

CRITICAL REVIEW OF UTILIZING CONSTRUCTED WETLANDS TO
SUSTAINABLY TREAT PETROLEUM INDUSTRY WASTEWATER

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For Grizz and Zoey, thanks for being the best.

ABSTRACT

Current practices regarding the treatment of petroleum industry wastewater rely on high energy consumption and the effluent maintains high nutrient levels. Post treatment, the high nutrient wastewater is discharged into local waterways and can lead to eutrophication in surrounding waters, thereby making the treatment process an environmentally, socially and economically damaging process. Both the high energy demand and elevated nutrient levels in the effluent are reasons to explore new methods to sustainably treat the petroleum industries wastewater. While the majority of industry uses the high energy process, some utilize constructed wetlands. A constructed wetland is a low energy treatment process that produces effluent with very low nutrient levels. In this study, a sustainability analysis of the two treatment processes showed the constructed wetland to be more sustainable. The analysis weighed metrics to fully understand the complete environmental, social and economic impacts of each process. The constructed wetland proved most sustainable in the economic and social categories, due to low associated costs and contributing to Hawai'i's sustainability initiative. Relatively closer scores in the environmental category showed both were efficient in hazardous component removal but lacking in nutrient reduction. The low energy demand and low waste produced by the constructed wetland were responsible for showing improved sustainability in the environmental category.

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1.0 INTRODUCTION

To refine crude oil into usable products, a large amount of water is required. In fact, the amount of water needed ranges from 0.4 to 1.6 times the amount of crude oil processed (Diya'uddeen et al. 2011). For every gallon of fuel put in a car, between 0.4 and 1.6 gallons of water is necessary for production. Based on a projected 30% increase of global energy demand by the year 2040, the estimated world usage of 105 million barrels per day (mb/d) equates to a potential wastewater production amount of 40 mb/d to 168 mb/d (Doman et al. 2017). The wastewater is hazardous and must be treated prior to being discharged.

The many refinery processes that consume water range from cooling, steam generation, cleaning, distillation and hydro-treating (El-Naas et al. 2016). Regardless of the use, as the water comes into contact with the petroleum products, many hazardous components are picked up into the water stream. Some of these hazardous constituents include polycyclic aromatics, oil and grease, phenolic compounds, nitrogen and sulfur in the form of ammonia and hydrogen sulfide respectively (Diya'uddeen et al. 2011). Because most petroleum industry wastewater is discharged into local waterways, treatment units are necessary to purify the water and bring the levels of contaminants in the effluent to within allowable limits set by local and federal regulators.

The treatment of refinery wastewater typically occurs in a two-stage process. The first stage is pre-treatment and is designed to remove suspended solids, immiscible liquids and solid particles (Renault et al. 2009). Most of the

separation is attained mechanically by gravity in separation tanks or API separators (Diya'uddeen et al. 2011). The second stage consists of advanced treatment and is designed to reduce effluent contaminants to within allowable limits. This is achieved by various processes including chemical oxidation and biological remediation where oxidation and reduction reactions occur and often consumes large amounts of electricity (Diya'uddeen et al. 2011).

While the treatment units reduce the hazardous components to within regulatory limits, higher levels of unregulated constituents are still discharged into these waterways. These components consist of total nitrogen, nitrate, nitrite, phosphorus and silica, and are considered as available nutrients for aquatic organisms. The high nutrient levels in the discharged effluent can lead to eutrophication in surrounding waters, thereby making the current treatment process an environmentally damaging process. Both the high energy demand and elevated nutrient levels in the effluent are reasons to explore new methods to sustainably treat the petroleum refinery wastewater.

The majority of the petroleum industry treats their wastewater with the high energy systems mentioned above, but a few utilize constructed wetlands to complete the task. Constructed wetlands are manmade systems designed to mimic the natural function of wetlands (Vymazal 2014). In doing so, the constructed wetland can purify the refinery wastewater utilizing natural vegetation, substrates and microbial activity (Vyzmal 2014). This is a low energy consumption treatment process that produces effluent with very low nutrient levels.

In this study, an analysis will be conducted on both treatment types to better understand the sustainability of each process. The sustainability of a process can be calculated using metrics within the three pillars of sustainability - economic, environmental and social. Each category carries equal weight and will provide a complete understanding of the processes impact. Balancing the most benefit within the three categories will ensure the most sustainable process is understood. In weighing both processes, the goal is to provide data to inform the petroleum industry, and policy makers, of the most sustainable process.

2.0 METHODS

For this critical review, a radar plot was used to compare the sustainability of the two wastewater treatment processes. The radar plot graphically displays data in a 2-D chart of multiple variables. Within the chart, a scoring system is represented by three concentric circles. This provides a visual representation of scoring for each individual variable as well as the category as a whole; in this case pertaining to the sustainability of the process.

To evaluate the relative sustainability of each process, a series of metrics, or variables, was developed to equally represent the three pillars, or categories, of sustainability - economic, environmental and social. For each individual metric, a ranking system was used to determine how well each process addressed the requirement for sustainability. On a scale of 1 to 3, 1 being a low score and 3 being high, each metric was ranked and a final radar plot was used to determine which process proved more sustainable.

Representing the standard, high energy wastewater treatment (HEWT) process, a petroleum refinery in Oahu, Hawai'i, that processes 56 thousand barrels per day (tb/d) of crude oil was used. This facility processes 17 tb/d of hazardous wastewater and discharges its effluent into the Pacific Ocean. For the constructed wetland treatment (CWT) process, data from previous studies as well as currently running sites was used. This data provided support showing the CWT could operate and treat the wastewater in a matter necessary to meet current regulatory limits regarding pollution. The local environment of the island of Oahu was also taken into consideration for the wetland.

2.1 Social Criteria

The social pillar consisted of metrics representing what the community would consider necessary for sustainability. First, how each process falls in line with the local government's sustainability vision was used. The local community, and their acceptance of the treatment facility, was the next metric taken into consideration. Next, cultural acceptance and concerns were taken into account. Corporate responsibility, smell and visual appearance were the final metrics of the social pillar.

Table 2.1 – Social Sustainability Metrics

Social Sustainability Metrics	
Hawai'i State Government Sustainability Vision	Local Community Acceptance
Cultural Acceptance	Corporate Responsibility
Smell	Visual Appearance

2.2 Economic Criteria

Within the economic pillar, cost was the main metric used. The cost metric was includes operating cost, maintenance cost and capital costs. The next metric was whether or not the process supported expansion of the facility, a return on investment, thereby increasing future value. Costs of redundancies was also taken into account. Future employment and training was considered to represent the impact on the workforce.

Table 2.2 – Economic Sustainability Metrics

Economic Sustainability Metrics	
Operating, Maintenance and Capital Costs	Support for Expansion of Facility
Cost of Redundancies	Employment Costs
Training Costs	Increased Future Value

2.3 Environmental Criteria

In the final pillar, impacts on the environment were quantified within the metrics. The first metric is global environmental impact, which covers marine ecotoxicity, global warming and ecosystem quality over the life cycle of the process. Next, biochemical oxygen demand (BOD) of the effluent was considered to determine treatment capabilities. Nitrogen and phosphorus levels in the discharged effluent were considered to represent the nutrient load. Energy usage was also looked at in this pillar. Finally, the waste produced by each process was contrasted.

Table 2.3 – Environmental Sustainability Metrics

Environmental Sustainability Metrics	
Global Environmental Impact	BOD
Nitrogen Reduction	Phosphorus Reduction
Energy Usage	Waste Production

3.0 RESULTS

3.1 Social Sustainability

The relationship between businesses and people extends beyond the customer. Typically, businesses focus on decisions intent on increasing profits. While this process usually involves an analysis of what the customer wants from a product, it fails to identify what society wants from the company. If company A has the same product as company B, but for or a cheaper price, and company A is rife with negative publicity, customers would likely purchase the products of company B. This highlights a need by business to understand how their decisions impact not only their customers, but their local communities and stakeholders. Incorporating these relationships into the decision making process will not only lead to better understanding your customer, but add to the assurance of survival of the business as a whole. In this section, metrics were developed to represent the social sustainability in relation to how the local petroleum industry treats their wastewater.

3.1.1 *Hawai'i State Government Sustainability Vision*

The Hawai'i State Government led by Governor David Ige recently launched a sustainability initiative with the following commitments – 100% increase in local food production by 2020, implement an Interagency biosecurity plan by 2027, protect 30% of priority watersheds by 2030, effectively manage 30% of nearshore ocean waters by 2030 and achieve 100% renewable electricity by 2045 (State of Hawai'i 2018). Referencing the last commitment of 100% renewable electricity by 2045, the largest utility provider in Hawai'i, Hawai'ian

Electric Companies, reported in 2017 that 27% of the electricity used by their customers comes from renewable sources. The remaining 73% comes from fossil fuel produced by local refineries (HECO 2018).

The current, HEWT process goes directly against many of the commitments laid out in the state's sustainability initiative. The high energy use and high nutrient effluent are the two contributing factors. Although, a change in source of electricity could contribute to the sustainability plan. The high levels of nutrients in the effluent goes against the management of nearshore waters commitment. Included in that management plan is a reduction of pollutants and considering the risk of algae blooms and eutrophication, the current treatment does not aim to protect the local reef and/or fisheries. Therefore, the HEWT process scores a 1 as it does not contribute to goals of the state's sustainability initiative.

The CWT process, on the other hand, offers many benefits that would help contribute to the sustainability initiative. The CWT would greatly reduce the electricity needed to effectively treat the wastewater, thereby directly assisting in the state's 100% renewable electricity goal. The CWT would also greatly reduce the nutrients/pollutants being discharged into local waterways thus supporting the 30% nearshore ocean water commitment. Due to the CWT directly helping Hawai'i achieve its sustainability goals, it receives a score of 3.

3.1.2 Local Community Acceptance

For an industry to operate and sustain itself within a community, understanding what the people of that group want and need for their future will

help to insure the longevity of that business. One contributing factor is whether or not the company is offering decent paying jobs, thereby supporting the local community. Another consideration is that of what each process will bring to the area, i.e. water quality of discharged effluent as well as invasive or unwanted flora or fauna. In essence, communities want what's best for their people and their land.

The HEWT has been operating in the area for fifty plus years and is considered accepted by the community. High paying jobs are supported by the HEWT and will continue to provide this benefit to the future community. Future generations may not benefit from it though. The high energy process contributes to climate change resulting in negative effects to marine ecosystems, something the local community is very attached to. Because this process is good for community jobs but does not address the potential negative ecological impacts, it was given a score of 2.

The CWT will add value to future communities by way of local ecosystem preservation as well as job security. The improved performance of the CWT in regards to water purification, as well as energy usage reduction, will ensure the local ecosystems remain healthy for future generations. An unknown factor is the potential impact a transported landscape would have on the local ecosystem. This must be considered in the design of the CWT and if possible, native wetland terrestrial and aquatic plants should be used for ecosystem preservation. Due to the simplification of the CWT design and operation, some high paying jobs will still be required but a net loss will occur due to this simplification. Considering the

ecosystem preservation and potential for local job loss, the CWT scored a 2 for the acceptance metric.

3.1.3 Cultural Acceptance

The Hawai'ian culture is often regarded for its value of "malama 'aina," which means to care for the land. In the book *Thinking Like an Island: Navigating a Sustainable Future in Hawaii*, we learn that prior to European contact "Hawai'i supported a population of a million or more because they had learned their ecological limits of their islands and how to live sustainably within them." Understanding the importance of sustainability to the Hawai'ian culture weighs heavily in this society based metric. To fully appreciate the sustainability of both wastewater treatment processes in regards to cultural acceptance, we must consider the cultural fit, cultural benefit, cultural acceptance and cultural ecological concerns.

When analyzing the cultural fit of the HEWT, immediately we find a contradiction to one of the Hawai'ian cultures core values. The high electricity demand of the HEWT does not contribute to the sustainability of natural resources; in this case it is due to the electricity source of fossil fuels. Next, the only benefit to the culture is that jobs are provided for people of the community. The cultural acceptance of the HEWT is lacking because as stated above, the HEWT process does not fall within Hawai'ian cultural practices of sustainable resource use and caring for the land. Acknowledging the cultural ecological concerns, the contribution of the HEWT to climate changes directly threatens the Hawai'ian Islands. Also, the discharge of high nutrient effluent onto local

waterways threatens reef communities, thereby negatively affecting cultural fishing practices of Hawai'i. Considering the only cultural benefit of the HEWT is that it will provide jobs, a score of 1 is given.

Considering the intent of the CWT is to utilize naturally occurring processes to perform a necessary function, i.e. purify wastewater naturally with little to no manmade energy input, the CWT greatly falls in line with Hawai'ian cultural practices. The cultural benefits of the CWT are reflected in the emergence of a sustainable process that represents a core value of the Hawai'ian culture. By creating a sustainable method within the industry, it benefits the culture in ensuring land and resources are being preserved for future generations. The CWT may be accepted culturally by presenting a process that utilizes less resources, all while producing better results. Ecologically speaking, a large reduction in electricity will help safeguard the islands from climate change and help strengthen nearshore reefs and fisheries. The CWT scores a 3 in this metric.

3.1.4 Corporate Responsibility

Corporate Social Responsibility (CSR) is a way for companies to benefit themselves by benefiting society. According to The Natural Marketing Institute's 2017 report on the "State of Sustainability in America," consumers consider a companies impact on the environment when deciding where to purchase goods (NMI 2017). In fact, 58% of customers are more likely to buy goods and services from businesses that practice environmentally sustainable habits (NMI 2017). Aside from the benefit of more customers, corporations with sustainability in mind

could also be better postured for future regulatory changes that are likely to occur. In the wastewater treatment case, tightening regulations of wastewater constituents would require large amounts of capital investments to meet the new specifications. Therefore, it would behoove corporations to consider these facts when making business decisions.

With the HEWT requiring large amounts of electricity, the simple fact that other options are available shows a potential customer that the corporation may not be doing all it could be in the realm of responsibility. Here, the company must accept their contribution to global warming by way of utilizing electricity sourced from fossil fuels. Also, even though the company is meeting the regulatory requirements of pollutants in the effluent, there is more the company could do to reduce these nutrients further. Considering the HEWT was a responsible thing done in the past to purify the wastewater, no upgrades with technology have been made. This shows the companies priorities of minimizing costs while pushing regulatory limits. This results in a score of 1 for the HEWT.

The CWT would replace the high energy HEWT with a more eco-friendly system, thereby showing the corporations responsibility to do better. The CWT would also lessen the use of natural resources, with benefits ranging from less greenhouse gas emissions to potential reuse of discharge water. Lastly, the company will be better prepared if local or federal governments tighten regulatory limits on water discharged to local waterways. By switching to a more eco-friendly and less natural resource dependent process, the decision shows an embodiment of corporate responsibility. This results in a score of 3.

3.1.5 Smell

It is important to consider the smell of a facility with its longevity, as populations are increasing and therefore moving people closer and closer to said, established facilities. When dealing with municipal wastewater, foul odors are often associated with treatment facilities and this is the same with petroleum industry wastewater. While the source of smells from municipal facilities are obvious, the source of these foul odors in refining are less apparent. In general, a petroleum refineries wastewater is said to have a sewer smell; which is produced by dimethyl sulfur, ethyl and methyl mercaptans (Jafarinejad 2016). In the refining case, these odors are produced by the volatilization of sulfur compounds (Jafarinejad 2016). With an odor threshold of 1-2 parts per billion (ppb), dimethyl sulfide and methyl mercaptan can be identified with a vegetable like smell and a decayed cabbage smell, respectively (Jafarinejad 2016). The odor threshold for ethyl mercaptan is 0.4-1 ppb and also smells of decaying cabbage (Jafarinejad 2016). Hydrogen Sulfide (H_2S) and Methane (CH_4) can also be produced in oxidation ponds used in petroleum industry wastewater treatment (Jafarinejad 2016). This occurs when dissolved oxygen (DO) levels in the oxidation ponds run low and anaerobic conditions persist.

The HEWT currently produces a steady supply of foul odors. These foul odors originate from the oxidation ponds and API separators. The rest of the treatment process is contained in pipes, tanks and pressure vessels which contain potential foul smelling vapors. Due to its coastal location and steady offshore breeze, these smells are often unnoticed to land inhabitants but do

affect passing boats. Considering all of these factors, a score of 2 is given. This represents a moderate containment of odor and limited exposure to the surrounding communities.

The odors produced by the CWT will be very dependent on design. Overall a reduction of odors will occur and to ensure this, a subsurface flow design would be imperative. In contrast, a free surface flow design would contribute to more volatilization of odorous chemicals and therefore increased levels of fould odors. Also, there is a potential for anaerobic conditions to occur which would lead to increased levels of H₂S and CH₄, effectively engulfing the surrounding area with foul smells. Due to the design dependency and potential for anaerobic conditions, the CWT also scored a 2 in this metric.

3.1.6 *Visual Appearance*

As the human population grows, new areas of land are needed to house as well as provide services for society. When considering the ideal home, one may see visual pollution as a negative aspect. Visual pollution can be anything that may restrict natural views or provide constant reminders of nearby industrial facilities. A study exploring stress recovery showed that natural environments contribute more towards recovery than urban settings (Ulrich et al. 1991). This could show us the importance of natural settings in relation to human stress levels. So when we consider the visual appearance of something and how it may affect its sustainability, the impact on the local communities view of visual pollution must be accounted for.

The HEWT requires the use of many large pressure vessels, tanks and piping, creating an image of industrial action on the horizon. This is often interpreted as visual pollution and is seen in a negative way for local community aesthetics. Also, considering the findings from Ulrich et al., something that may hamper the stress recovery process surely would not be considered sustainable for any community. Therefore, a score of 1 is given to the HEWT.

The CWT will replace the tanks, pressure vessels and piping with a natural looking landscapes. The abundance of plants and attraction of local fauna to the area will make this industrial process appear as a natural part of the landscape. Seeing that there is a relationship between natural settings and stress recovery, this would contribute greatly to the sustainability of the proposed process (Ulrich et al. 1991). The CWT scores a 3 in this metric.

This concludes the analysis of the social factor in sustainability. In total, the HEWT scored 8 and the CWT scored 16, as shown in table 3.1.1. This shows that when considering the social sustainability of the two processes, the CWT is more sustainable. Figures 3.1.1 and 3.1.2 display a visual representation of these findings.

Table 3.1.1 – Social Metric Totals

Social metrics	HEWT	CWT
Hawai'i State Sustainability Vision	1	3
Local Community Acceptance	2	2
Cultural Acceptance	1	3
Corporate Responsibility	1	3
Smell	2	2
Visual Appearance	1	3
Total	8	16

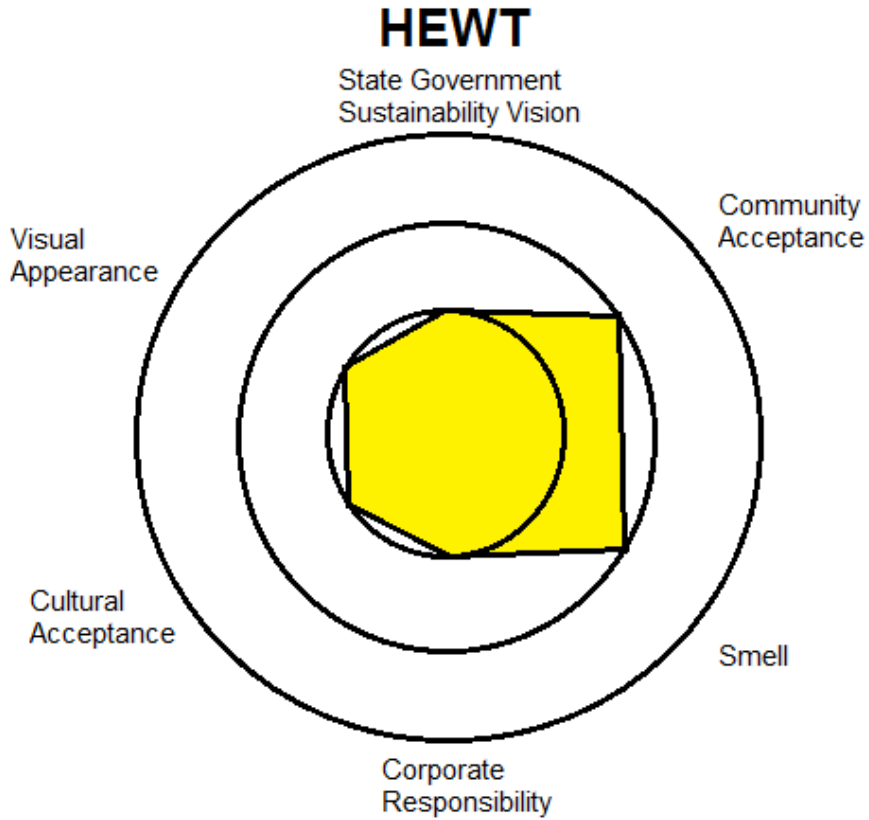


Figure 3.1.1 – HEWT Radar Plot for Social Metrics

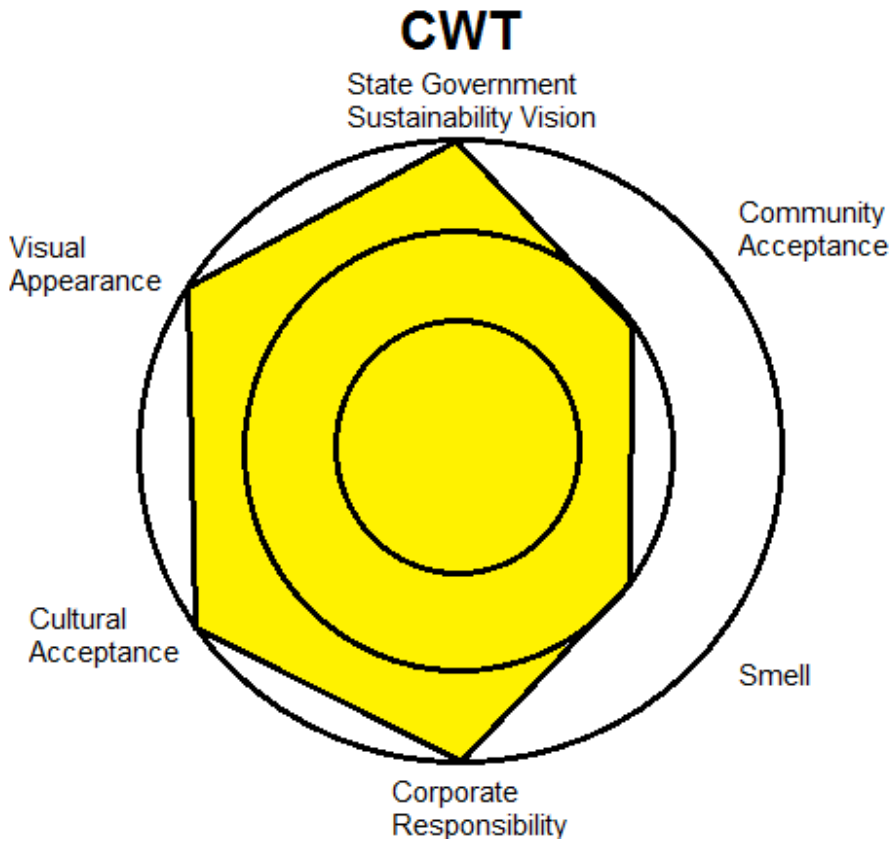


Figure 3.1.2 – CWT Radar Plot for Social Metrics

3.2 Economic Sustainability

The goal of many businesses is plain and simple; make money. This represents societies adaptation to survival by way of earning money to be able to provide for basic needs. The health of an economy, by today's standards, is gauged by the change in gross domestic product (GDP); this represents all products produced by said economy. While this standard focuses only on products produced, the narrow view does not account for other factors that contribute to the longevity, or survival, of these economies. When sustainability of an economy is considered, individual companies and their practices must be considered to represent a full, detailed understanding of any economies future. Further, individual business decisions that affect a company's economic sustainability will more likely contribute to the overall sustainability of an economy.

3.2.1 *Operating, Maintenance and Capital Costs*

In this cost metric, we compared the capital, operating and maintenance costs of a HEWT process versus a CWT process. For a realistic understanding of these costs, an analysis conducted by the DOW Chemical Company was used. In this study, a past business decision was evaluated on a financial and environmental level. The company needed a facility to treat wastewater from an industrial complex that included plastic production and organic chemical production facilities; the two choices proposed were a HEWT and a CWT facility. (DiMuro et al. 2014). Dow chose the CWT and after twenty years of operation, conducted the analysis (DiMuro et al. 2014).

When looking at capital costs involved in the project, the CWT cost DOW 1.5 million dollars (MD) and took 18 months to complete (DiMuro et al. 2014). The HEWT, at the time, was proposed to cost 40 MD and estimated to take 48 months to complete (DiMuro et al. 2014). For operating and maintenance costs, actual numbers from 1995 for the CWT were a combined 122 thousand dollars (DiMuro et al. 2014). In comparison, the HEWT was estimated to have cost 3 MD in 1995 dollars (DiMuro et al. 2014).

Considering the above information, utilizing the HEWT for petroleum industry wastewater results in high operating and maintenance costs. In a society where costs across the board are increasing, an already expensive process may prove to put strain on a company's future bottom line. This fact contributes by no means to the economic sustainability of the company. The resulting score is a 1 for this metric.

For the CWT scenario, especially when compared to the HEWT, the overall capital, operating and maintenance costs provide for a more economically sustainable outlook. While the costs are still significant, the massive reduction in costs would surely be an economic benefit for the company. Considering these facts, the CWT scores a 3.

3.2.2 Support Expansion of Facility

In this metric we weigh the future support of each process on the potential for expansion of the facility. Contributing to this metric are each processes return on investment as well as net present value (NPV). The NPV of a process, in this case the HEWT versus the CWT, is used to estimate the profitability of the

process. The NPV shows the process as an investment, which in turn provides financial data for the company. Understanding the NPV will provide the necessary information regarding whether or not there is a return on investment.

To understand the NPV of these wastewater treatment processes, we again refer to the research conducted by DOW. In it, a total NPV savings of 282 MD was achieved over the CWT projects lifetime (DiMuro et al. 2014). This was attributed to the minimal equipment requirement and low operating and maintenance costs (DiMuro et al. 2014). Also contributing to this was the low energy and material input to the CWT (DiMuro et al. 2014). The operational flexibility of the CWT was also a factor in the NPV; the four-cell wetland provided isolation options to preserve the majority of the wetland if any issues were detected (DiMuro et al. 2014). While the CWT covered a 44.5 hectare area, the high energy demand of the HEWT contributed more to land usage and loss due to upstream fossil fuel recovery and use (DiMuro et al. 2014).

The HEWT represented in this study showed high capital, operating and maintenance costs and proved to be more detrimental to the environment over time. This results in a score of 2 for the HEWT. With a savings of 282 MD over the projects lifetime, the CWT beats out the HEWT when looking at NPV and the future expansion of the refinery. Therefore, a score of 3 goes to the CWT for this metric.

3.2.3 Cost of Redundancies

In a facility that operates 24 hours a day and 7 days a week, and slow down of operation will hurt the bottom line. In a petroleum refinery, if oil is being

refined, wastewater is being produced. A slow down or complete stop of wastewater treatment could lead to a slow down or eventually a complete stop of oil refining due to wastewater storage limitations. Therefore, it is imperative to have built in redundancies to prevent these potential production issues. In some cases, redundancies can be expensive. This metric also includes the required downtime needed for lawful operation of pressure vessels and associated equipment. United States federal law states that as a basic requirement, “each pressure vessel must be examined every 5 years” (Cornell 2018). One way to account for this requirement is to align a total refinery shutdown at once, thus preventing the slowdown of operations for only one vessel at a time.

Another redundancy factor to consider is that of the computerized control systems. This system controls all of the equipment in the process and is also in need of built in redundancies. This is achieved by way of installing two physical networks operating side by side with one being on standby and thereby providing a system prepared for continuous operation.

When the HEWT was first designed, redundancies were considered and implemented by way of installing spare pumps, blowers and bypass lines. This initial investment in capital insured the operational integrity of the treatment facility. Having ways to continue the flow of water were critical to ensuring this. Being that the process is highly reliant on its computer controlled network, capital costs were also used in developing this redundant system. Overall, this greatly increased the projects cost and continues to add to costs per periodic

breakdowns and required compliance inspections. Considering all of these factors, the HEWT scores a 1 for this metric.

For the CWT to have built in redundancies, the main aspect of continued water flow needs to be taken into account. This is because the CWT design does not require the same amount of pumps, blowers and vessels as the HEWT. Further, the design must include ways to maintain the majority of the CWT to remain in operation if any portion of the CWT were to require maintenance downtime. To account for this, the design must include the use of a multi-cellular wetland which allows complete isolation of individual cells while not affecting total wastewater throughput. The lack of equipment needed results in an overall less chance for operation stoppage. Add that to the low capital costs and the fact that the wetland could be built quickly (DiMuro et al. 2014), and we see very low costs associated with ensuring the operational integrity of the CWT. The CWT received a score of 3 in this metric.

3.2.4 Employment Costs

Labor costs are an integral part of a company's full understanding of proposed sustainability of a process. Labor costs are costs associated with the labor of operating and maintaining a process. This would even include any engineering support that would be necessary to sustain the treatment facility. For this metric, the DOW will be used as it provides actual labor costs for wetlands and other, energy intensive processes.

Based on information sourced from DOW, the HEWT would require the equivalent of twelve full-time employees making between 100-120 thousand

dollars per year (DiMuro et al. 2014). This is due to the skilled labor needed to operate and maintain the equipment used in this process. The HEWT scores a 1 for this metric.

The CWT, reported by DOW, requires the equivalent of 0.75 employees making between 100-120 thousand dollars per year (DiMuro et al. 2014). This is because the CWT process is very simple and does not require the use of much of the equipment needed for the HEWT. Based on this information, the CWT scores a 3 in this metric.

3.2.5 Training Costs

Training is an important factor to consider when developing a new process. Processes that involve many moving parts and sophisticated computerized controls require advanced training to ensure operational integrity. Companies want to train their people the best they can to protect their assets and provide a smooth operation. The training will provide operators with plant knowledge necessary for any troubleshooting that may arise. In the petroleum industry, an operator is typically required to fulfil 240 hours of specific unit training before they are allowed to operate the plant on their own. Due to this long and expensive training process, training costs must be considered in the sustainability of a process.

When considering the required twelve full-time employees needed to operate and maintain the HEWT, at a pay rate of 100-120 thousand dollars per year, we see an initial total training cost of 144-200 thousand dollars. While this is mostly upfront costs, this training includes only basic skills and does not

represent continued and advanced training that will be required as time goes on. The HEWT scores a 2 for the training cost metric.

Based upon the required 0.75 employees making between 100-120 thousand dollars per year to operate the CWT, an initial training cost of 9-11 thousand dollars will be had. This is a very low cost considering the alternative. The lack of moving parts, computerized controls and simplicity of the CWT design all account for this low cost. This also translates into less of a need for advanced training required by the HEWT. Therefore, a score of 3 for the CWT.

3.2.6 Increased Future Value

A good business decision considers the impact on future value. While increasing this future value is typically the goal, the understanding is that increasing future value adds to the sustainability of the business. When considering future value, two factors can assist in understanding this. First is corporate responsibility. As learned in the social sustainability section, a company who is eco-friendly is shown to benefit by way of appealing to the majority of consumers (NMI 2018). Lower operating and maintenance costs also contribute to the increased future value of a business.

The HEWT shows corporate responsibility in that it is a process designed to reduce the amount of pollutants in the discharged effluent. While this does remove potentially hazardous constituents to within regulatory limits, it does so in a way heavily reliant on electricity. Due to this electricity being sourced from fossil fuels, the contribution to global warming increasingly outweighs the responsibility earned by purifying the wastewater. The associated costs of the

HEWT are also high and the process does not prepare the company for future tightening of regulatory discharge limits. As much of what has been stated above could lead to an actual decrease in future value, a score of 1 was given to the HEWT.

As for the CWT, the corporate responsibility shown with this decision would fall right in line with increasing the companies public image. This would be achieved by way of showing the company recognizes change is needed and cares for the environment. Associated operating and maintenance costs are also minimal, thereby adding to increased future values. Lastly, the improved functionality of the CWT better prepares the company for any future tightening of regulatory discharge limits. Considering these factors, the CWT scores a 3 in this section.

This concludes the analysis of the economic factor in sustainability. In total, the HEWT scored 8 and the CWT scored 18 as shown in table 3.2.1. This shows that when considering the economic sustainability of the two processes, the CWT is more sustainable. Figures 3.2.1 and 3.2.2 display a visual representation of these findings.

Table 3.2.1 – Economic Metric Totals

Economic metrics	HEWT	CWT
Operating, maintenance and Capital Costs	1	3
Support Expansion of Facility	2	3
Cost of Redundancies	1	3
Employment Costs	1	3
Training Costs	2	3
Increased Future Value	1	3
Total	8	18

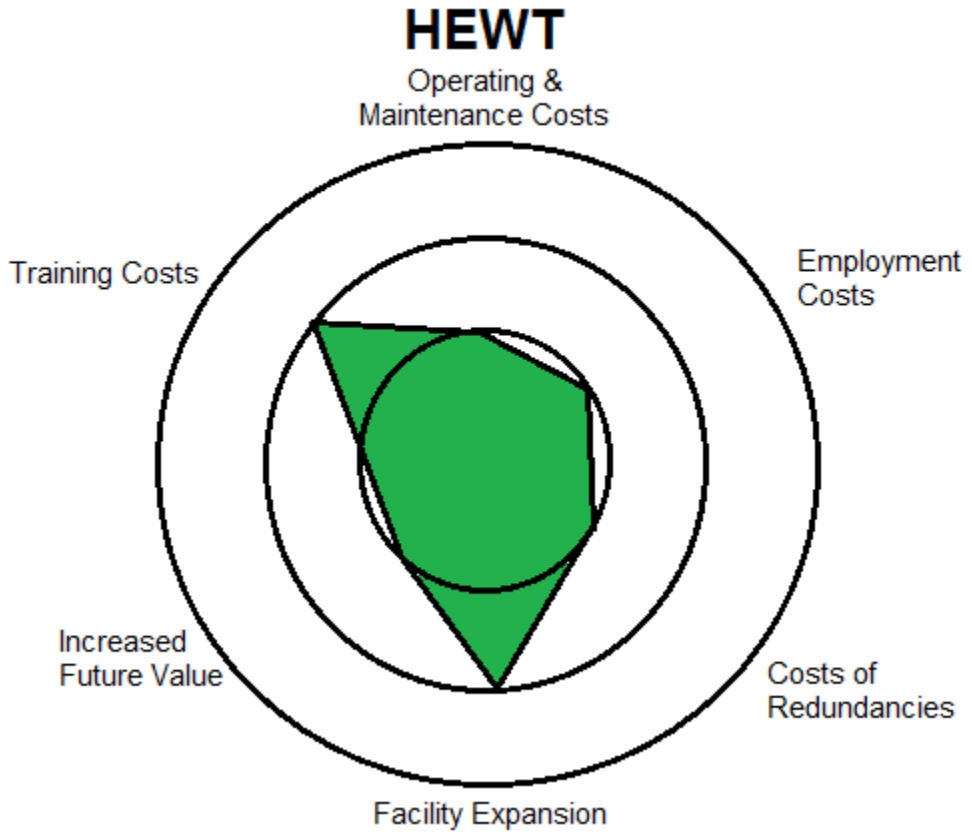


Figure 3.2.1 – HEWT Radar Plot for Economic Metrics

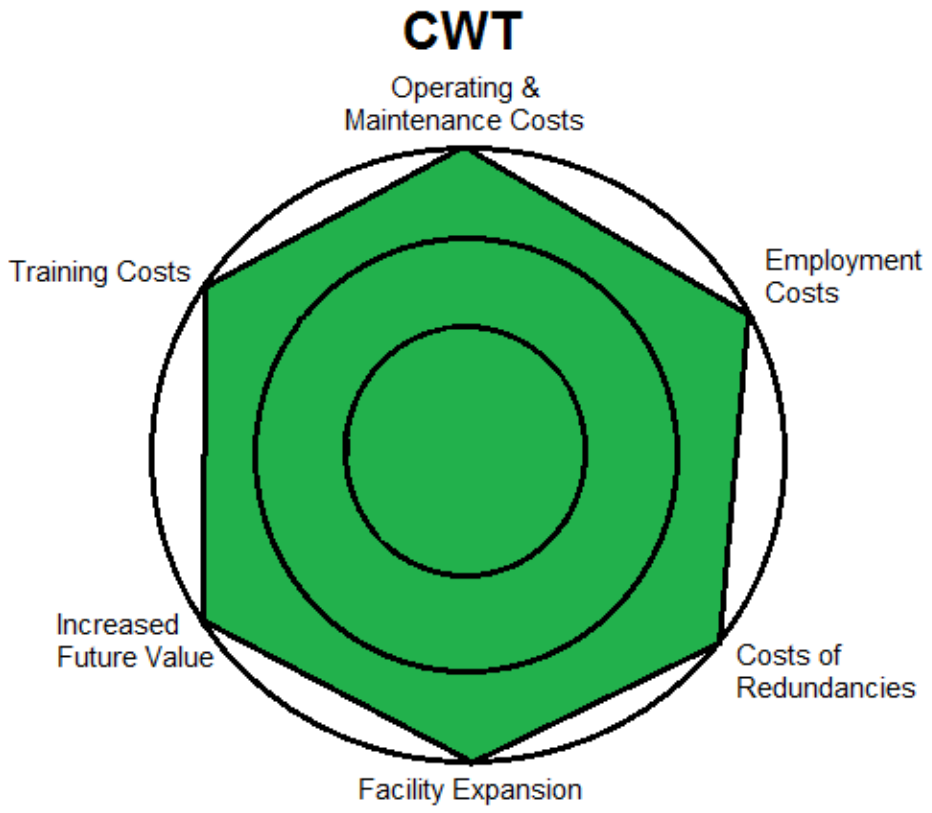


Figure 3.2.2 – CWT Radar Plot for Economic Metrics

3.3 Environmental Sustainability

Environmental sustainability is a measure of how a process affects the condition of the environment. From safeguarding raw materials to ensuring waste systems are not overloaded, environmental sustainability protects humans (Goodland 1995). There is a strong relationship between economic and environmental sustainability and this is related to the use of natural resources (Goodland 1995). Environmental sustainability considers inputs into processes and assesses impacts on life-support systems necessary for human life and in this case, production (Goodland 1995). The following metrics will help determine the environmental sustainability of the HEWT and CWT processes.

3.3.1 *Global Environmental Impact*

A life cycle analysis (LCA) provides information to help understand the full, global environmental impact of a process (DiMuro et al. 2014). An LCA considers all inputs and outputs during the building, operating and closing down stages over the lifetime of a process (Dimuro et al. 2014). An LCA is often referred to as a cradle-to-grave study, with boundaries covering when resources are recovered from the earth to when these resources make their way back into the earth (DiMuro et al. 2014). Therefore, the LCA provides an outlook that can lead to the prevention of inadvertent environmental consequences and ensure a processes potential for sustainability is understood (Dimuro et al. 2014).

For this metric, a previous LCA on a hypothetical sequencing batch reactor, comparable to the HEWT, and a fully operational constructed wetland was used for sustainability scoring. This LCA was conducted utilizing SimaPro

7.3.3 software with Ecoinvent v2.2 used to model utility operations (DiMuro et al. 2014). Within SimaPro, the midpoint impacts were sourced from using the TRACI method (DiMuro et al. 2014). This method reflects the following impact categories – global warming potential, fossil resource use, acidification potential, marine eutrophication potential, smog formation potential and ozone depletion potential (DiMuro et al. 2014). The eutrophication category used the ReCiPe model (DiMuro et al. 2014).

For both the HEWT and CWT designs, the following input parameters were used - total flow rate of 3,468 gpm coupled with inlet concentrations of 500 ppm total organic carbon (TOC), 1,500 ppm chemical oxygen demand (COD), 875 ppm BOD₅, and TSS of 918 kilograms per day (kg/d) (DiMuro et al. 2014). The outlet parameters were based on effluent regulatory limits set by the United States Environmental Protection Agency (EPA) (DiMuro et al. 2014). Lastly, a project lifetime of 30 years was chosen (DiMuro et al. 2014). The results reflected in table 3.3.1 below, represent potential impacts per one cubic meter, or 264 gallons, of treated water. (DiMuro et al. 2014).

Table 3.3.1 – SimaPro based Environmental Impact (DiMuro et al. 2014)

Impact Category	Unit	HEWT	CWT
Ozone Depletion	kg CFC – 11 eq	3.3 x 10 ⁻⁷	6.6 x 10 ⁻⁹
Global Warming	kg CO ₂ - eq	3.7	1.5
Smog	kg O ₃ - eq	0.0606	0.0014
Acidification	kg SO ₂ - eq	0.0076	0.0002
Marine Eutrophication	kg N - eq	0.0003	0.0013
Fossil Fuel Depletion	MJ Surplus	1.07	0.031

Based upon these results, we find that the lower inputs of energy and materials of the CWT leads to a less impactful life cycle in the fossil fuel use, acidification, global warming, smog and ozone depletion categories (DiMuro et al.

2014). For marine eutrophication, the CWT used in the model had a lower reduction efficiency for nitrogen, thus resulting in a greater life cycle impact in this category (DiMuro et al. 2014). When considering all impact categories, the CWT has an overall less impact on the environment, resulting in a score of 2. Being the more impactful process, the HEWT scores a 1.

3.3.2 Biochemical Oxygen Demand (BOD)

BOD is a measure of organic matter within a sample of water. BOD represents the amount of dissolved oxygen needed by microorganisms to breakdown, decompose, organic matter within the water (Knight et al. 1999). If the BOD is high, that means there is a lot of organic matter in the water. A high BOD is considered bad because it indicates there will be less dissolved oxygen available for higher order organisms, as in fish, in the body of water (Knight et al. 1999). A standard test for BOD is BOD₅. BOD₅ is the amount of dissolved oxygen given in milligrams per liter (mg/L) utilized by microorganisms to decompose and therefore stabilize organic matter over a five day period (Knight et al. 1999).

Another reason high BOD is considered bad is because it indicates the potential for anaerobic conditions. Anaerobic conditions occur when there is not enough dissolved oxygen to support aerobic decomposition of organic matter. While regular aerobic decomposition primarily releases carbon dioxide (CO₂), anaerobic decomposition can lead to the release of noxious gasses such as H₂S and CH₄ (Knight et al. 1999).

In petroleum refinery wastewater, hydrocarbons, phenols, oil, grease and sulfur compounds can all contribute to a high BOD (IES 2017). BOD is important

for sustainability due to ecosystem and food web security. An effluent discharged with a high BOD can lead to low dissolved oxygen levels in surrounding waterways. This could lead to eutrophication and negatively affect fish populations in the area.

The HEWT can effectively keep BOD well within permitted limits. While much of the organic compounds are removed in the pre-treatment process, the oxidation ponds of the secondary treatment utilize biological remediation to further decompose any remaining organic compounds. The ponds are stocked with a proprietary blend of bacteria to perform this aerobic oxidation process. Mechanical aeration is necessary in this pond due to the high demand of dissolved oxygen. By the time the effluent is discharged, and after it is mixed with 1,000 gpm of pass through brine water, the BOD₅ must be below 27.4 mg/L as a daily max and below 15.2 mg/L as a monthly average; all per regulatory limits (IES 2017). Based on an industry average of 327 mg/L in petroleum refinery wastewater prior to treatment, as seen in figure 3.3.2, the HEWT reduces BOD between 92-95% (Ishak & Malakahmad 2013). This results in a score of 3 for efficient removal.

To rank the CWT in this metric, a CWT in operation at Amoco's Mandan, North Dakota oil refinery with a given hydraulic loading rate of 1.2 centimeters per day (cm/d), was used (Vymazal 2014). This 1.2 cm/d hydraulic loading rate translates to a flow rate of 365 gpm. As reported, this CWT has an effective reduction rate of 98% for BOD (Vymazal 2014). The free water surface constructed wetland consists of an API separator, for primary treatment, a 6

hectare biological oxidation pond, followed by 11 individual ponds / wetlands with a total area of 16.6 hectares (Vymazal 2014). Utilizing the industry average of 327 mg/L BOD in the influent, the 98% BOD reduction rate delivers a BOD of 6.54 mg/L in the discharged effluent; well below regulatory limits (Vymazal 2014). The 98% reduction rate results in a score of 3 for this metric.

Table 3.3.2 – Petroleum Industry Inlet Wastewater Parameters (Ishak & Malakahmad 2013)

Inlet Parameters	Range (mg/L)	Average (mg/L)
COD	744-1673	1209
BOD ₅	205-448	327
pH	7.50-9.41	8.46
TSS	280-340	310
Ammonia Nitrogen	40-45	43
Oil & Grease	48-97	73
Phosphorus	1.67-1.73	1.7
TOC	184-217	201
Phenols	1.16-1.44	1.30
Sulphides	14-17	16
Benzene	33.31-34.36	33.85

3.3.3 Nitrogen Reduction

In the form of ammonia (NH₃), nitrogen can be toxic. Vertebrates are all susceptible to ammonia toxicity and can experience convulsions, coma and death (Randall & Tsui 2002). While the majority of ammonia in aquatic environments is sourced from agricultural run-off and the decomposition of biological wastes (Randall & Tsui 2002), petroleum industry wastewater also contributes (Ishak & Malakahmad 2013). Ammonia is used in petroleum refining processes for things such as catalysts and pH control, and is also produced as a side reaction in catalytic cracking units (IES 2017). Ammonia is soluble in water and therefore makes its way into the refinery wastewater stream (IES 2017).

As plants can use ammonia as a nutrient source, the potential for algae blooms becomes a concern for wastewater producers. An algae bloom in refinery

wastewater could lead to a violation of discharge limits by increasing the concentration of total suspended solids (TSS) in the effluent. The regulatory limits for TSS in the discharged effluent are 19.1 mg/L as a daily maximum and 12.2 mg/L as a maximum monthly average (IES 2017). If the high ammonia effluent triggers an algae bloom in the local waterway, eutrophication and subsequent fish losses can occur. This is why it is important to consider ammonia reduction for sustainability as a high level could negatively impact reef inhabitants populations.

Nitrification, the biological degradation of ammonia, is another process associated with nitrogen in the refinery wastewater. Aerobic bacteria utilize oxygen (O_2) to convert ammonia to nitrite (IES 2017). Microorganisms further the conversion and turn the nitrite into nitrate, which is then available as another source of nitrogen for plant uptake (IES 2017). Nitrate is also converted to nitrogen gas (N_2) by bacteria and this process is called denitrification (IES 2017). In the denitrification case, the N_2 is released into the atmosphere (IES 2017).

For the Hawai'i based HEWT, an effective reduction rate of 93% is reported (IES 2017). This is backed up by lab results showing an inlet concentration of 20 ppm and a monthly average concentration of 1.5 ppm ammonia in the effluent (IES 2017). This reduction takes place in the form of nitrification in the oxidation ponds and requires the use of mechanical aeration for O_2 supply (IES 2017). While the reduction rate is efficient, the need to mechanically aerate requires inputted energy and therefore results in a score of 2 for this metric.

For the CWT operation, a bench scale model with a 95% ammonia reduction rate was used (Huddleston et al. 2000). The study notes the likely responsible reduction mechanism included microbial nitrification / denitrification, as well as uptake by plants (Huddleston et al. 2000). In this CWT, nitrification took place in the oxidized surface of the waterlogged soil (Huddleston et al. 2000). Another contributor to the nitrification was the aquatic plant *Typha Latifolia*, commonly known as a cattail. (Huddleston et al. 2000). The cattail was chosen because it is known to translocate O₂ to the rhizosphere, thereby oxygenating it (Huddleston et al. 2000). It is important to note the importance of plant and substrate when considering the 95% reduction rate. This produces a score of 2 for the CWT.

3.3.4 Phosphorus Reduction

Another essential nutrient for plant and organism growth is phosphorous (P). P in petroleum refinery wastewater is primarily from storm runoff and atmospheric deposition (IES 2017). A phosphate based corrosion inhibitor injected into cooling water is another potential source of P in the wastewater (IES 2017). Other sources include decaying animal and plant matter, i.e., microorganisms in oxidation ponds (IES 2017).

As it is an essential nutrient of plants and organisms, high levels of P in the wastewater could contribute to algae blooms and subsequent eutrophication of discharge waters. Therefore, it is important to consider P levels in refinery wastewater for this sustainability analysis.

The HEWT does not have any specific treatment mechanism for P reduction. This is primarily due to the fact that P is not limited in the effluent per the regulatory permit (IES 2017). The only regulatory requirement is to sample for orthophosphate phosphorous and total phosphorus four times a year, and to report the results (IES 2017). The bacteria in the oxidation ponds of the HEWT are the only sink for P in this process. Any excess P in the ponds could cause an algae bloom in the downstream impounding basin (IES 2017). An algae bloom in the impounding basin could lead to an increase in pH in the discharged effluent. This could occur due to nighttime CO₂ uptake by the algae, therefore leading to a violation of the permitted pH of the effluent (IES 2017). The permitted pH of the effluent is no less than 6 and nothing greater than 9 (IES 2017). This lack of reduction potential results in a score of 1.

Considering the large amount of plants and microorganisms necessary for CWT function, P would be an essential nutrient just to maintain CWT health. As P greatly interacts with the flora and fauna of the CWT, sustainable storage on both short and long term cases is provided (Knight et al. 1999). This storage is facilitated by organism life cycle on the short term and sediment / soil accretion on the long term (Knight et al. 1999). An operational CWT at Chevron's Richmond, California, refinery has an effective P reduction rate of 34% (Knight et al. 1999). This CWT covers 36.4 hectares and processes 1,742 g/min of wastewater (Knight et al. 1999). Another CWT, owned and operated by Yanshan Petrochemical in Beijing, China, processes 18,345 g/min of wastewater with a P reduction rate of 72% (Knight et al. 1999). The CWT in Beijing covers 50

hectares (Knight et al. 1999). Based on these reduction rates and the need of P for CWT operation, a score of 1 is given.

3.3.5 Energy Use

One of the main differences between the HEWT and CWT processes is the amount of electrical energy needed to perform each operation. While the environmental impact of this was accounted for in the SimaPro analysis conducted by Dimuro et al. in 2014, the actual input will be quantified here to represent the usage as an individual sustainability metric. The data in this metric provides information regarding only the required amount of energy and does not specify the source, i.e., renewable or fossil fuel.

The HEWT that was used in the Dow research had an estimated electricity input of 7,500,000 kilowatts per year (kw/yr) (Dimuro et al. 2014). The CWT that operated for 20 years had an electrical demand of 260,000 kw/yr, greatly outperforming the HEWT (DiMuro et al. 2014). Considering the difference of 7,240,000 kw/yr, the CWTs minimal, required energy input proves to be the more sustainable of the two. This is by way of pure input and again, does not represent a specific source of energy. Therefore, the CWT scores a 3 and the HEWT a 1.

3.3.6 Waste Production

Oily sludge, one of the largest waste products in the petroleum industry, is produced during oil exploration, transportation, storage and refining activities (Hu et al. 2013). It typically contains petroleum hydrocarbons and other solids, and is considered hazardous waste in many countries (Hu et al. 2013). To minimize threats to the environment, humans and to reduce costs, the oily sludge is

treated prior to being disposed of (Hu et al. 2013). To properly treat the oily sludge, it is mixed with the refinery wastewater stream and thereby managed in the treatment facility (Hu et al. 2013). The majority of hydrocarbons are separated out in mechanical separators in the pre-treatment stages, leaving a multitude of options regarding further purification. In the end, an accumulation of solids needing disposal, is given (Hu et al. 2013). According to an investigation conducted by the EPA, United States refineries each produce an average of 30,000 tons of oily sludge annually (Hu et al. 2013). In China, this number is estimated at 3 million tons for each refinery on an annual basis (Hu et al. 2013). When sustainability of a process is being assessed, it is important to account for all potential waste products and their means of disposal.

The HEWT processes oily water sludge first by going through a mechanical separation system (IES 2017). Here, the majority of liquid hydrocarbons are separated from the water (IES 2017). The remaining product then goes to the oxidation ponds where aerobic bacteria oxidize and consume remaining constituents (IES 2017). Over time, the bacteria die and accumulate with other solids at the bottom of the ponds; dredging is necessary to remove the biomass (IES 2017). The dredged sludge is then processed through a centrifuge which separates the solids from the majority of the water (IES 2017). The centrifuge process is costly as it requires a large energy input to perform the process (Hu et al. 2013). The remaining solids are left to dry and once dry, are sent off to a local landfill (IES 2017). Landfill disposal provides a low cost option and provides a large treatment capacity (Hu et al. 2013). Alternatively, landfill

disposal is limited due to its slow degradation process as well as the large occupation of land (Hu et al. 2013). This results in a score of 1 for this sustainability metric.

The CWT will have the same mechanical separation capabilities in the pre-treatment phase as this process is merely powered by gravity. After the mechanical separation phase, the largest contributor to further contaminant removal of the CWT will be based on plant and substrate selection (Wu et al. 2015). Plants provide for pollutant removal by augmenting removal processes and their uptake of nutrients, i.e., nitrogen and phosphorous (Wu et al. 2015). Substrates remove contaminants from wastewater by way of complexation, adsorption, exchange and precipitation (Wu et al. 2015). The capacity of both plant and substrate removal is largely based on environmental conditions and loading rates (Wu et al. 2015). The CWT, therefore, produces the majority of its waste in the form of vegetation and has many sustainable options for disposal. The primary method appearing most sustainable is to compost it, converting it to fertilizer available for plant uptake. While this process does contribute to VOC emissions during the aerobic / anaerobic composting process (Smet et al. 1999), it becomes a wash as the oxidation and subsequent drying of the HEWT sludge emits similar VOCs (IES 2017). Therefore, the final use of CWT biomass waste contributes to future plant growth and is more sustainable than the HEWT landfill disposal method. This results in a score of 3 for the CWT.

This concludes the analysis of the environmental factor in sustainability. In total, the HEWT scored 9 and the CWT scored 14, as seen in table 3.3.3. This

shows that when considering the environmental sustainability of the two processes, the CWT is more sustainable. Figures 3.3.1 and 3.3.2 display a visual representation of these findings.

Table 3.3.3 – Environmental Metric Totals

Environmental Metrics	HEWT	CWT
Operating, maintenance and Capital Costs	1	3
Support Expansion of Facility	2	3
Cost of Redundancies	1	3
Employment Costs	1	3
Training Costs	2	3
Increased Future Value	1	3
Total	8	18

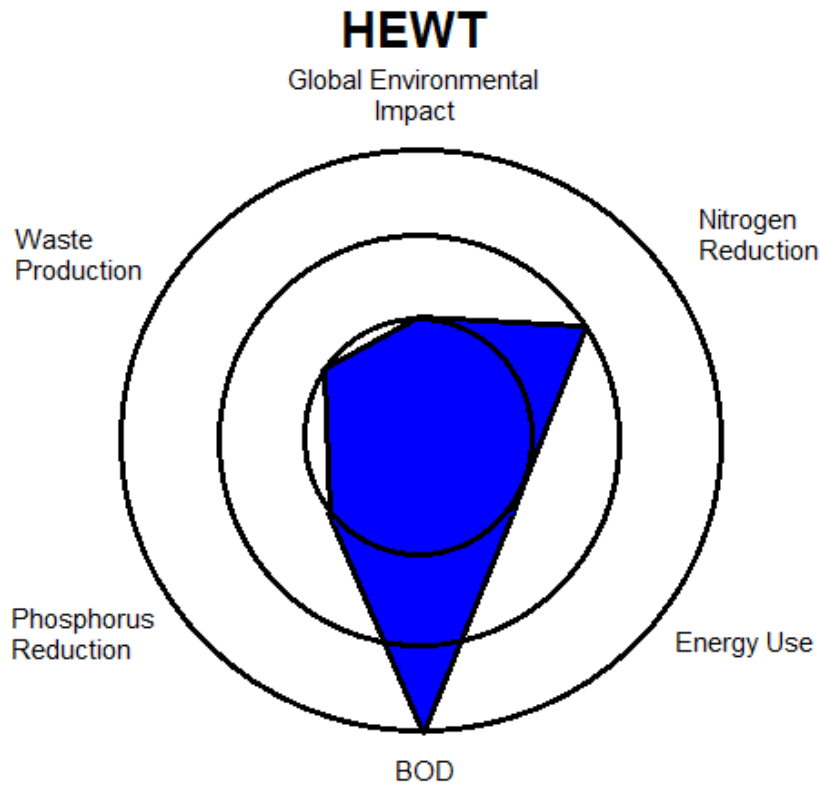


Figure 3.3.1 – HEWT Radar Plot for Environmental Metrics

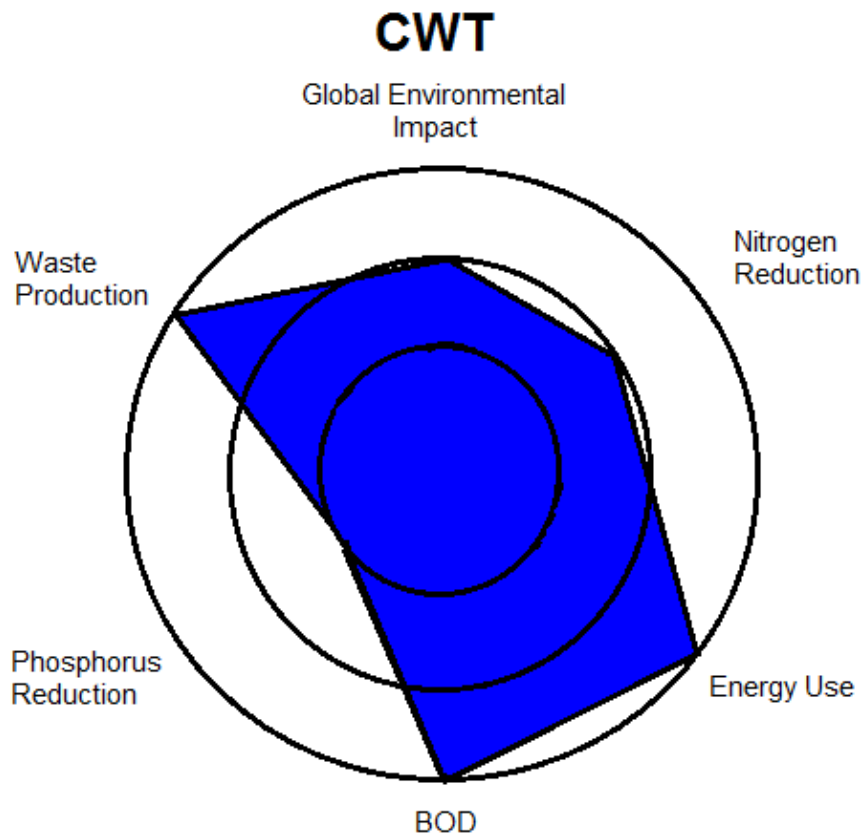


Figure 3.3.2 – CWT Radar Plot for Environmental Metrics

3.4 Radar Plots

For each of the final radar plots, the totals from tables 3.4.1 and 3.4.2 were used. The final plots combine metrics from all three categories to provide the overall sustainability representation, by way of the scoring method used.

Table 3.4.1 – HEWT Totals

HEWT					
Social		Economic		Environmental	
Criteria	Score	Criteria	Score	Criteria	Score
Hawai'i State Sustainability Vision	1	Operating & Maintenance Costs	1	Global Environmental Impact	1
Community Acceptance	2	Employment Costs	1	Nitrogen reduction	2
Smell	2	Costs of Redundancies	1	Phosphorus Reduction	1
Corporate Responsibility	1	Facility Expansion	2	Energy Use	1
Cultural Acceptance	1	Increased Future Value	1	BOD	3
Visual Appearance	1	Training Costs	2	Waste Production	1
Total	8		8		9

Table 3.4.2 – CWT Totals

CWT					
Social		Economic		Environmental	
Criteria	Score	Criteria	Score	Criteria	Score
Hawai'i State Sustainability Vision	3	Operating & Maintenance Costs	3	Global Environmental Impact	2
Community Acceptance	2	Employment Costs	3	Nitrogen reduction	2
Smell	2	Costs of Redundancies	3	Phosphorus Reduction	1
Corporate Responsibility	3	Facility Expansion	3	Energy Use	3
Cultural Acceptance	3	Increased Future Value	3	BOD	3
Visual Appearance	3	Training Costs	3	Waste Production	3
Total	16		18		14

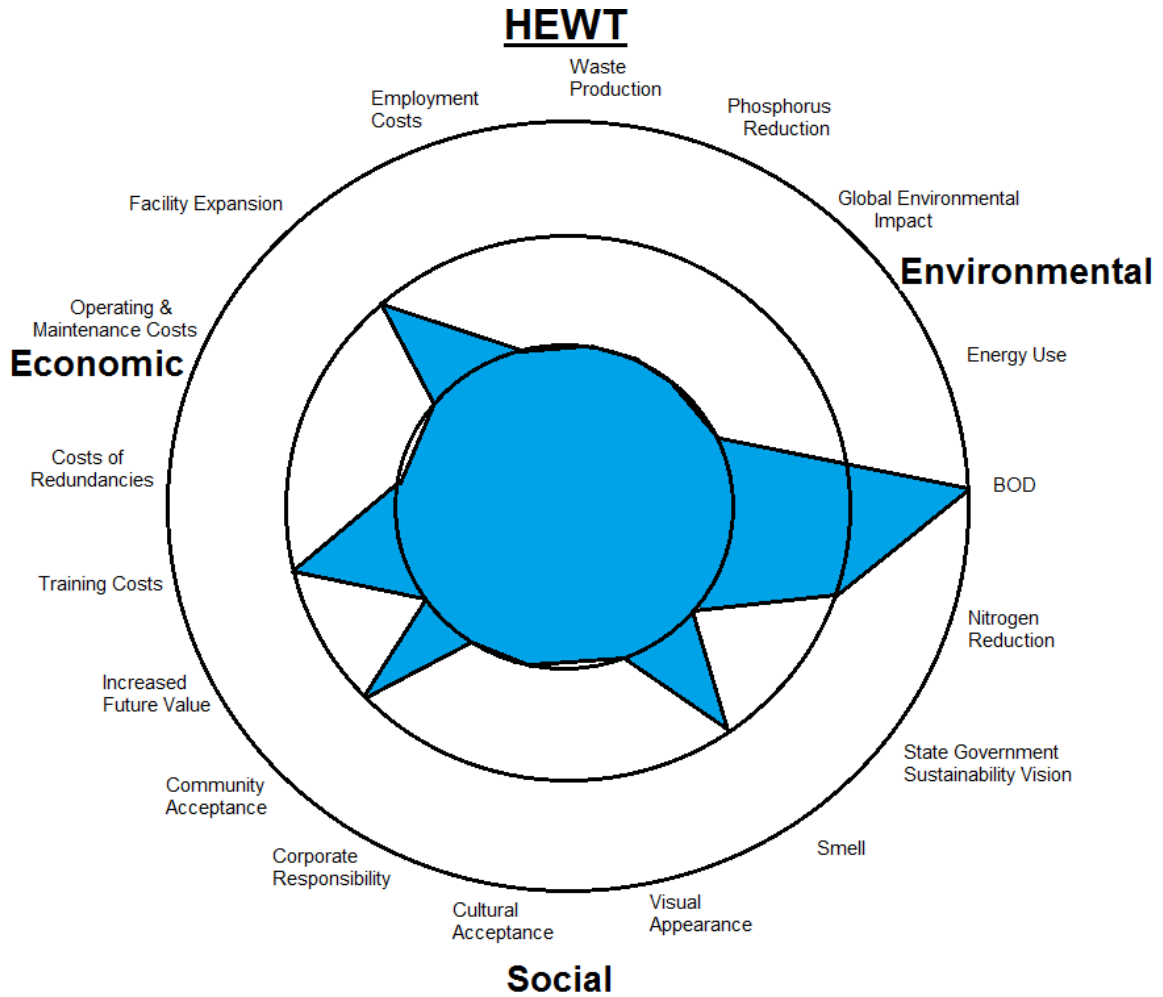


Figure 3.1 – HEWT Combined Radar Plot

The radar plot in figure 3.1 shows the total scores for the HEWT process. The low scores within the majority of the metrics displays a relatively small central shape with a few spikes jutting out, somewhat equally among the three pillars. A radar plot with higher scores, evenly distributed among the pillars, would represent a sustainable process by way of showing a large central mass encompassing the chart. Therefore, based on the small central mass with few spikes, this radar plot shows the HEWT is not sustainable.

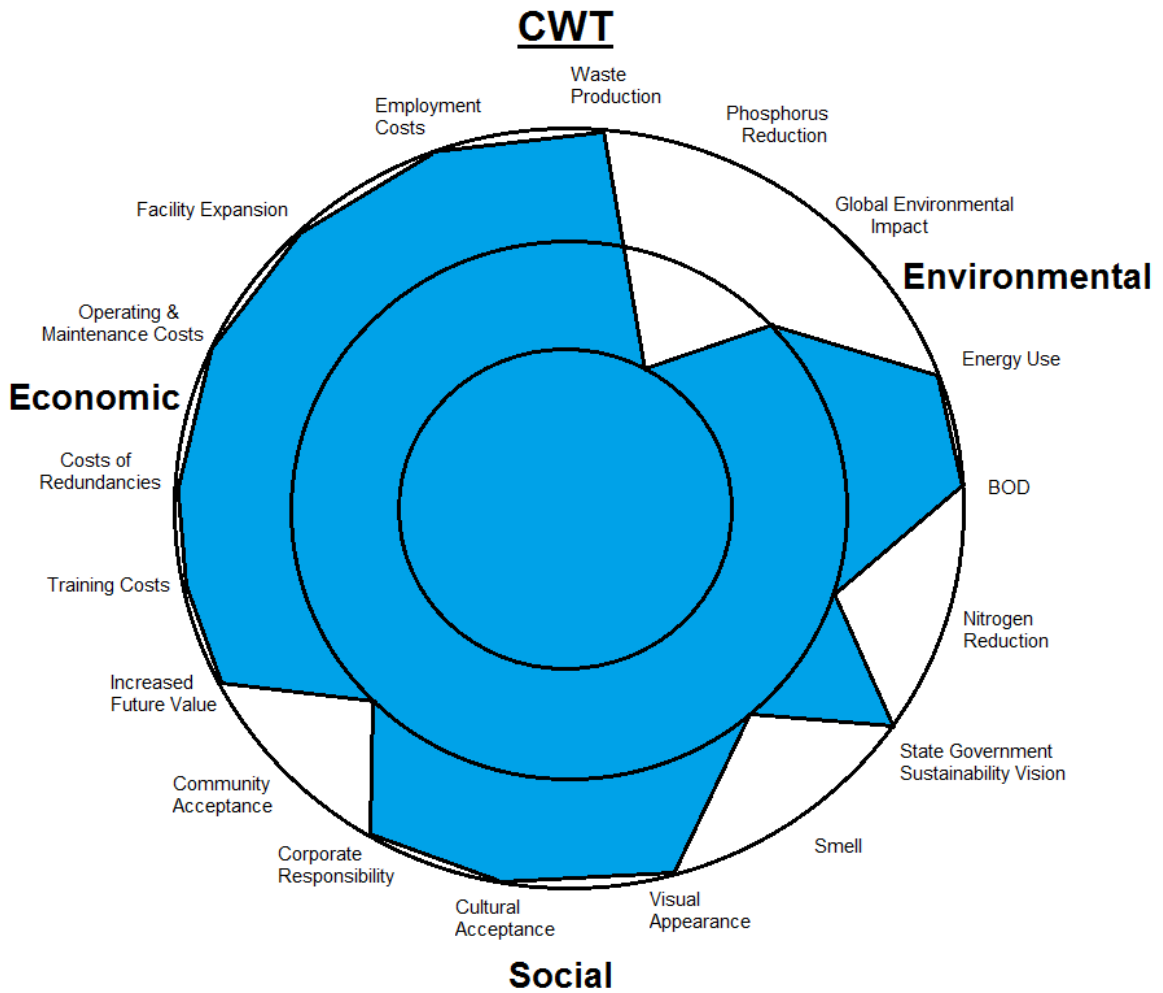


Figure 3.2 – CWT Combined Radar Plot

The radar plot in figure 3.2 shows totals from the CWT process. The large central mass with very few inverse spikes, represents a majority of higher scores within the sustainability pillars. When compared to the HEWT radar plot, it is very clear the CWT outperforms. Therefore, the resulting large central mass with very few inward points, indicates a more sustainable process.

HEWT on CWT Composite

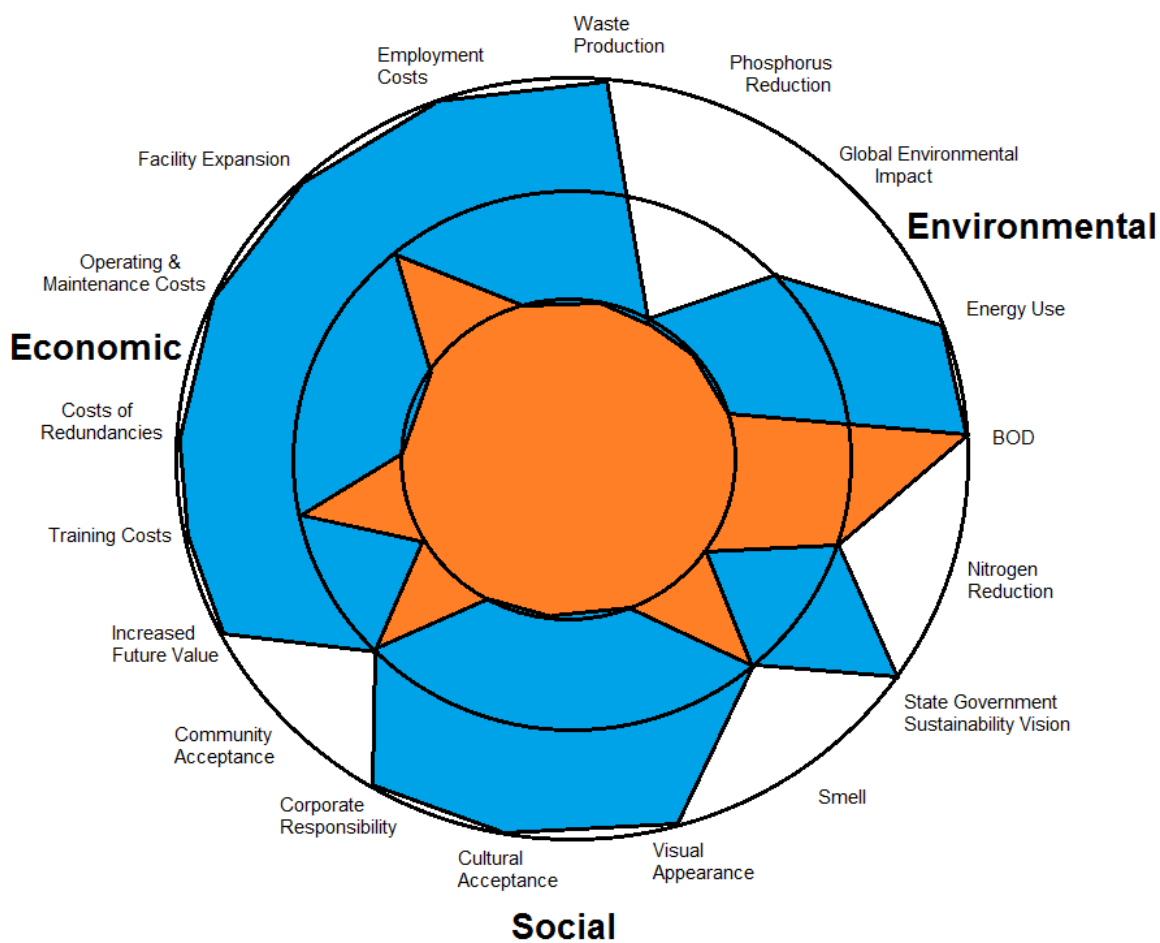


Figure 3.3 – HEWT on CWT Composite

The composite radar plot in figure 3.3 presents an understanding of relative sustainability in the HEWT and CWT processes. The comparatively opposite scores in the economic and social categories highlights the potential for sustainable operation utilizing the CWT. The CWT outperformed the HEWT in the environmental pillar as well, but was relatively closer in score. Nonetheless, the composite radar plot clearly shows the CWT is more sustainable in relation to the HEWT.

4.0 DISCUSSION

In the social category, the CWT consistently beat out the HEWT when analyzing the sustainability of each process. While the HEWT scored 2's for the smell and community acceptance metrics, a 1 was given for the remaining metrics. This was primarily based on the HEWTs resource demand and overall, unsustainable practices. The CWT shined in this category as it directly contributes to a more sustainable future. This is understood by the Hawai'i State Government's sustainability initiative as well as mirroring the values of the Hawai'ian culture.

The biggest surprise of the analysis was to find the CWT greatly outperformed the HEWT in the economic category. The main reason here was the low associated costs with the development, operation, maintenance, employment and training of the CWT. Also, the contribution of the CWT to facility expansion and increased future value weighed heavily. These factors were responsible for the CWTs perfect 3s in this category. While the HEWT slightly contributed to facility expansion and relatively lower training costs, the high costs associated with the operation, maintenance and employment metrics produced low scores. The findings in this category will be good to show industry the potential savings found in this sustainability analysis.

Of the three categories, the environmental metrics proved to be the closest in reference to sustainability. THE HEWT scored high in the BOD and N reduction metrics, proving its potential for continued use. The main difference here was the low energy use and waste produced by the CWT. These

considerations led to the CWT proving to be more sustainable. The similarities in the environmental category could underscore the need for further research in wastewater purification techniques.

5.0 CONCLUSION

Understanding the demands of future society will help to ensure longevity on our changing planet. Practices that take place without regard to complete impacts on a social, economic and environmental processes, do not contribute to this. To be sustainable, consideration of these factors must be incorporated into decision making. While a decision may benefit a single category, the impacts on the other two could prove detrimental and therefore imply a net negative result. As shown in this study, when two processes are compared side by side, a better understanding of the long term social, economic and environmental impacts will be known.

To treat petroleum industry wastewater, a CWT process is the sustainable choice. The benefits in the social, economic and environmental categories were all greater for the CWT when compared to the current industrial norm HEWT. Considering this and then questioning the lack of CWT facilities in the petroleum industry, the reason may be the need for more developmental research; the use of CWTs to treat municipal waste and storm water is well established and is less well developed in the treatment of agricultural and industrial wastewaters (Knight et al. 1999). Some of the challenges associated with CWTs in the petroleum industry are the successful application and sustainable operation of them (Wu et al. 2015). The research done in this paper will contribute to understanding the sustainable operation of one. To ensure sustainability of the CWT, the following key elements must be considered in the developmental phase. To ensure efficient pollutant removal, the supply of O₂ and carbon along with the large

production of biomass must be priorities (Wu et al. 2015). To provide a sustainable treatment performance for the CWT, it is imperative to select the proper substrate and plants, optimal water depth, feeding mode and fully account for loading rate coupled with hydraulic retention time (Wu et al. 2015). With this, a process is most efficient and better prepares us for what's to come.

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