity needed: 0.00198 kWh [108] * **F** = 3094.64 kWh of electricity
        - Electricity price in ON is $0.125 per kWh
        - Total price of electricity needed = $0.125 * (3095) = $387

Apply the conversion factor from per well to per product:

Method: **From Well Drilling**, the conversion from per well to per product is 1362

- ➔ The total cost of Oil Condensate Removal per product is equal to:
    - ◆ (Total cost of Energy Consumption of Air Compressor Per Well) / (Factor) = 0.28414 $

Appendix I: Cost Calculations for Manufacturing: Water Removal

Apply the conversion factor from per well to per product:
Total Cost of Water Removal per Well:
72,660 $ / well in 2006 [125]; using CPI conversion to 2002, 64,832 $ / well

Method: **From Well Drilling**, the conversion from per well to per product is 1362

➔ The total cost of Water Removal per product is equal to:
- ◆ (Total cost of Water Removal Per Well) / (Factor) = 47.6$ per product

Appendix J: Cost calculations for Manufacturing: Natural Gas Liquids (NGLs) Extraction

Apply the conversion factor from per well to per product:
Total Cost of Natural Gas Liquids (NGLs) Extraction:
12,506,611$ in 2017 [126]; Using a CPI conversion to 2002, 9,117,910$ in 2002

Method: **From Well Drilling**, the conversion from per well to per product is 1362

➔ The total cost of Natural Gas Liquids Removal per product is equal to:
- ◆ (Total cost of Natural Gas Liquids Removal Per Well) / (Factor) = 6694.5$

Appendix K: Cost calculations for Manufacturing: Gas Sweetening

Apply the conversion factor from per well to per product:
Total Cost of Gas Sweetening per Well:
2.52 million dollars/well [127]; using CPI conversion to 2002, 2.02 million dollar/well

Method: **From Well Drilling**, the conversion from per well to per product is 1362

➔ The total cost of Gas Sweetening per product is equal to:
- ◆ (Total cost of Gas Per Well) / (Factor) = 1483.11$

Appendix L: Cost calculations for Transport: Transmission Pipelines

Calculation:

These pipelines are often between 16 - 48 (assume 32 inches, mean) inches in diameter [44].

- ➔ Assume the pipeline thickness is half the diameter of the pipeline to avoid leakage, meaning is it 16 inches in thickness [128]
- ➔ Pipeline diameter is equal to 0.813 m
- ➔ Pipeline thickness is equal to 0.41 m
- ➔ There exists 840,000 km of transmission pipelines in CAN [129]
- ➔ These exists 5,060 wells in Canada, which means there is (840,000 km / 5060 wells) = 166 km of pipeline per well

Step #1: Find the area of the outer diameter of the casing

- *2*pi*r^2*L = 2*pi*(* $\frac{0.813}{2})^2 * 166 \times 10^3$ *= 172349 m^2*

Step#2: Find the volume of well casing used

- Total Volume = Total Surface Area x Thickness of the well casing
  *= 172,349 m^2 * 0.41 m = 70,663 m^3*

Step #3: Find the total mass of carbon steel

- Density of Carbon Steel = 7.85 g/cm^3 [114]
- Mass of Carbon Steel Used = (7.85 g/cm^3) * (*70,663 m^3) * (10^3* $\frac{cm^3}{m^3}$)
  = 554.7 x 10^6 g of carbon steel = 554.7 x10^3 Kg of Carbon Steel

Step #4: Calculating the total cost of carbon steel

→ The price of Carbon Steel in 2015 was 461.14 USD / tonne [115]

→ Using a CPI conversion, the price of Carbon Steel in 2002 is: $\frac{461 \frac{USD}{tonne} \text{ in } 2015 \times 179.880 \ (CPI \text{ in } 2002)}{237.017 \ (CPI \text{ in } 2015)}$
= 350 USD/tonne in 2002

→ The total price of Carbon Steel used is: 554.7 tonne * 350 USD/tonne = 194,145 USD

Apply the conversion factor from per well to per product:

Total Cost of Transmission Pipelines per Well:

Method: **From Well Drilling**, the conversion from per well to per product is 1362

- ➔ The total cost of Transmission Pipelines per product is equal to:
  - ◆ (Total cost of Transmission Pipelines Per Well) / (Factor) = 142.544$

Appendix M: Cost calculations for Transport: Metering Stations

Apply the conversion factor from per well to per product:

Total Cost of Metering Stations per Well:

20,000$ in 2020[130]; using CPI conversion [131], 13,909$ in 2002

Method: **From Well Drilling**, the conversion from per well to per product is 1362

- ➔ The total cost of Metering Stations per product is equal to:
  - ◆ (Total cost of Gas Per Well) / (Factor) = 10.212$

Appendix N: Cost calculations for Transport: Valves

Apply the conversion factor from per well to per product:

Total Cost of Valves per Well:

30$ / valve → 9000$ per processing plant in 2020; using CPI conversion [131], 6,259$ in 2002

Method: **From Well Drilling**, the conversion from per well to per product is 1362

- ➔ The total cost of Valves per product is equal to:
  - ◆ (Total cost of Gas Per Well) / (Factor) = 4.6$

Appendix O: Calculations and Explanations for AEW of Natural Gas Water Heating

Table 16 lists the detailed calculations and explanations for our final AEW of the Natural gas Water Heating Cycle.

Table 16: Detailed Calculations for AEW of every Natural Gas Water Heating Life Stage

Cash Flow	**Net Present Worth and Final Annual Equivalent Worth**
Raw Materials Cost (P)	The total initial cost of raw materials as a net present worth is: $P = \$5602.75$ The NPW is converted to AEW over a common lifetime of 20 years: $A = P\frac{i(1+i)^N}{(i+i)^N-1}$

	$A = 5602.75 \frac{0.05(1+0.05)^{(20)}}{(1+0.05)^{20}-1}$ $A = \$449.58$
Manufacturing Costs (P)	The total manufacturing cost as a net present worth is: $P = \$8914.61$ The NPW is converted to AEW over a common lifetime of 20 years: $A = P \frac{i(1+i)^{N}}{(i+i)^{N}-1}$ $A = 8914.61 \frac{0.05(1+0.05)^{(20)}}{(1+0.05)^{20}-1}$ $A = \$715.33$
Transportation of Materials/Product Costs (P & F)	The natural gas water heating system has an average lifetime of 10 years, and is analyzed over a common lifetime of 20 years as a common basis to the Solar Water Heating system. The first lifetime has an initial cost of transportation related to the natural gas distribution: $P = \$157.36$ The NPW is converted to AEW over a common lifetime of 20 years: $A = P \frac{i(1+i)^{N}}{(i+i)^{N}-1}$ $A = 157.36 \frac{0.05(1+0.05)^{(20)}}{(1+0.05)^{20}-1}$ $A = \$12.63$ There is a single cost at year 0 and year 10 for tank transportation. The NPW at year 0 is: $P = \$50$

	The cost at year 10 is converted from a future cost to NPW: $P = F(1+i)^{-N}$ $P = 50(1+0.05)^{-10}$ $P = \$30.70$ The total NPW is: $P = \$80.70$ The NPW is converted to AEW over a common lifetime of 20 years: $A = P\frac{i(1+i)^{N}}{(i+i)^{N}-1}$ $A = 80.70\frac{0.05(1+0.05)^{(20)}}{(1+0.05)^{20}-1}$ $A = \$6.48$ The total AEW is: $A = \$19.11$
Initial Purchase Cost (P)	The initial purchase cost as a net present worth is: $P = \$1500$ Note that the initial purchase cost is strictly the cost the buyer would pay for the natural gas system. The NPW is converted to AEW over a common lifetime of 20 years: $A = P\frac{i(1+i)^{N}}{(i+i)^{N}-1}$ $A = 1500\frac{0.05(1+0.05)^{(20)}}{(1+0.05)^{20}-1}$ $A = \$120.36$
Maintenance Costs (A)	The AEW of the maintenance costs over a lifetime of 20 years:

	$A = \$105$
Operational Costs (A)	The AEW of the operational costs over a lifetime of 20 years: $A = \$1511.5$
Replacement Costs (F)	A replacement cost occurs at year 10: $F = \$1500$ The NFW is converted to AEW over a time of 10 years: $A = F \frac{i}{(i+i)^N - 1}$ $A = 1500 \frac{0.05}{(1+0.05)^{20} - 1}$ $A = \$45.36$
Disposal Cost (F)	The natural gas water heating system has an average lifetime of 10 years, and the common lifetime is 20 years, therefore a disposal cost will be paid twice at year 10 and year 20. The disposal cost is: $F = 150$ The AEW of the first disposal cost at year 10 is: $A = F \frac{i}{(i+i)^N - 1}$ $A = 150 \frac{0.05}{(1+0.05)^{10} - 1}$ $A = \$11.93$ The AEW of the second disposal cost at year 20 is: $A = F \frac{i}{(i+i)^N - 1}$

	$A = 150\frac{0.05}{(1+0.05)^{20}-1}$ $A = \$4.54$ The total AEW is: $A = \$16.47$
Salvage Value (F)	The average lifetime of the system ends evenly with the common lifetime, therefore the salvage value is: $A = \$0$
Final AEW	$A = \$2972.81$

Appendix P: Costs of Individual Solar Panel Materials

Table 17 depicts the specific costs for the solar panel materials.

Table 17: Cost breakdown of Pre-Manufacturing Stage

Material	Quantity of Material Used per One unit of Product (kg) [14]	Cost of Material (CAD/kg)	Total Cost of Material Used (CAD)
Aluminum	10	2.28 [132]	22.80
Cover Glass	11.3	5.42 [122]	61.25
Copper Pipes	22.6	7.46 [121]	84.30
Polyurethane Insulation	2	2.78 [123]	5.56
Cardboard	1.8	0.14 [124]	0.25
TOTAL			174.16

Appendix Q: Costs of Individual Solar Heating Tank Materials

Table 18 lists the detailed calculations and explanations for our final AEW of the Solar Thermal Water Heating Cycle.

Table 18: Costs of Individual tank materials for Solar Water Heating

Tank Materials	Cost
Stainless Steel	$3.20/kg [119] $485.5 kg Total Cost: $1553.6
Magnesium	$2.10 USD / pound or $1.32 CAD/kg [120] 1.4 kg Total Cost: $1.85
Copper	$7.46/kg [121] 40 kg Total Cost: $298.4
Glass	$5.42/kg [122] 61 kg Total Cost: $330.62
Polyurethane Insulation	$2.78/kg [123] 4.88 kg Total Cost: $13.57
Cardboard	$0.14/kg [124] 2.5 kg Total Cost: $0.35
Aluminum	$2.28/kg [132] 7.5 kg Total Cost: $17.1
TOTAL	$2215.5

Appendix R: Calculations and Explanations for AEW of Solar Water Heating

Table 19 lists the detailed calculations and explanations for our final AEW of every Solar Water Heating Cycle.

Table 19: Detailed Calculations for AEW of every Solar Water Heating Life Stage

Cash Flow	**Net Present Worth**
Raw Materials Cost (P)	The present worth of the raw materials is converted to an annual cost by the following calculations: $A = P\frac{i(1+i)^N}{(i+i)^N-1}$ $A = 2389.66\frac{0.05(1+0.05)^{20}}{(1+0.05)^{20}-1}$ $A = \$191.75$
Manufacturing Costs (P)	The present worth of the manufacturing cost is converted to an annual cost by the following calculations: $A = P\frac{i(1+i)^N}{(i+i)^N-1}$ $A = 929.12\frac{0.05(1+0.05)^{20}}{(1+0.05)^{20}-1}$ $A = \$74.55$
Transportation of Materials/Product Costs (P)	The present worth of the delivery cost is converted to an annual cost by the following calculations: $A = P\frac{i(1+i)^N}{(i+i)^N-1}$ $A = 50\frac{0.05(1+0.05)^{20}}{(1+0.05)^{20}-1}$ $A = \$4.01$
Initial Purchase Cost (P)	The present worth of the purchase cost is converted to an annual cost by the following calculations: $A = P\frac{i(1+i)^N}{(i+i)^N-1}$ $A = 10250\frac{0.05(1+0.05)^{20}}{(1+0.05)^{20}-1}$ $A = \$822.49$
Maintenance Costs (A)	The maintenance cost is already an annual cost, no conversion is needed:

	$A = \$643.5$
Operational Costs (A)	The operational cost is already an annual cost, no conversion is needed: $A = \$196.17$
Replacement Costs (F)	The future worth of the replacement cost is converted to an annual cost by the following calculations: $A = F\frac{i}{(i+i)^N - 1}$ $A = \$0$
Disposal Cost (F)	The future worth of the disposal cost is converted to an annual cost by the following calculations: $A = F\frac{i}{(i+i)^N - 1}$ $A = 150\frac{0.05}{(1+0.05)^{20} - 1}$ $A = \$4.54$
Salvage Value (F)	The future worth of the salvage value is converted to an annual cost by the following calculations: $A = F\frac{i}{(i+i)^N - 1}$ $A = \$0$
Final AEW	**$1937.01**

Appendix S: Assumptions made for Economic Analysis

Assumption of Interest Rate

- Interest rate was based on the energy sector as it applies to both natural gas and solar water heating.
- This interest was found to be a constant 5% over the analysis period [11]
- Problems with the assumption:
    - It assumes a constant interest rate of the energy sector which is not true. The interest rate depends on the ever changing economy and the company itself.
    - It would have been more appropriate to use the minimum attractive rate of return (MARR) of the UofT residential housing as this analysis is done from their perspective.

Assumption of Maintenance Cost

- Assumed all possible repairs each system may require would occur once during lifetime
- Allows for analysis to consider the worst possible scenario in terms of economic loss, and provides a fair basis to compare
- In reality, this cost can be influenced by factors such as manufacturer, materials used, and whether maintenance duties required by user are undergone
- The many repairs that were assumed to be needed may not occur at all during the system's lifetime
- The maintenance for the Natural Gas Water heating system was found to be $105/yr, and for Solar Water heating to be $643.5/yr. (Table 1)(Table3)

Assumption of Disposal Cost

- Among the several disposal options available, recycling was chosen as there are several recycling plants near UofT
- The recycling cost, $150, was assumed the same for both forms of water heating even though solar water heating has an additional component that requires recycling: solar collectors (Table 1)(Table3)
- The whole product was assumed to be recycled even though insulation is not necessarily always recycled

Assumption of Lifetime

- Assumed the lifetimes of each system were an average of the lifetimes found through various sources (Natural Gas was assumed 10 year lifetime, and Solar was assumed 20 years)[3][4]
- The common lifetime used for the annual equivalent worth analysis was 20 years
- The values for the lifetime however are heavily dependent on many factors including the system manufacturer, proper yearly maintenance, water quality, and quality of installation.
- Overall, the change in lifetime would not cause major changes in the cost, due to any extra costs in maintenance being balanced out by savings in both replacement cost and extended usage

Appendix T: The inputs, outputs, air emissions, waste/heat emissions of the Pre-manufacturing process in Natural Gas

Table 20 lists the inputs and outputs for every process in the Premanufacturing stage of Natural Gas Water heating.

Table 20: The Inputs, Outputs, Air Emissions, Waste/Heat Emissions of the Natural Gas Pre-manufacturing process

Natural Gas Pre Manufacturing Process	Input	Output	Air Emissions	Waste/ Heat Emissions (Hazardous /NonHazardous)
Well Drilling (Natural Gas Extraction) [113]	**Fuel Gas**: 4.24 m^3 **Diesel Oil**: 0.0234 L	**Raw Natural Gas:** 100 m^3 **Condensate**:17.78 kg	**CO2**= 25,430 g **CO** = 65.31 g **CH4**= 13.85 g **N2O**= 1.59 g	Hazardous Waste = 6.58 g Non-hazardous Waste = 8.78 g
Inlet Gas Compression *(**Note**: Assume 141,607 MWh Natural Gas Input where applicable)*	**Electricity**: 1.76 x 10^{-4} $\frac{MWh}{kg\ natural\ gas}$ [133]	**Electricity Demand for mechanical work, lighting etc.**: 557MWh [134]	**Nitrogen oxides**: equal to 1.0 g/bhp-hr **Carbon monoxide**: equal to 1.5g/bhp-hr **Volatile organic compounds**: equal to 1.0 g/bhp-hr [135]	**Hot Water**: 5,053 MWh [134] **Vents and Leakage Emissions**: 546 MWh [134]
Well Casing	**Carbon Steel**: 0.0236 kg [30]	N/A	**CO2** = 11.7 g **NOx** = 0.242 g **CO** = 0.0555 g **NMVOC** = 0.00647 g **SO2** = 0.0052 g **Dust (PM10)** = 0.0071 g [114]	N/A
Well Cementing	**Cement:** 28,425 kg [31][117]	N/A	**Particulate matter** **Organic HAP** **Mercury** **Acidic Gases** **Dioxin/Furan** [136]	N/A

Important Notes:

1) Inlet Gas compression utilizes reciprocating engines [137]. The air emissions above show the air emissions with this engine working on Natural Gas [135]. These correspond to an electric working capacity of around 1,141 kW [135].

Appendix U: The inputs, outputs, air emissions, waste/heat emissions of the Manufacturing process in Natural Gas

Table 21 lists the inputs and outputs of the different processes in the manufacturing stage for Natural Gas Water heating.

Table 21: The Inputs, Outputs, Air Emissions, Waste/Heat Emissions of the Natural Gas Manufacturing process

Natural Gas Manufacturing Process	Input	Output	Air emissions	Waste/ Heat Emissions (Hazardous /NonHazardous)
Oil Condensate Removal [108]	**Water:** 0.057 m3 **Electricity:** 0.00198 kWh **HP steam:** 0.036 kg	Sale Gas: 100 m3 Coproducts: Ethane: 18.53 m^3 Propane: 4.79 m^3 LPG: 23.19 m^3 NGL: 4.06 m^3 CO2: 50.80 m^3 [108]	**CO2**: 8,5787 g **SO2**: 3.8 x 10^{-5} g **CO**: 1.2 x 10^{-3} g **NOx**: 2.14 x 10^-3g [108]	**Mercury removal sieve water**: 5.45 x 10^{-4} g **Used oil**: 9.19 x 10^{-4} g [108]
Water Removal [132]	**Reboiler Energy**: 1.52 x 10^-1 BTU/scg NG product **Reboiler Fuel**: 1.48 x 10^-4 kg NG fuel/kg NG product [133]	N/A	CO2: 4.24 x 10^-4 kg CO2/ kg NG N2O: 2.26 x 10^-9 kg N2O/kg NG CH4 (for combustion): 8.10 x 10^-9 kg CH4/kg NG CH4 (for venting): 3.37 x 10^-4 kg CH4/kg NG [133]	N/A
NGL extraction *(Based on an output of 1 Kg of Natural Gas)*	**Electrical Power**:1.38 x 10^-5 MWh [133] **Natural Gas:** 1.19 kg [133]	**Natural Gas (***with no NGLs present):* 1.00 kg **Natural Gas Liquids:** 0.19 kg [133]	**Leakage of fluorocarbons**: *This includes CFCs, HCFCs, and HFCs* [133]	N/A
Gas sweetening *(Based on an output of 1 Kg of Natural Gas)*	**Natural Gas** (unsweetened): 1.0016 kg **Water**: 2.75 x	**Sweetened Natural Gas**: 1.00 kg **Evaporated**	(*ALL in Kg*) CO2: 1.6 x 10^-6 CH4: 2.75 x 10^-5	**Lead**, *including heavy metal emissions to the air:* 1.83 x 10^-11 kg

	10^-3 kg [140] [138]	**Water:** 2.75 x 10^-3 [140]	NO: 8.73 x 10^-9 SO2: 2.2 x 10^-8 CO: 3.07 x 10^-6 [139]	[140]

Important Notes:

- Following Gas Sweetening, the two mains products H_2S and CO_2 are utilized are made use of processes outside the boundary set for this project:
  - CO_2 :
    - Reinjection process to enhance the oil recovery process [141]
    - Vented to the environment, thus becoming an air emission [141]
  - H_2S :
    - Mixed with H_2S scavengers to produce iron sponges [141]
    - Claus process to convert H_2S to sulphur for use as a sale gas and to avoid releasing as an air emission [142]
- Following NGL extraction, NGL fractionation occurs in a process by which three important by - products are produced, namely ethane, propane, and butane [34]

Appendix V: The inputs, outputs, air emissions, waste/heat emissions of the transport Natural Gas

Table 22 lists the inputs and outputs of the processes in the transport life stage for Natural Gas Water heating.

Table 22: The Inputs, Outputs, Air Emissions, Waste/Heat Emissions of the Natural Gas Transport process

Natural Gas Pipeline Transport	**Input**	**Output**	**Air emissions**	**Waste/ Heat Emissions (Hazardous /NonHazardous)**
Transport of Natural Gas in Pipelines	Natural Gas Carbon Steel [133]	N/A	SO2 Steam Inorganic emissions to fresh water [133]	Leakage of Methane *(could result in the explosion of pipeline due to high volatility)* [143]

Appendix W: Impact Analysis Categories (Characterization)

- Global Warming
  - Scale: Global
  - Indicator: Greenhouse Gases (Converted to Kg CO_2 eq)
  - Rationale: this impact category was chosen based on research found in the PCR [14] that indicated a large amount of greenhouse gases being produced in different life stages of the product.
- Acidification
  - Scale: Regional, Local
  - Indicator: Substances that lead to acidification (Converted to Kg SO_2 eq)
  - Rationale: this impact category was chosen based on research found in the PCR [14] that indicated large amount of substances that lead to acidification being produced in different life stages of the two products under consideration
- Photochemical Smog
  - Scale: Local
  - Indicator: Non-Methane Hydrocarbon (Converted to Kg PM2.5 eq)

    - Rationale: this impact category was chosen based on research found in the PCR [14] that indicated large amount of non-methane hydrocarbons being produced in different life stages of the two products under consideration
- Eutrophication
    - Scale: Local
    - Indicator: Substances that lead to eutrophication (Converted to Kg N eq)
    - Rationale: this impact category was chosen based on research found in the PCR [14] that indicated large amount of substances that lead to acidification being produced in different life stages of the two products under consideration
- Ozone Depletion
    - Scale: Global
    - Indicator: Substances that lead to ozone Depletion (Converted to Kg CFC-11 eq)
    - Rationale: this impact category was chosen based on research found in the PCR [14] that indicated large amount of substances that lead to acidification being produced in different life stages of the two products under consideration

Appendix X: Sensitivity Analysis of the Gas Sweetening Process

Significant Issue:

- The Gas Sweetening technology has a significant effect on the environmental impacts in the impact assessment due to its high cost of procedure per well. There exists different sweetening technologies, and two main cases will be analyzed with respect to the base case.

Sensitivity Analysis:

A basic simple amine natural gas sweetening plant is compared to two different operating Natural Gas sweetening plants Figure 27 [144].

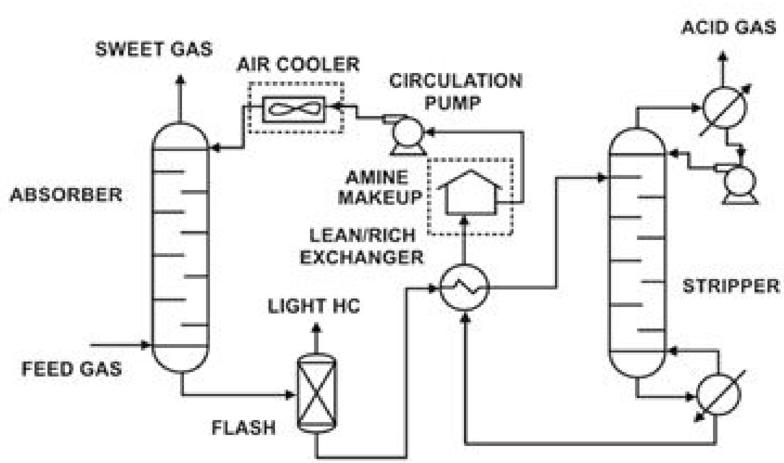

Figure 27. Base Case [144]

Change in the first case (Vapor recompression case): The base case configuration was changed by introducing a vapor stream which is recompressed, which results in the diminishing of heat energy consumed in the process. The parameter being changed is heat input to the process by replacing the Lean/Rich exchanger for an LNG, as shown in Figure 28 [144].

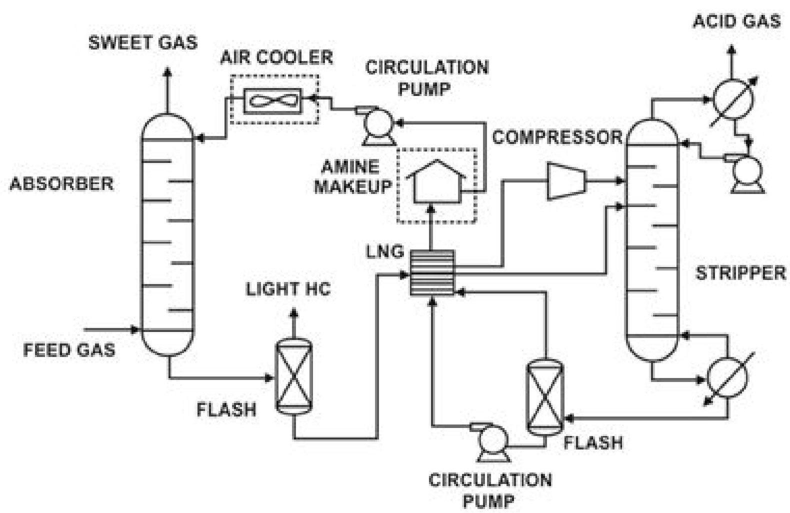

Figure 28. Vapor Compression Case [144]

Change in the second case (Two-stage membrane case): The process is simplified using different technology, as shown in Figure 29, namely two polymeric membrane modules, and this changes the pressure at the output by decreasing it. The parameter being changed here is the pressure [144].

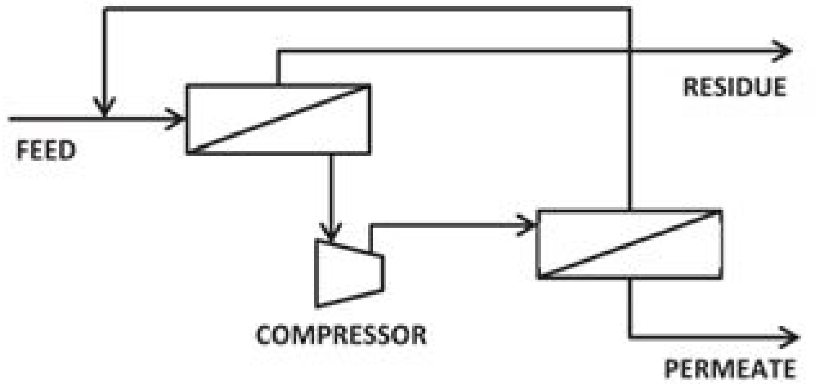

Figure 29. Two-stage membrane case [144]

The GHG emissions and CH4 wasted during the gas sweetening process for the Vapor Compression case and Membranes case with respect to the Base case is shown in Table 12 [144].

Table 23: Data for Sensitivity Analysis

	Base Case	Vapor Recompression	Membranes
GHG emission (Kg/hr) [104]	380.21	304.87	74.15
CH4 wasted (% m) [104]	0.73	0.73	4.8

Conclusion: This study draws two main points in relation to the parameters defined above:

- There exists a high possibility of increasing the efficiency of the sweetening process of Natural Gas. The membrane configuration reduces the GHG emissions in comparison to the other processes as shown on Figure 30.

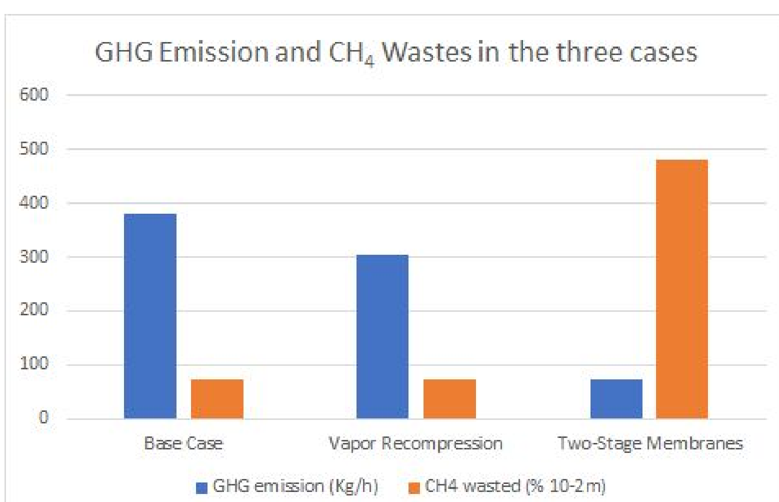

Figure 30. Greenhouse gases emission (GHG) and methane (CH_4) wastes in the three cases

- This shows that changing the temperature at which the process operates does not have a major impact on the overall efficiency of the cycle. However, as we decrease the pressure at the output, we reduce the greenhouse gases impact.
    - **Effect on study**: Decreasing the GHG emissions decreases the global warming potential in the total output of the different sectors in the TRACI impact assessment for gas sweetening . Gas sweetening has a global warming effect of 5383.7. This value is 2-3 orders of magnitude larger than the rest of the manufacturing processes (See Table 8), causing a large uncertainty in the comparison with Solar Water Heating. This uncertainty is introduced due to the variation of gas sweetening processes.
- The amount of CH_4 (i.e natural gas) wasted remains high despite a decrease in the operating temperature; however, a decrease in the output pressure in the processing plant prior to transport could result in the waste (i.e leakage) of processed natural gas.
    - **Effect on study**: The Transmission Lines global warming impact is orders of magnitude larger than the rest of the transport processes in Natural Gas Transport (See Table 8). This is due to the leakage which could occur at the output of the gas sweetening process as explained by the decrease in output pressure.

10.0 Attribution Table

Table 24 lists the attribution table for this document.

Table 24: Attribution Table for Group 12

Section/Members	Kareem Maarouf	Matilda Khoshaba	Cyril Guirgis	Yusuf Elgharib
Executive Summary		✓	✓	
Introduction	✓	✓	✓	✓
Economic Analysis		✓	✓	
Hybrid LCA	✓	✓	✓	✓
Societal Analysis	✓			✓
Sensitivity Analysis (Hybrid LCA)	✓			✓
Summary and Recommendation	✓	✓	✓	✓
Appendix	✓	✓	✓	✓
References	✓	✓	✓	✓