Used Oil Management – Technology Options Report

A Submission to SPREP

5 April 2022

MRA Consulting Group

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A Submission to Secretariat of the Pacific Regional Environmental Program (SPREP) as part of the Committing to Sustainable Waste Actions in the Pacific (SWAP) project

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Version History

Ver	Date	Status	Author	Approver	Signature
0.1	31/03/2022	Draft	Sean Paul	Samuel Swain	Required on final only
1.0	5/04/2022	Final	Sean Paul	Samuel Swain	

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Table of contents

List of Tables

List of Figures

Acronyms

Terminology	Definition
ACT	Activated Clay Treatment
cSt	centiStokes
kcal/kg	Kilocalories per kilogram
MRA	MRA Consulting Group
PAH	Polycyclic aromatic hydrocarbon
PCB	Polychlorinated biphenyl
PLC	Programmable Logic Controller
PNG	Papua New Guinea
ppm	Parts per million
SPREP	Secretariat of the Pacific Regional Environmental Program
SWAP	Committing to Sustainable Waste Actions in the Pacific
vol%	Volumetric percent
wt%	Weight percent

Executive Summary

This report seeks to assist small island nations in the Pacific region to select technology options for the management of used oil. The study has focused on countries involved in the Committing to Sustainable Waste Actions in the Pacific (SWAP) Project, including Samoa, Solomon Islands, Tonga, and Vanuatu.

Research was undertaken through a desktop-based review of publicly available resources, regional used oil audits and interviews with used oil management technology providers. An overview of the sources, characteristics and risks (to both human health and the environment) associated with used oil is provided to contextualise the discussion. The waste management hierarchy was then applied to potential technology options to summarise the most common approaches to treating used oil.

Key options feasible to the Pacific context were identified through a screening selection. These options were analysed for their primary technological, legal, economic and environmental considerations. Used oil management technologies included in this detailed analysis were:

1. Direct burning in controlled incineration;
2. Pyrolysis;
3. Mild processing followed by fuel blending or reuse; and
4. Activated clay treatment.

Case studies showcasing some of these options have been presented to help understand the challenges and opportunities for used oil management in the Pacific region.

The resulting comparison of technology options forms a decision-making tool for Pacific islands to apply their respective economic, social, geographical, environmental and operational constraints to decide the most appropriate treatment option.

1 Introduction

1.1 Background

Small island nations face a host of logistic and financial barriers in implementing waste management technologies. Current practices often require wastes to be exported for overseas processing, which can be associated with high upfront costs and negative environmental impacts. Additionally, nations loose potential benefits from on-island processing of waste, including job opportunities and revenue from recovered products.

One such potentially recoverable waste stream is used oil. The intention of this report is to assist the Secretariat of the Pacific Regional Environmental Program (SPREP), as part of the Committing to Sustainable Waste Actions in the Pacific (SWAP) Project, in providing guidance to Pacific Island Countries (PICs) wishing to develop on-island used oil management technology. The study will focus on countries involved in the SWAP project, including Samoa, Solomon Islands, Tonga, and Vanuatu.

Research has been undertaken through a desktop-based review of publicly available resources, data provided by SPREP and interviews with used oil management technology providers. An overview of the sources, characteristics and risks (to both human health and the environment) associated with used oil is provided to contextualise the discussion. The waste management hierarchy is then applied to potential technology options to summarise the most common approaches to treating used oil. The combination of these considerations allowed key options feasible to the Pacific context to be selected for a detailed comparative analysis. The resulting comparison table forms a decision-making tool for Pacific islands to apply their respective economic, social, geographical, environmental and operational constraints to decide the most appropriate treatment option.

The sustainable management of used oil results in a range of positive environmental, economic and operational outcomes for small island nations. A summary of some of the benefits of used oil management are presented in Table 1.

Table 1 Benefits from the sustainable management of used oil

Environmental	Economic	Operational
• Prevent contamination to water sources and soil from inappropriate storage/disposal; • Avoid emissions (e.g., dioxins and heavy metals) from open burning; • Recycling conserves finite resources; and • By producing lubricating oils from recycled base oils, one-third of the emissions are generated when compared to crude oil.	• Requires only one litre of recycled base oil to generate 0.63 litres of new lubricating oil (compared to needing 42 litres of crude oil); • Creates jobs and drives innovation; • Decrease reliance on foreign oil supplies; and • Produces saleable end products or electricity generation.	• Recycled oil meets the same standards as virgin base oil; • Provides revenue to support collection and storage systems; • Decreases used oil stockpiles; and • Decrease the need for used oil exports for processing.

1.2 Sources of used oil

Engine oil plays a major role in daily life through its importance in both transportation and industrial processing. The primary role of engine oil is to increase the lubrication of moving parts by preventing their direct contact, hence reducing the impacts of friction and heating. Additional benefits include:

- Acting as engine coolant;
- Internal engine and parts cleaning;
- Prevention of clogs;
- Protection against corrosion; and
- Sealant against external contaminant.

Table 2 outlines additional details of the different functions, composition and properties of common types of oils.

Table 2 Common types of oil available for recycling

Oil Type	Function	Composition	Properties
Crankcase/ engine/ motor oil	Lubricating moving engine parts by reducing friction.	Mixture of lubricating base stock (70-90%) with additives (10-30%) which include dispersants, detergents, anti-foaming agents and corrosion inhibitors.	Have high resistance to heat and low adsorption of contaminants (e.g., non-combusted fuel).
Gear lubricants and greases	Capable of lubricating surfaces that are hard to reach or contain compared to other oils.	Mixture of liquid lubricants and a thickener (typically soap and other additives) dependent on the application.	Capable of withstanding extreme pressures of automotive or industrial gearboxes.
Hydraulic oil	Primary intermediary in hydraulic energy systems, with secondary functions including heat transfer, contamination removal, sealing and lubrication	Commonly a mixture of oils, butanol, phthalates, adipates, polyalkylene glycols, corrosion inhibitors and other additives (e.g., anti-erosion).	Have low compressibility, predictable friction and viscosity stability over a range of temperatures (i.e., high viscosity index).
Heat transfer oils	Designed to provide reliable internal heat transfer across high temperature ranges.	Common additives decrease oxidative effects from heating, necessary to minimise carbon deposits that inhibit heat transfer.	Exhibit low viscosity, good thermal stability, high flash point and good heat transfer properties.

The major sectors that require oils and lubricants for their operations (hence are the major generators of used oils) are the automotive, industrial, marine and power sectors. An understanding of the major generation sources is important in achieving best practice used oil management, including storage, handling, transportation and reuse considerations.

The potential for circular economy outcomes - where collected and pre-processed wastes are used as feedstocks for new products – is reliant on these sectors to both provide used oil as treatment feedstocks and act as end-markets for recovered products.

Table 3 gives an overview of the common types of oils used by each sector. The primary type of oil or lubricant used by the generator will determine the characteristics of the resulting used oil, including the types of additives and common contaminants.

Table 3 Common types of oils and lubricants by sector

Automotive sector	Industrial sector	Marine sector	Power sector
• Crankcase oil; • Waste transmission fluids; • Gear lubricants; • Hydraulic oils; and • Minor amounts of solvents used in the service areas.	• Hydraulic oils; • Turbine oils; • Gas engine oils; • Metal cutting oils; • Compressor oils; • Heat transfer oils; and • Refrigeration oils.	• Lubricating oils; and • Greases.	• Transformers internal coolant.

The quantity of used oil consumed by major sectors is summarised in Figure 1. This data is presented on a global basis as data specific to the Pacific context is not available. It could be assumed that the proportion of industrial used oil would be lower in the Pacific context (due to less secondary industries active in the region) while the marine sector would be a greater proportion (due to the reliance on shipping between islands).

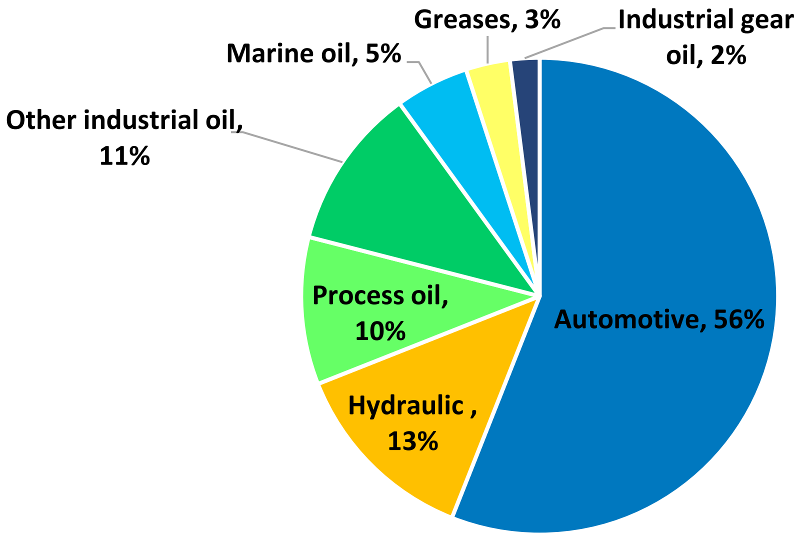

Figure 1 Global consumption of oils and lubricants by sector[1]

The automotive sector is the dominate user of oils and lubricants. Used oil is primarily generated through a large quantity of small-scale generators including service stations, garages and automotive fleet service area (e.g., bus depots). This presents additional logistic challenges when compared to large scale industrial, marine and power generators where bulk quantities can be collected and stored on site. Small-scale generation requires additional used oil handling and transportation while also allowing additional avenues for oil contamination or environmental pollution.

[1] Andrews, L. "Compendium of Recycling and Destruction Technologies for Waste Oils." *United Nations Environment Programme*, (2008)

1.3 Used oil characteristics

1.3.1 Chemical properties

The mechanical and thermal weathering of lubricating oil results in a degradation of both the base oil and the additives used to improve performance. Depending on type and length of the oils use, it will exhibit different chemical properties from its virgin oil counterpart. Some of these changes make the oil unfit for purpose, such as a decreased viscosity and flash point. Once this degradation occurs, used oil must be replaced with virgin oil to maintain engine performance.

There is no standard international specification for used oil characteristics, with properties changing country-to-country dependent on major sector sources and the type of collection and storage system adopted.[2] This creates complications for used oil processing, as end products must meet strict criteria for final product quality control. If recovered oils are combusted, chemical properties will determine the heat and emissions generated. If recovered base oils are used to manufacture new lubricating oils, their properties must be identical to virgin base oils to allow for marketability.

A detailed understanding of used oil properties should be conducted prior to selecting a management technology, as certain processes are sensitive to heavily contaminated feedstocks. Past used oil studied in the Pacific region have focused on generation rates, rather than chemical compositions. Average used oil properties are presented in Table 4, with comparison to averages for virgin motor oil.

Table 4 Comparison of chemical properties of used oil and virgin oil[3]

Property or test	Used motor oils	Virgin motor oil
Viscosity, at 40°C, cSt	15 – 180	Up to 210
Specific gravity at 15.6°C	0.87 – 0.94	0.85 – 0.92
Water, vol %	0.2 – 33.8	Traces
Bottom sediment and water, vol %	0.1 – 42	Nil
Gasoline dilution, vol %	2.0 – 9.7	Nil
Flash point, °C	79 – 220	>200
Ash, Sulfated, wt %	0.03 – 6.43	0.78 – 1.0
Carbon soot, wt %	1.82 – 4.43	Nil
Fatty oil, wt %	0 – 60	Nil
Chlorine, wt %	0.17 – 0.47	Nil
Sulfur, wt %	0.17 – 1.09	>0.03
Zinc, ppm	260 – 1,787	Nil
Calcium, ppm	211 – 2,291	Nil
Barium, ppm	9 – 3,906	Nil
Phosphorus, ppm	319 – 1,550	Nil
Lead, ppm	85 – 21,676	Nil
Aluminium, ppm	<0.5 – 758	Nil
Iron, ppm	97 – 2,401	Nil

[2] Giovanna, F. D., et al. "Compendium of used oil regeneration technologies." *United Nations Industrial Development Organization and International Centre For Science and High Technology, Trieste* (2003).
[3] Andrews, L. "Compendium of Recycling and Destruction Technologies for Waste Oils." *United Nations Environment Programme*, (2008)

1.3.2 Contaminants

The aging of oils introduces contaminants that must be removed during processing. These contaminants can present a range of risks to human health and the environment. Due to the hazardous nature of used oil contaminants, it is listed under the Basel Convention hazardous waste classification (categories Y8 and Y9).

Contaminants often arise from:

- External ingression during engine operation (e.g., dust, water or non-combusted fuel);
- Internal generation or degradation of substances (e.g., denatured additives, metal debris or soot); or
- Inappropriate mixing or environmental contamination during used oil collection, handling and storage.[4]

The type and quantity of certain contaminants is largely dependent on the used oils source and the method of collection and storage. Common contaminants and their effects on the environment or engine performance are listed in Table 5.

Table 5 Key issues related to common used oil contaminants

Contamination	Source	Issues
Vegetable oil	Rape oils, sunflower oils, cooking oils and esters incorrectly mixed with used oil	• Fuel cracking and decreased engine efficiency • Fouling • Off-gases from combustion
Solvents	Laundries and spent solvents incorrectly mixed with used oil	• Corrosion
Water	Combustion by-product, ingress into engine fans or poor handling or storage of used oil	• Increased energy costs for separation • Waste waters from separation require treatment
Metals	Mechanical engine wear or additives used to increase oil performance	• Friction and wear • Heavy metal pollutants
Polycyclic aromatic hydrocarbons (PAHs)	Incomplete combustion and long drain interval	• Toxicity
Polychlorinated biphenyls (PCBs)	Transformer oil additive	• Toxicity
Silica	Additive used in antifreeze, industrial oils and brake fluid	• Catalyst poisoning
Chlorine	Contamination of chlorinated solvents and lubricating oil additives	• Corrosion • Dioxins generated on combustion
Waxes and paraffins	Fuel slops disposal	• Poor lube opacity

[4] Rațiu, S. A., et al. "A review on the contamination of used engine oil." *Romanian Journal of Automotive Engineering* 26.4 (2020).

Contamination	Source	Issues
Sulfur	Additives and fuel engine leakage	• Sulfur oxides generated on combustion • Corrosion • Increased energy costs to separate
Carbon soot	Incomplete engine combustion	• Fouling • Decreased separation efficiency

The most hazardous contaminants include PAHs, PCBs and heavy metals. Aromatic compounds are considered to be the most acutely toxic component of used oil, such as benzo(a)pyrene formed during incomplete fuel combustion. As a minimum, used oil treatment technologies are expected to reduce hazardous contaminants below a safe level to allow treated oils to be handled and used without excessive risks.

Legislation exists in SWAP countries regulating the importation and management of petroleum products, such as the Solomon Islands *Petroleum Act 1987*. Although, no legislation has been identified in the Pacific region that establishes allowable criteria or specifications for used oil reuse (whether in burning or base oil feedstocks).

Table 6 presents the US EPA specifications for allowable contaminant levels and chemical properties for used oil to be burnt for energy recovery. If contaminants exceed the allowable limits, strict environmental monitoring and control measures must be in place to minimise impacts to human health and the environment.

Table 6 US EPA Used Oil specification for burning

Parameter	Allowable Limit
Arsenic	5 ppm
Cadmium	2 ppm
Chromium	10 ppm
Lead	100 ppm
Total halogens	4,000 ppm
PCB	2 ppm
Flash point	38 °C minimum

1.4 Risks to human health and the environment

Certain contaminant concentrations in used oil must be managed due to their negative impacts on human health and the environment. The risks of these impacts are a driving motivator for the sustainable management of used oils. Management techniques must prioritise the minimisation of risks associate with used oil during all stages of its lifecycle.

Some common means of exposure to used oil hazards include:

- Used oil that is inappropriately disposed (i.e., through dumping, disposal to sewer or open burning) which impacts local air and water quality;
- Damaged storage vessels resulting in leaks;
- Poor personal protection or handling protocols during collection and transportation; and
- Excessive reuse of old or heavily contaminated used oil.

Open burning is a particular concern as a used oil disposal method due to the uncontrolled generation of ash (containing heavy metals) and emissions (including dioxins, furans, carbon monoxide, sulfur oxides and organic compounds). Emissions can settle in water sources, accumulate in soils and persist up the food chain to impact human health. Strict emission controls should be in place for any used oil processing system.

Each nation will have varying legislative controls to minimise the negative impacts of used oil. These must be consulted during the decision-making process for used oil management techniques.

The potential impacts of used oil exposure include:

- The contamination of drinking water with concentrations as low as 1 ppm; [5]
- The destruction of food resources and natural habitats;
- Impacts to local fauna including toxic contamination, impaired reproduction, damaged intestinal tracts, reduced fur insulation and reduced feather water repellence; and
- Chronic and acute damage to human health.

Some of the properties that make used oil a risk to human health include:

- Carcinogenic, genotoxic and fetotoxic;
- Impacts on immunological and reproductive systems; and
- Damage to kidneys, liver, heart, lungs and nervous system.[6]

[5] Irwin, R. J., et al. "Environmental contaminants encyclopedia: Alkanes entry." *Journal of Chemical Information and Modelling* (1997)

[6] Dorsey, Alfred, Carolyn Rabe, and Sujatha Thampi. "Toxicological profile for used mineral-based crankcase oil." (1997).

2 Research methodology

This study has relied primarily on desktop research to generate a decision-making tool to assist with the implementation of used oil management technologies. The tool can be used to inform planning decisions within the context of Pacific Island nations, although specific contextual considerations (such as geographical, financial and socio-political requirements) need to be applied by those using the tool. The diverse context of the Pacific region has been considered during the research.

2.1 Data quality and limitations

The research and data used throughout this report is based on a desktop review of publicly available resources, data provided by SPREP and MRA industry knowledge. Due to the variety of countries and types of used oil included in this study, several data quality and limitation concerns were encountered throughout the desktop review.

Available data was often more than five years old and overall, significant gaps existed in the availability of data for each nation or each nation's major islands. Therefore in many cases, assumptions have been made to extrapolate waste data from nations of a similar size that have a higher quality of data.

Used oil reports often rely on oil import data to estimate used oil generation rates. It was found that assumptions used in the calculation method for generated used oil were not consistent between studies, making their comparison inaccurate.

Recent audit data provided by SPREP was considered the most accurate data available, although these studies would need to be expanded to every nation in the region to provide the highest quality of understanding.

2.2 Interviews

MRA conducted interviews with waste management organisations and used oil treatment technology providers operating in the Pacific. These interviews provided additional insight into the local challenges and opportunities for used oil processing in the Pacific region. MRA and SPREP would like to thank the following:

- Leigh Ramsey and Gael Ferguson (NuFuel Ltd);
- Cyril Prudhomme (Tahiti, Ingénierie Process);
- Kori Chan (TWM Group); and
- Patrick Selles (Sarl Ixos).

3 Used oil management overview

3.1 Waste management hierarchy

Used oil management option have wide variability in their technological sophistication, process end-products, environmental benefits and financial constraints. Figure 2 broadly classifies preferable used oil management options based on a waste hierarchy structure.

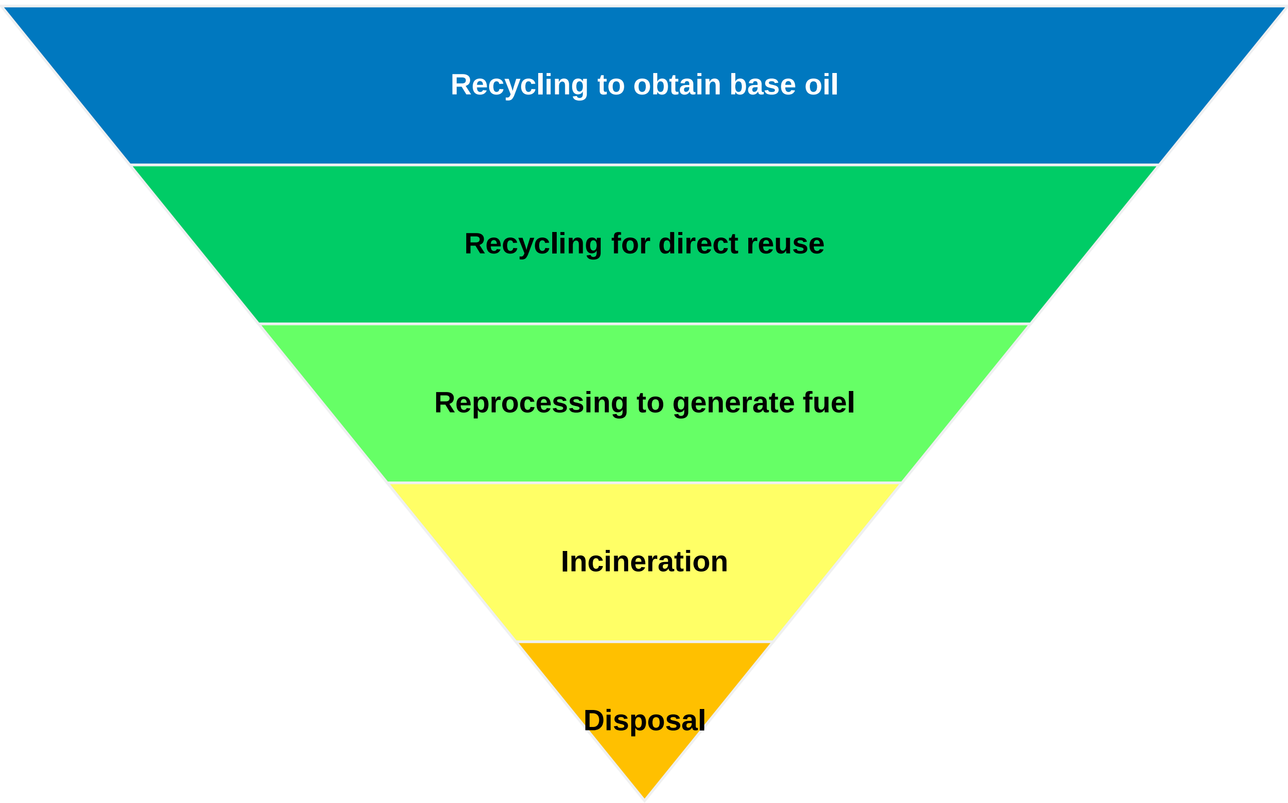

Figure 2 Used oil management options waste hierarchy

Disposal (including landfilling, dumping and open burning) should be minimised, even if that means replacement with a lower preference treatment method such as incineration. The complete recycling of used oil into base oil is considered the highest order management method. This method most closely aligns with circular economy principals, resulting in overall energy savings and reduces negative environmental impacts. Nevertheless, high order management options are associated with capital and technological requirements that can be difficult to achieve for small island nations.

3.2 Treatment categories

There are four broad methods of used oil processing that fall into the bands of the waste hierarchy structure. These methods are:

1. Re-refining used oil to obtain base oil;
2. Reclaiming used oil for direct reuse;
3. Burning following used oil reprocessing; and
4. Direct burning or incineration

Figure 3 displays these treatment method categories with waste hierarchy colour coding.

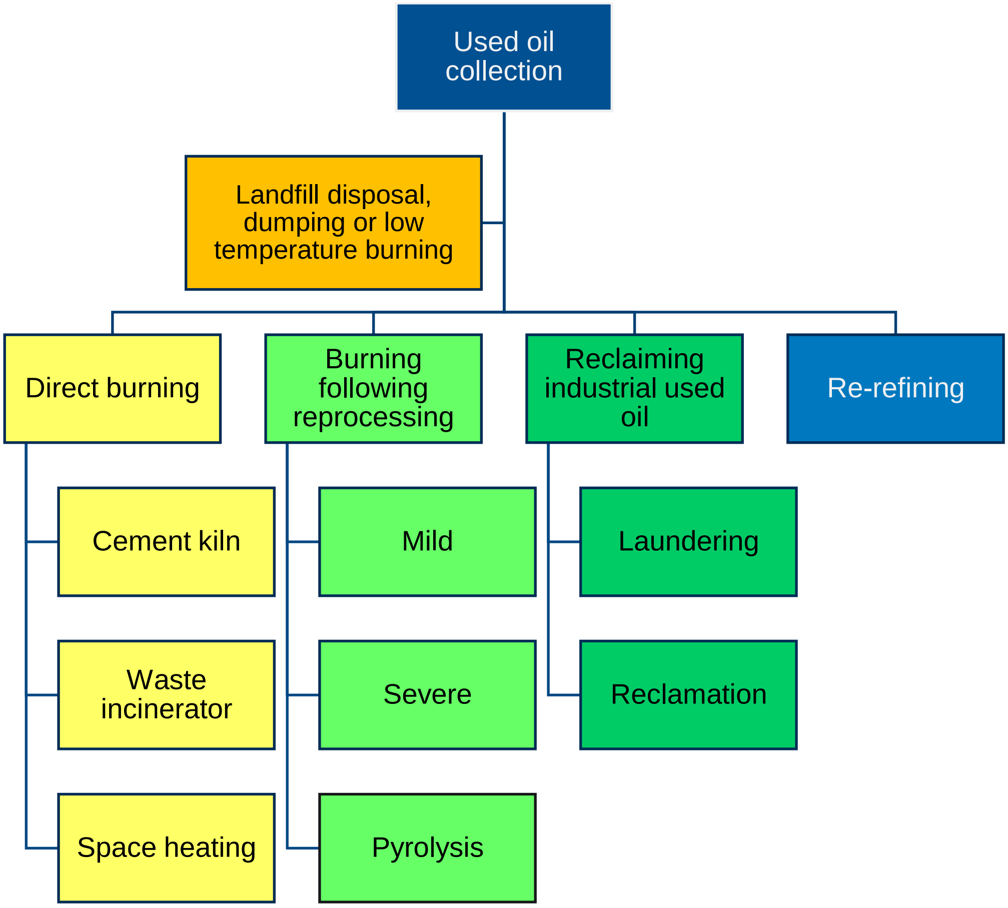

Figure 3 Common used oil management techniques with waste hierarchy colour coding

Mutual to each of the treatment methods are requirements for used oil collection, transportation, storage, record keeping and emission controls. The sensitivity of the treatment option will determine the specific requirements for used oil management, such as restrictions on used oil mixing or the acceptable storage periods. Detailed comparisons of management techniques conducted in Section 4 provide details of these considerations. Additional considerations should be made for the collection and treatment of oil filters (which contain approximately 240 ml of used oil) and oil containers.

3.2.1 Re-refining

Re-refining is the highest order treatment option for mixed used oils. This process recycles used oils to generate new lubricating base stock, ready for modification for future reuse. The process is usually only recommended in conjunction with existing oil refinery operations to decrease high capital costs, make use of existing facilities and utilities, achieve higher value by-product recovery (i.e., gas oils) and ensure more efficient pollution controls. The final base oil products from re-refinery are nearly identical to virgin oil base stocks. By generating new lubricating oils from recycled base oils, manufactures can decrease reliance on crude oil reserves while achieving overall energy savings. One-third of the emissions are generated by producing lubricating oils from recycled base oils when compared to crude oil.

Various re-refinery technologies exist at all stages of development, included long-term industrial applications to lab-scale pilots. Some common treatment processes include:

- Activated clay treatment or solvent extraction;
- Vacuum distillation or evaporation; and
- Hydrogenation or ultra-filtration.

System can also utilise thermal cracking of used oils to produce gasoline. A summary process flow diagram for used oil re-refinery is outlined in Figure 4.

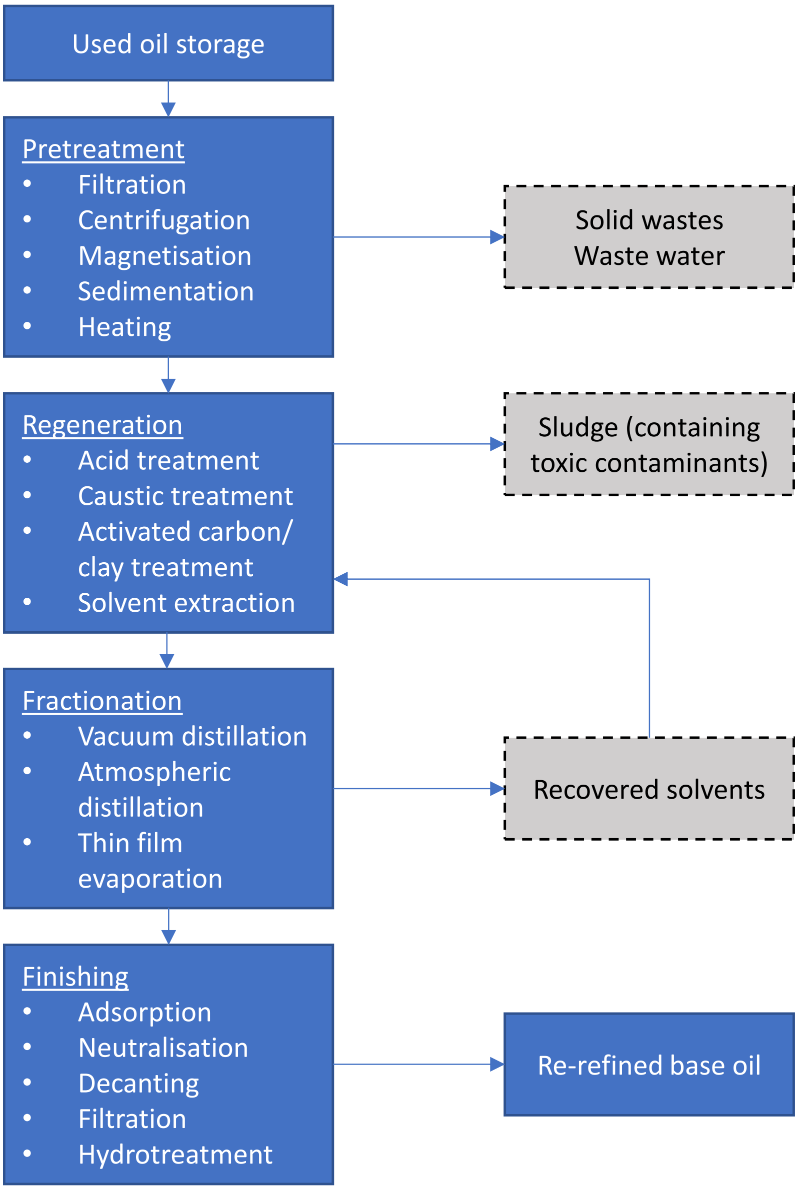

Figure 4 Primary stages of used oil re-refinery, including conventional technologies used[7]

The volumes of used oil generated on individual Pacific Islands would not make re-refinery a viable local management option. Most commercially operating used oil re-refinery plants have annual capacities of between 20,000 to 130,000 tonnes.[7]

This would require used oil to be collected from multiple regions and neighbouring nations for consolidation. Existing refineries (such as those found in Port Moresby, Australia or New Zealand) could be converted to accept used oil from the Pacific region.

Developing a consolidated treatment operation may unfairly burden host countries with the handling and disposal of process by-products, including oil contaminated wastewater and residual wastes and sludges. Processing would require additional costs to cover the management of process wastes.

[7] Diagram adapted from: Sánchez-Alvarracín, Carlos, et al. "Characterization of Used Lubricant Oil in a Latin-American Medium-Size City and Analysis of Options for Its Regeneration." *Recycling* 6.1 (2021): 10.

3.2.2 Reclamation

Used oil reclamation (also known as reconditioning) is a treatment option appropriate for single source industrial used oils of a known composition. These originate from large scale industrial oil users such as power plants.

The likelihood of contamination in motor oil (due to environmental exposure during use, collection, storage and transportation) mean that quality products cannot be guaranteed during the reclamation process.

Systems can be designed to accept either a single type of industrial oil (specialised processing) or a range of oil types through adjustments of system parameters (generalised processing). Designs are often specialised towards hydraulic oils, heat transfer oils, turbine oils and transformer internal coolants.

Reclamation usually involves:

1. Heating;
2. Filtration or centrifugal separation;
3. Dewatering under vacuum; and
4. Regeneration with fresh additives.

Onsite reclamation allows used oils to be regenerated for direct reuse. This prolongs the life of used oil and reduces waste generation. Treatment equipment can be small scale with low capital investment, although are restricted in the sources of used oil that it can accept.

Ongoing quality monitoring is also required to determine when recycled used oil is no longer suitable for reclamation. At this point, a different treatment method is required to dispose of more heavily contaminated used oil.

Based on used oil audits conducted in the Pacific region[8] the major industrial lubricating oil users that would benefit from onsite oil reclamation are power generation companies (e.g., Electric Power Company, Solomon Islands Electricity Authority and Tonga Power Limited) and primary industries (e.g., mining and forestry). Some power plant facilities already have capacity to collect and store oils on site, but current none are engaging in onsite processing.

3.2.3 Burning following reprocessing

Used oil can be treated to varying degrees prior to direct burning or mixture with other fuel oils. Reprocessing often involves the removal of water and contaminants that can result in harmful emissions. This improves the engine performance of blended fuels and decreases the risk of negative impacts from burning.

Mild processing steps typically include:

1. The addition of demulsifiers;
2. Heated settling tank to remove water and sediment; and
3. Filtration as needed.

An alternative processing method involves the generation of diesel fuel through pyrolysis. Used oil is heated in the absence of oxygen to crack heavy oils into lighter fuels, which are then condensed for collection. Non-condensable gas oils can be collected for heating of the pyrolysis combustion chamber.

More severe processing includes an additional stage such as:

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[8] Specifically: *Used Oil Audit Survey in Samoa* (2012), *Contemporary Used Oil Audit in Solomon Islands* (2014), *Contemporary Used Oil Audit in Tonga* (2014) and *Establishment of Used Lubricants and Oil Management System in Papua New Guinea* (2017).

- Flash column separation (for improved water separation);
- Light vacuum distillation (to recover light ends and gas oil); or
- High vacuum distillation (to remove oil residue).

More advanced processing stages are required to decrease metal contents below 1 ppm.

Reprocessed used oil are usually blended with fuel oil at a 10wt% proportion. Blending is limited by the remaining ash content and oil viscosity following treatment. Blended fuels are often used as bunker fuel, with recommendations made to monitor and control the quality of air emissions.[9]

Reprocessed used oil can also be burnt directly with lower environmental risks than burning unprocessed oil. This is often carried out in industrial heating applications, such as limestone drying or power station start up fuel.

To date, all used oil processing systems that have been deployed in the Pacific region can be classified under this category. Low technical expertise, mobility and demand for final fuel products makes this approach easier to implement than other options. They can be transported to major generation sources, or situated near fuel product offtake markets (e.g., ports for bunker refuelling).

3.2.4 Direct burning

Direct burning of used oil has the benefit of heat and/or electricity recovery that is not achieved during open burning. This treatment method does not employ any pre-treatment, making it the lowest cost management option.

By ensuring higher temperature incineration, aromatics in used oils can be degraded to prevent toxic emissions. Nevertheless, the generation of dioxins resulting from chlorine contamination and heavy metals in ash mean that direct burning still has the potential for negative impacts to human health and the environment.

Comparative studies on air emission from different used oil processing options have found heavy metal air emissions from direct burning without emission controls are 2-2100 times higher than other techniques (Table 7).

Table 7 Inventory of key heavy metal air emissions based on Equivalent Functional Units* (EFU)[10]

Heavy metals	Human toxicity potential (kg DCB equiv)	Direct burning (EFU)	Re-refining (EFU)
Zinc	2.6	729	1.2
Copper	2.9	35	0.017
Lead	1.2	29	1.6
Chromium	2.5	1.2	0.48
Cadmium	130	0.89	0.011

**Note: mg of air emissions per L of fuel*

Many countries have legislated used oil contamination thresholds for unrestricted direct burning (i.e., the US EPA Used Oil Specifications). Low contamination used oils can be burnt in space heaters for small scale heat generation. High-contamination oils require specific controlled burning with dedicated emission controls, such as in hazardous waste incinerators, industrial furnaces or high temperature cement kilns.

[9] Denton, J. E., et al. "Used oil in bunker fuel: a review of potential human health implications." *Office of Environmental Health Hazard Assessment Integrated Risk Assessment Section (IRAS)* (2004).
[10] Boughton, Bob, and Arpad Horvath. "Environmental assessment of used oil management methods." *Environmental Science & Technology,* 32(2) (2004): 353-358.

High ash content used oils can lead to furnace fouling, decreasing process efficiency and increasing operation costs. Halogen contaminants can also lead to corrosion in combustion plants. The lack of large industrial boilers or cement clinker production in the Pacific Islands decreases the viability of direct burning. This management option is most feasible when it utilises existing infrastructure to decrease upfront costs. Although dedicated air emissions controls are required to minimise the potential for negative environmental impacts.

3.3 Option assessment

The common requirements of a feasible technology option have been reflected in the screening questions used to select technology options for detailed comparison in the decision-making tool (refer Section 4). The broad range of potential technology options have also been considered in the option selection process.

The screening questions and the assessment of potential technology options is presented in Table 8.

Table 8 Selection of used oil management options for detailed analysis

Technology option	Alignment with waste hierarchy	Is there available local expertise to operate the technology?	Are generated quantities of used oil sufficient for process viability?[11]	Does the technology comply with regulation?[12]	Is it an Environmentally Sound Technology?[13]	Is the upfront capital achievable for Pacific nations?
Direct burning in space heaters	Incineration	Yes	Yes	Yes	No	Yes
Direct burning in controlled incineration	Incineration	Yes	Yes	Yes	Yes	Yes
Mild processing followed by fuel blending	Reprocessing to generate fuel	Yes	Yes	Yes	Yes	Yes
Mild processing followed by flash column separation	Reprocessing to generate fuel	Yes	Yes	Yes	Yes	Maybe
Mild processing followed by light vacuum distillation	Reprocessing to generate fuel	Maybe	Yes	Yes	Yes	Maybe
Mild processing followed by high vacuum distillation	Reprocessing to generate fuel	No	Maybe	Yes	Yes	No

[11] Whether on a local or multinational/ consolidated level
[12] Details concerning the transboundary movement of used oils can be found in the SPREP (2015) "Waste assessment guide for the export and import of used lubricants and used oils". Specific local regulatory requirements must be considered on a context specific basis.
[13] A detailed definition for Environmentally Sound Technologies can be found in the OECD (1997) "Glossary of environment statistics, studies in methods", no. 67. *Organisation for Economic Co-operation and Development*

Technology option	Alignment with waste hierarchy	Is there available local expertise to operate the technology?	Are generated quantities of used oil sufficient for process viability?[11]	Does the technology comply with regulation?[12]	Is it an Environmentally Sound Technology?[13]	Is the upfront capital achievable for Pacific nations?
Pyrolysis	Reprocessing to generate fuel	Yes	Yes	Yes	Yes	Yes
Reclamation/ reconditioning	Recycling for direct reuse	Yes	Yes	Yes	Yes	Yes
Acid clay treatment	Recycling to obtain base oil	Maybe	Yes	Maybe	No	Yes
Activated clay treatment	Recycling to obtain base oil	Maybe	Maybe	Maybe	Yes	Maybe
Hydrogenation	Recycling to obtain base oil	No	No	Yes	Yes	No
Solvent extraction	Recycling to obtain base oil	No	No	Yes	Yes	No
Ultra-filtration	Recycling to obtain base oil	No	No	Yes	Yes	No

4 Management options

This section will compare management options identified in Table 8 as being feasible for implementation in the Pacific. These include:

- Direct burning in controlled incineration (Section 4.1);
- Pyrolysis (Section 4.2);
- Mild processing followed by fuel blending or reuse (Section 4.3); and
- Activated clay treatment (Section 4.4).

Each of these options are identified as being preferable to disposal in the waste hierarchy of management techniques.

Due to the similar processing stages required to generate blended fuels and treating single stream industrial oils for reuse (i.e., used oil reclamation/ reconditioning), these management techniques have been grouped for detailed discussion.

Activated clay treatment (ACT) has been identified as the only advanced treatment option viable for the low annual used oil generation rate in the Pacific region. High processing costs and technical expertise may still make implementation unviable in the short term.

Prior to using the decision-making tool for selecting a used oil management technology, it is recommended that a full Used Oil Inventory Review is completed. As the decision-making tool is not tailored to specific applications (rather it is general for the Pacific region), additional details need to be gathered prior to the analysis. It is recommended that the review include:

- Major sources and generators of used oil (including location, existing storage capacity and quantities);
- Total used oil generation rate (tpa) and capture rate (%);
- Average used oil characteristics and contaminants; and
- Existing collection, transportation and storage arrangements.

The comparison is structured into four major sections: Technological, Legal, Economic and Environmental. Under each of these sections, different focus areas have been identified to assist in the comparison of potential technology options. A summary table comparing each option is provided in Appendix A.

4.1 Direct burning in controlled incineration

4.1.1 Technological

Table 9 Direct burning - technological overview

Focus area	Direct burning in controlled incineration

Technology overview and relation to waste management hierarchy	• Direct burning involves the bulk destruction of unprocessed used oil at high temperatures with ancillary energy capture.
	• Energy capture can be:
	  ○ Steam for direct use;
	  ○ Steam for electricity generation;
	  ○ Hot water; or
	  ○ Hot air for drying.
	• Emission controls are required due to lack of pre-processing (resulting in potentially high levels of toxic contaminants). Some potential emission control systems include:
	  ○ Flue gas recirculation;
	  ○ Wet scrubbing;
	  ○ Activated carbon injection; and
	  ○ Electrostatic precipitation.
	• The performance of emission controls should be continuously monitored to minimise environmental damage.
	• In small scale units, vaporising burners have been identified as producing less emissions than air atomising burners.[14]
	• Used oils can be emulsified with water (between 5-25wt%) through high sheer mixing prior to burning. Emulsified fuels result in less internal carbon build-up (improving heat transfer performance and decreasing cleaning requirements) and less particulate/ NOx air emissions.[15]
	• Direct burning is the lowest ranking on waste hierarchy after disposal due to the potential for environmental damage.

Acceptable feedstocks (i.e., types of oil accepted and their condition)	• No restriction on the type or quality of oil that can be combusted from an operational perspective. • The high heating capacity of used oils make them an efficient fuel source for high temperature burns. • Highly contaminated oil will increase the risk of harmful emissions and may fall under legislative restrictions. This will necessitate regulated burning conditions and emission controls.
Recommended requirements for collection, transportation, and storage of feedstocks	• Direct burning plants are most beneficial when co-located with systems requiring industrial heating. Large industrial centres are also primary generation areas for used oil, decreasing transport distances and handling requirements. • Bulk storage of used oil is acceptable prior to direct burning. High sheer mixing or water emulsification prior to burning can improve combustion characteristics. • The potential for high throughput capacity by direct burning means that used oil stockpiles can be decreased in volume.
Volumes required for efficient use	• Systems can be scaled to the availability of feedstock and the requirements of energy capture systems (i.e., the amount of steam needed for a particular industrial process).

[14] Hall, Robert E., W. Marcus Cooke, and Rachael L. Barbour. "Comparison of air pollutant emissions from vaporizing and air atomizing waste oil heaters." *Journal of the Air Pollution Control Association* 33.7 (1983): 683-687.
[15] Hsuan, Chung-Yao, et al. "Water-In-Oil emulsion as boiler fuel for Reduced NOx emissions and improved energy saving." *Energies* 12.6 (2019): 1002.

Focus area	Direct burning in controlled incineration
	• Consistent feedstocks are required for efficient operation, meaning large scale systems will need access to long term supply. • Smaller scale systems can be employed although should be held to the same operating and emission control standards as larger systems. In practice, small scale systems typically rely on the pre-treatment of used oil to remove contaminants rather than the control of air emissions.

Process outputs and their associated reuse options	1. Combustion heat – can be used for industrial heating.
	2. Fly ash – should be treated as a potentially hazardous waste (enriched with heavy metals) and undergo controlled disposal. No readily commodifiable uses have been identified for incineration fly ash.[16] Other treatment methods for fly ash include:
	  ○ Magnetic/ eddy current separation;
	  ○ Sintering;
	  ○ Electrodialytic remediation
	  ○ Thermochemical treatment; and
	  ○ Inorganic or organic binding.
	3. Bottom ash – typically exhibit lower hazardous characteristics to fly ash and can be used to replace primary aggregates in civil construction projects (following testing for its safe use).[17]

Facility/ technology footprint and geographical requirements	• Facility footprints will depend on the boiler scaling, type of air emission control equipment and the potential inclusion of on-site fly ash treatment. • Facilities should be located away from heavily urbanised zones to minimise the impacts of potential air pollution. Prevalent wind directions should be considered when choosing the site location. • Facilities should be located near disposal areas for by-product ash to decrease transportation requirements.
Technological and processing complexity (i.e., maintenance constraints, training requirements and technical expertise)	• Direct burning incinerators or boilers have low technological and processing complexity, with no major maintenance constraints identified. • Regular internal cleaning is required to maintain efficient heat transfer. Cleaning requirements can be decreased through water emulsification. • Technical expertise will vary determined by the complexity of the air emission control system in place. This may need regular maintenance/ replacement of parts (e.g., filter bags) or electrical control.
Scalability	• Boiler systems are highly scalable to the supply of used oil and requirements for heat generation. • Systems typically range from less than 3 MWh to over 75 MWh energy generation. This translates to between 2 L per hour to over 5,000 L per hour of used oil.
Conversion efficiency	• New industrial oil burners can reach heat capture efficiencies of up to 80%.[18]

[16] Fabricius, Anne-Lena, et al. "Municipal waste incineration fly ashes: From a multi-element approach to market potential evaluation." *Environmental Sciences Europe* 32.1 (2020): 1-14.
[17] Kumar, Sanjeev, and Davinder Singh. "Municipal solid waste incineration bottom ash: a competent raw material with new possibilities." *Innovative Infrastructure Solutions* 6.4 (2021): 1-15.
[18] IEA ETSAP. "Technology Brief I01 – Industrial combustion boilers." *Combustion Industrial Testing* (2010): 1-5

4.1.2 Legal

Table 10 Direct burning - legal overview

Focus area	Direct burning in controlled incineration
Impact of legislation related to the shipping and exportation/ importation of used oil and process outputs (i.e., standards, requirements and insurance)	• It is recommended that boilers are scaled to process local generated quantities of used oil. Potential does exist to accept internal used oil (e.g., BlueScope Pacific Steel Pty. Ltd. in Fiji accepts used oil from Tuvalu and the Cook Islands) although shipping and insurance costs present a financial barrier to improved used oil recycling rates.
Impact of international conventions and agreements	• If air emissions are not controlled, processing may trigger regulation under the Stockholm and Rotterdam Conventions due to the atmospheric release of heavy metals, PAHs and PCBs from combusted used oil.
Existing waste control measures	• Processing must comply with local legislation controlling air emission standards (e.g., the Solomon Island Environment Act 1998).

4.1.3 Economic

Table 11 Direct burning - economic overview

Focus area	Direct burning in controlled incineration
Process outputs and their market value	• Energy generation is the marketable process output of direct burning. The market value is determined by the substitution of more expensive fuel sources (e.g., timbre or natural gas) with cheaper used oil. • Typically used oil is purchased as $0.20 USD per litre compared to petroleum oil at $1.25 USD per litre.[19]
Capital expenditure (i.e., equipment purchase cost, ancillary services and infrastructure/ civil engineering requirements)	• Boiler capital expenditure is estimated to be 3% of the life-time processing cost. The typical cost of an oil-fired fire-tube boiler that generates 4,700 kg/hr of steam will be approximately $60,000USD. Different burner systems (e.g., direct air heating system) will have different associated costs. • Smaller systems processing approximately 2-5 L per hour of used oil can be purchased for between $2,000 - $5,000USD. Small scale systems do not require any ancillary services or civil engineering. • Details on the types and costs for air emission control systems can be found in the US EPA Air Emission Control Cost Manual.[20]
Transport and installation cost	• Large scale systems can be constructed from locally available materials, dependent on design complexity. Existing industrial burners/ boilers can be adapted to accept used oil with the addition of air emission control systems. • International transportation of air emission control components may be required. Shipping for these components is estimated to be approximately $2,500USD. • Small scale systems typically include transportation costs in upfront costs.
Operational expenditure (i.e., labour, maintenance, replacement parts, utilities, material handling, storage etc.)	• Typically, operational and maintenance expenditure constitute 1% of the life-time processing costs. High-cost fuel sources (e.g., natural gas) can constitute 96% of the life-time processing cost, although this is expected to be a lower proportion for low cost used oil.
Technology lifespan	• The technical performance lifespan of industrial burners is 25 to 40 years.[21]

[19] Pacific Regional Data Repository for SE4ALL. "Pacific Fuel Price Monitor – Quarter 1 2019"
[20] Available: https://www.epa.gov/sites/production/files/2020-07/documents/c_allchs.pdf
[21] IEA ETSAP. "Technology Brief I01 – Industrial combustion boilers." *Combustion Industrial Testing* (2010): 1-5

4.1.4 Environmental

Table 12 Direct burning - environmental overview

Focus area	Direct burning in controlled incineration
Process emissions and by-product requirements	• Used oil should be burnt at the highest possible temperature with optimal oxygen mixing to ensure complete combustion. Additional air emission controls and monitoring should be in place to maintain acceptable flue gas composition. Without emission controls, restrictions should be in place regarding acceptable used oil feedstocks (refer Table 6). • Fly ash should be collected and disposed to a hazardous waste landfill with leachate control or undergo further processing (refer Table 9).
Water and electricity consumption	• Direct burner systems will require minimal electricity, dependent on computer-based system control/ monitoring. • Water consumption rates will be largely dictated by the energy capture system (i.e., steam generation for heat transfer) and whether water can be recycled through the system. Other water consumption requirements will be for internal cleaning or potential water-in-oil emulsification.
Risks to environment	• Negative environmental impacts of fly and bottom ash disposal to landfill, resulting in leachate enriched with salts and heavy metals.[22] • If air emissions are not controlled or if systems are not monitored, air pollutants can include a range of heavy metals, chlorinated compounds, carbon monoxide, sulfur dioxide, nitrous oxides and particulate dusts.
Risks to human health	• Risks to human health include heated elements, oil fires resulting from leaks and toxic air emissions resulting from incomplete combustions/ poor venting and scrubbing of emissions.
Benefits and impacts to environmental and human health	• Direct burning represents an overall improved treatment option when compared to used oil disposal or open burning due to the ability to capture energy and control emissions. If these systems are not in place, then the environmental impacts may outweigh the benefits.

4.2 Pyrolysis

4.2.1 Technological

Table 13 Pyrolysis – technological overview

Focus area	Pyrolysis
Technology overview and relation to waste management hierarchy	• Pyrolysis is a thermochemical treatment method that involves heating organic compounds in the absence of oxygen. The non-combustion environment results in the decomposition of molecular bonds, changing the chemical and physical properties of the feedstock. • Pyrolysis systems are typically comprised of: 1. Sealed heating chamber or retort; 2. Condenser; 3. Reflux column or catalytic converter; 4. Water cooling system; and 5. Gas accumulator and liquid fuel trap. • When applied to used lubricating oil, heavy oil molecules are cracked into lighter diesel, naphtha and gas oil molecules.

[22] Kanhar, Altaf Hussain, Shaoqing Chen, and Fei Wang. "Incineration fly ash and its treatment to possible utilization: A review." *Energies* 13.24 (2020): 6681.

Focus area	Pyrolysis
	• Cooling results in the condensation of liquid fuels and the separation of non-condensable gases. • Collected gases are typically recycled internally to heat the pyrolysis chamber. • Pyrolysis results in a fuel that can be collected and used in a variety of applications, resulting in its higher ranking in the waste hierarchy compared to direct burning. Although as the product can only be burnt, with no potential for material resource recovery (only energy recovery), it ranks lower than other recycling techniques.
Acceptable feedstocks (i.e., types of oil accepted and their condition)	• The lack of sensitive processing equipment and capture of all process emissions means a wide variety of used oil feedstocks can be accepted by pyrolysis treatment. • Pyrolysis can additionally be used to process used oil containers into a liquid fuel. Prior shredding to increase plastic density improves process efficiency. • Additional feedstock quality controls are recommended for systems employing catalytic conversion to improve the lifespan of catalysts. • Other acceptable waste materials include mixed plastics and used tyres.
Recommended requirements for collection, transportation, and storage of feedstocks	• Small scale or mobile systems can rely on local/ island-based aggregation of feedstocks. Potential to co-location at major generation sources such as ports or power plants. • Larger stationary plants may require inter-island transportation or consolidation with other waste streams (i.e., tyres and plastics).
Volumes required for efficient use	• Pyrolysis systems are adaptable to different size operations, from single batch operations running at less than 1 tonne per day to large continuous operation plants at over 200 tonnes per day. Equipment scaling can be tailored to available feedstocks.
Process outputs and their associated reuse options	1. Diesel fuel – used in combustion engines or for electricity generation. 2. Naphtha (dependent on condenser operation) – petroleum solvent or burner fuel. 3. Gas oil – internal recycling for unit heating. 4. Ash – typically 2-3% of process throughput. Can be disposed as inert by-product. Potential use as an absorbent for oil spills, which can then be pyrolyzed.
Facility/ technology footprint and geographical requirements	• Small scale batch operation (< 1 tonne per day) with footprint less than $5m^2$. • Large scale continuous operation (e.g., up to 30 tonnes per day) with footprint of $480m^2$. • Pyrolysis plants can be robust to various climate conditions. They can also be constructed as 'mobile' or 'stationary' plants to adapt to local requirements.
Technological and processing complexity (i.e., maintenance constraints, training requirements and technical expertise)	• Small scale operations have low technological and processing complexity. Variables that need to be controlled by operators include temperatures in the reaction vessel (measured via an internal temperature probe or external laser heat gun) and flowrates of coolant water. Low temperatures will decrease the conversion yield of products and increase processing times. High temperatures will increase the collected proportion of fuel gas. • Medium and large scale systems typically have automated process controls, also known as Programmable Logic Control (PLC). This requires additional electrical expertise to install and maintain the function on process computers. • Mechanical pumps and motors employed in higher capacity applications also require regular maintenance. • Higher degrees of product control can be achieved with the addition of catalytic conversion (typically zeolite). Catalysts are susceptible to

Focus area	Pyrolysis
	coking, sintering and poisoning. The presence of carbon soot and sulfur in feedstocks will increase the rate of catalyst deactivation.
Scalability	• Highly scalable system can be tailored to the available feedstocks and technological complexity.
Conversion efficiency	• >95% conversion to usable output products (with ability to adjust heating parameter to control ratios between liquid and gas fuel products).

4.2.2 Legal

Table 14 Pyrolysis – legal overview

Focus area	Pyrolysis
Impact of legislation related to the shipping of used oil and process outputs	• Internal consolidation of feedstocks for small scale processing will unlikely trigger legislative requirements. • International consolidation of feedstocks will require prior consent agreements for transboundary movement along with insurance related to hazardous waste shipments. • The generation of petroleum based liquid fuels may trigger legislative requirements under local laws (e.g., the Solomon Islands Petroleum Act 1987). • Exportation and trade of liquid fuel products must align with internal fuel conventions.[23]
Impact of international conventions and agreements	• Transboundary consolidation of feedstocks will require approval under the Basel Convention and Waigani Convention. • Highly contaminated used oil may trigger regulation under the Stockholm and Rotterdam Conventions due to contamination of lead, PAHs and PCBs.
Existing waste control measures	• National Waste Management legislation or Strategy policy should be consulted for local requirements regarding the collection, transportation and storage of used oil. • Liquid fuels should comply with local air quality emission standards to be used in combustion applications.

4.2.3 Economic

Table 15 Pyrolysis – economic overview

Focus area	Pyrolysis
Process outputs and their market value	• Typical diesel-like yields for pyrolysis are up to 85% of feedstocks.[24] Tax inclusive diesel prices in the Pacific region can range between \$0.8 to \$1.8 USD per litre.[25] • Remaining gas oil products would require pressurised storage for marketability. It is recommended that gas oils are reused onsite for heating.
Capital expenditure (i.e., equipment purchase cost, ancillary services and	• Supplier estimates for small scale (155 L per day batch system with manual operation) are approximately \$20,000USD inclusive of equipment purchase costs, ancillary services and training.

[23] No standard international regulations exist for pyrolysis oil and the lack of finishing treatment makes pyrolysis products unfit for marketing at diesel. Source: Costenoble, O. "Worldwide Fuels Standards. Overview of specifications and regulations on (bio) fuels." *NEN–Netherlands Standardization Institute* (2017).
[24] Phetyim, Natacha, and Sommai Pivsa-Art. "Prototype co-Pyrolysis of used lubricant oil and mixed plastic waste to produce a diesel-like fuel." *Energies* 11.11 (2018)
[25] Pacific Regional Data Repository for SE4ALL. "Pacific Fuel Price Monitor – Quarter 1 2019"

Focus area	Pyrolysis
infrastructure/ civil engineering requirements)	• Supplier estimates for medium scale (350 L per day semi-continuous system with automated operation) are approximately $115,000USD exclusive of transportation, ancillary services and training. This scale system is estimated to exceed the annual used oil generation rate for any individual Pacific Island nation (annual processing capacity of approximately 87,600 tpa assuming a 5 day per week operation).
Transport and installation cost	• Transport and installation costs should be included in purchase price for small scale systems. • Medium scale systems can often be loaded for shipment in a standard 20-ft container with "plug and run" connectivity (to electricity, gas and water supply). Shipping costs vary annually, although estimates from North Asia to Pacific Islands are $2,500 to $4,000 USD.
Operational expenditure (i.e., labour, maintenance, replacement parts, utilities, material handling, storage etc.)	• Small scale systems can be run with minimal external electricity and heating requirements. Start-up heating can rely on direct burning of used oil or other fuel sources (e.g., timbre). Process heating can rely on collected oil gases. • Small scale systems can also rely on local knowledge and training for maintenance and replacement parts. • Medium scale systems will be associated with additional costs for labour, maintenance, electricity, start-up fuel (approximately $6,000 USD per year excluding labour). • Additional costs are associated with systems that employ catalytic conversion to high quality diesel end-products. Under correct operation (i.e., control of catalyst deactivating feedstocks), annual catalyst replacement costs are approximately $7,000 USD per year.
Technology lifespan	• Due to low reliance on moving parts or complex unit operations, pyrolysis systems are expected remain operation for 10+ years.

4.2.4 Environmental

Table 16 Pyrolysis - environmental overview

Focus area	Pyrolysis
Process emissions and by-product requirements	• Gas capture results in minimal atmospheric emissions during operation. The atmospheric release of oil gases should be avoided due to high carbon monoxide concentrations. • High temperature and low residence time increase the yield of condensable liquid fuels. Low temperature and high residence time increase the proportion of char/ ash by-products.[26] • Low quantities of ash produced may contain trace quantities of heavy metals (depending on feedstock quality and operation parameters). They should be disposed in a controlled manner.
Water and electricity consumption	• Electricity is required for temperature monitoring equipment in all systems (achievable via a 9V battery). Medium scale systems will need additional electricity for PLC and pump controls. Diesel products can be used onsite for electricity generation to internalise requirements. • Cooling water is required for the condensation of heating pyrolysis gas. Approximately 200 – 1,000 L of water should be available onsite for cooling, although this water can be recycled for continued use after cooling between batches.
Risks to environment	• Pyrolysis presents a low environmental risk due to the internal containment of gas oils.

[26] El-Mekkawi, Samar A., et al. "Reducing the environmental impact of used lubricating oil through the production of fuels by pyrolysis." *Environmental Nanotechnology, Monitoring & Management* 14 (2020): 100308.

Focus area	Pyrolysis
	• The burning of gas oils for unit heating have the potential to generate dioxins and furans if the pyrolysis reaction is incomplete.
Risks to human health	• Risks to human health include heated elements, oil fires resulting from leaks and toxicity in the event of oil gas release. • Heated, pressurised reaction chambers present a risk of explosion.
Benefits and impacts to environmental and human health	• Pyrolysis represents an overall beneficial treatment method when compared to used oil disposal or direct burning. • Converting heavy oils into lighter diesel fuels improves their combustion characteristics during burning and improves the quality of air emissions.

4.3 Mild processing followed by fuel blending or reuse

Due to the similar processing stages required to generate blended fuels and treating single stream industrial oils for reuse (i.e., used oil reclamation/ reconditioning), these management techniques have been grouped and discussed below.

4.3.1 Technological

Table 17 Mild processing - technological overview

Focus area	Mild processing followed by fuel blending or reuse
Technology overview and relation to waste management hierarchy	• Mild processing involves the removal of major contaminants from used oil. If feedstocks are from a mixed source or are highly contaminated, process output are either burnt directly or blended with diesel fuel. If feedstocks are from a single industrial source with low contamination, output products can be reused in their original application. • Processing decreases air pollutants caused by burning, improves fuel or lubrication characteristics, reduces fouling or corrosion of engines and improves used oil marketability. • Mild processing does not return used oil completely to its virgin state, nor is it capable of removing all contaminants such as heavy metals. • All lubricants will eventually reach a condition where they can no longer be reused due to excess contaminants. At this stage, fuels can be burnt or sent to advanced recycling. • Mild processing stages typically include: 1. Pre-straining through coarse (½") strainer to remove large debris; 2. Heating via coils or circulation heater to increase oil temperature and decrease viscosity; 3. Settling stage which can be shortened through the addition of demulsifiers or through centrifugal separation; and 4. Filtration of residual fine sludges. • Certain process steps can be omitted depending on the level of contamination of the feedstock and the desired quality of process outputs. • For reuse, final reclaimed oil sweetening involves the addition of fresh lubricating oils or fresh additives to improve oil performance. • Additional equipment requirements include diaphragm pumps, mixing motors, oil and diesel storage tanks and computer aided controls. • Mild processing ranks in the middle of the waste hierarchy, as process outputs can either be used as fuel or recycled back into their original application.
Acceptable feedstocks (i.e., types of oil accepted and their condition)	• The performance of mild processing is dependent on the quality of used oil feedstocks. Mixing of different types/ sources of used oil should be avoided to improve the quality and confidence in process outputs.

Focus area	Mild processing followed by fuel blending or reuse
	• If feedstocks are from mixed sources (e.g., small automotive workshops), process outputs should be blended with fuels for burning. • If feedstocks are from single source industrial generators (e.g., transformer oil, hydraulic oil or turbine oil), reclaimed products can be reused in their original application. • Additional care should be taken in treating turbine oil due to its critical requirements for cooling, sealing, lubricating and preventing corrosion during operation. • Process design and technology selection can be tailored to the typical sources of used oil. • Used oil highly contaminated in heavy metals or aromatic/ chlorinated hydrocarbons should not be processed via this method. Contaminants may not be fully removed and can result in environmental pollution or harm to human health. • On-going monitoring of oil quality should be conducted to ensure used oils are suitable for treatment (dependent on specifications given by technology provider). • Systems can typically process between 1,000 L to 6,000 L per hour of used oil.
Recommended requirements for collection, transportation, and storage of feedstocks	• Used oil collection systems should facilitate the source separation of common types of used oil (e.g., crankcase/ lubricating oils, transmission/ hydraulic oils, greases and compression oils). • Mild processing systems can employ small/ mobile designs to be situated close to major used oil generation points. • Extended storage periods prior to treatment should be avoided due to the potential for environmental contamination (e.g., water or rust). • Pre-straining can be included in the collection of used oils.
Volumes required for efficient use	• Systems do not require continuous operation for efficient use, hence they are adaptable to variable availability of feedstocks.
Process outputs and their associated reuse options	1. Processed lubricating oil – can be used directly in industrial heating application, blended with diesel to a desired ratio for use in combustion engines or reused in its original industrial application. Testing should ensure products meet performance specifications set out by the original equipment manufacturer or standards organisation (e.g., the American Society of Testing and Materials).[27] 2. Oily wastewater – requires treatment prior to environmental discharge. 3. Sludge – requires controlled disposal (e.g. chemical fixation) or incineration.
Facility/ technology footprint and geographical requirements	• Technology footprints are dependent on the number of processing units included, although typically entire systems can be contained within a 20-ft shipping container or smaller. • Enclosed systems have the advantage of protection from environmental/ climatic variables. • Oil heating duties prior to settling will vary depending on atmospheric temperature. Used oil is typically heated to 60°C.
Technological and processing complexity (i.e., maintenance constraints, training requirements and technical expertise)	• The lack of advanced processing typically results in low technological complexity or maintenance requirements. • Certain components may need to be replaced on a regular basis (e.g., pump diaphragms and oil filters), although designs accommodate their easy replacement.

[27] More details on product testing and relevant standards can be found at: Nadkarni, R. A., and R. A. Nadkarni. *Guide to ASTM test methods for the analysis of petroleum products and lubricants*. Vol. 44. West Conshohocken: ASTM International, 2007.

Focus area	Mild processing followed by fuel blending or reuse
	• Digital process controls, such as Supervisory Control and Data Acquisition (SCADA) software will require some electrical systems knowledge.
Scalability	• Systems can be scaled through parallel operations to decrease used oil transportation and handling requirements (i.e., locating systems near major generation sources).
Conversion efficiency	• Conversion efficiencies are dependent on the quantity of major contaminants in feedstocks, although centrifugal separation has been shown to separate over 95% of water and particulates.[28]

4.3.2 Legal

Table 18 Mild processing - legal overview

Focus area	Mild processing followed by fuel blending or reuse
Impact of legislation related to the shipping and exportation/ importation of used oil and process outputs (i.e., standards, requirements and insurance)	• Mild processing operates at scales appropriate for on-island generated volumes. The international consolidation of feedstocks is not recommended due to financial barriers. • The exportation of processed oil products must align with local and international trade regulations and will likely necessitate strict product testing. On-island use process products (e.g., diesel electricity generators) are recommended.
Impact of international conventions and agreements	• The transboundary export of process products may require Basel and Waigani Convention licensing. Annex I of the Basel Convention lists "Waste mineral oils unfit for their originally intended use" as a waste stream requiring control.
Existing waste control measures	• Blended fuels should comply with local air quality emission standards to be used in combustion applications. • Reconditioned lubrication oils should meet the technical requirements set by equipment manufacturers. Use of off-specification oils may impact equipment warranty. • Product testing should demonstrate combustion characteristics (if applicable), product viscosity, remaining contaminants and other parameters required by local waste control measures.

4.3.3 Economic

Table 19 Mild processing - economic overview

Focus area	Mild processing followed by fuel blending or reuse
Process outputs and their market value	• Blended fuels can closely match performance standards of non-blended diesel fuels. Hence the market value of process outputs is determined by the percentage substitution of diesel with cheaper processed used oil. Depending on the viscosity and remaining contaminants in processed used oil, blends typically range from 7-15%. • Benefits will be heightened for systems deployed in rural/ isolated locations due to higher fuel costs. • If used oils are reconditioned for industrial reuse, then the market value will be determined by savings gained from extending the life of lubricating oils. • There are potential constraints in product offtake if engine manufacturers resist the reuse of processed used oils. Oil processors should ensure

[28] Cambiella, A., et al. "Centrifugal separation efficiency in the treatment of waste emulsified oils." *Chemical Engineering Research and Design* 84.1 (2006): 69-76.

Focus area	Mild processing followed by fuel blending or reuse
	consistent product quality to maintain offtake confidence. Additional government incentives could be initiated to ensure product offtake.
Capital expenditure (i.e., equipment purchase cost, ancillary services and infrastructure/ civil engineering requirements)	• Process capital expenditure is estimated between \$200,000 to \$700,000 USD • Containerised units do not require any additional ancillary services or infrastructure.
Transport and installation cost	• Shipping and commissioning costs are estimated between \$10,000 to \$50,000 USD
Operational expenditure (i.e., labour, maintenance, replacement parts, utilities, material handling, storage etc.)	• Total operational expenditure is estimated between \$5,000 to \$20,000 USD per year inclusive of maintenance (dependent on process throughput). • Potential reagents used in processing include surfactants or demulsifiers to improve the removal of water. • Critical replacement parts are typically included in original equipment purchases. • Ongoing replacements may be required if oil filtering is included in the design (approximately \$150 USD for every 100,000 L of treated oil). • Systems can be operated by 1-2 full time employees conducting regular parts cleaning and minor maintenance. One staff member is required to have technical maintenance abilities (including electrical and mechanical system skills). • Pumps automate flowrates of feedstocks and products from storage tanks, minimising the requirements for material handling.
Technology lifespan	• The technical performance lifespan of used oil processing equipment is 15+ years.

4.3.4 Environmental

Table 20 Mild processing - environmental overview

Focus area	Mild processing followed by fuel blending or reuse
Process emissions and by-product requirements	• Oily wastewater separated from used oil must be treated before release into the environment. This can be carried out at conventional wastewater treatment facilities, although transportation and handling requirements should be considered during system design. • Residual sludge should be treated as hazardous waste and undergo controlled disposal. This could include chemical fixation to decrease the potential for leachate contamination.
Water and electricity consumption	• No water is consumed by used oil processing technology. • Use of on-site diesel generators utilising blended diesel products can meet process electricity needs. Otherwise, systems will need access to 3-phase 240V power connection. • Electricity demand is largely variable and dependent on the process design and equipment used. Systems can range from below 8 kWh to over 100 kWh during operation.
Risks to environment	• Poor leachate management at sludge disposal locations can contaminate water sources with heavy metals or aromatic/ chlorinated hydrocarbons. • Wastewater can cause oil contamination to water sources if not appropriately collected and treated prior to disposal. • Risk of residual contaminants in blended fuels can result in polluting air emissions.
Risks to human health	• Risk of toxic contamination during handling and disposal of sludges. • Risk of toxic contamination if blended fuels remain highly contaminated post-processing. Blended fuels should not be burnt in indoor space heaters with poor ventilation.

Focus area	Mild processing followed by fuel blending or reuse
Benefits and impacts to environmental and human health	• Processing allows for improved environmental outcomes when compared with other direct burning options due to reduced risks of air pollutants. Non-renewable fuels are displaced with recovered materials for combustion. • Higher order benefits are achieved if oils are reused prior to their eventual combustion.

4.4 Activated clay treatment

4.4.1 Technological

Table 21 Activated clay treatment - technological overview

Focus area	Activated clay treatment (ACT)
Technology overview and relation to waste management hierarchy	• ACT involves the treatment of heavily contaminated or complex mixtures of used oil into a product that can be reused. • The process creates a lubricating oil base stock that is comparable in quality to virgin petroleum base stock. Process outputs can be sweetened with fresh additives and sold as a recycled product. • ACT processing stages typically include: 1. Pre-treatment heating, filtration and dehydration; 2. Vacuum distillation or thin film evaporation of entrained water; 3. Activated clay contacting (usually at 120°C for 2 hours); and 4. Final product recovery and purification. • Activated clay is regenerated at the end of each process cycle, although becomes exhausted after six months to one year of operation. Spent clay can be disposed as a non-hazardous waste to landfill. • Advanced processing steps improve product colour, odour and sulfur content when compared to mild processing. • Vacuum distillation followed by clay contacting offers a less polluting and more economically viable treatment solution for small scale plants with capacity range between 10,000 and 30,000 tonnes per year.[29] • ACT is considered an advanced re-refinery technology option, hence requires modern processes that are expensive to operate when all safety and environmental considerations are factored into design. No re-refinery operations are active in the Pacific region. • Re-refinery is the highest order category in the waste management hierarchy due to the recovery of base oils from a range of mixed feedstocks.
Acceptable feedstocks (i.e., types of oil accepted and their condition)	• Processing can significantly reduce sulfur and aromatic/ chlorinated hydrocarbon concentrations. • Feedstocks can be accepted from a range of automotive or industrial sources.
Recommended requirements for collection, transportation, and storage of feedstocks	• An ACT processing plant will require an organised collection and transportation network to consolidate feedstocks to a centralised treatment facility. • Depending on the size of the facility, feedstocks may need to be sourced from multiple islands/ neighbouring nations. Backloading of lubricating oil shipments could be arranged to decrease transportation costs. • Onsite storage should utilise bunded containers capable of capturing 110% of the container volume in the event of damage/ leak.

[29] El-Fadel, M., and R. Khoury. "Strategies for vehicle waste-oil management: a case study." *Resources, conservation and recycling* 33.2 (2001): 75-91.

Focus area	Activated clay treatment (ACT)
Volumes required for efficient use	• ACT plants can be designed to accept throughputs between 50 to 10,000 litres per hour. • Once plants are operational, they must have consistent access to feedstocks to maintain economic viability.
Process outputs and their associated reuse options	1. Lubricant base stock – used for manufacturing into recycled lubricating oil. 2. Gas oil – internal recycling for unit heating. 3. Oily wastewater – requires treatment prior to environmental discharge. 4. Distillation residual – can be used as asphalt extender or undergo fixation and disposal to landfill. 5. Spent clay – requires further handling and disposal to landfill.
Facility/ technology footprint and geographical requirements	• Stationary re-refinery facilities will have the largest footprint of considered technology options, with very limited potential for a mobile unit design. • Plant footprint can range between 450 to 2,000 m^2. Geographical position should consider access to consistent feedstocks, fresh processing clay and disposal locations for spent clays and residuals.
Technological and processing complexity (i.e., maintenance constraints, training requirements and technical expertise)	• ACT processing requires trained and experienced oversight for safe and optimal plant performance. • Facilities can require up to 40 full time operating staff for high-capacity plants. • Regular technical maintenance and cleaning is required of critical process units.
Scalability	• ACT is the most scalable advanced re-refinery treatment option due to its viability in small scale plants.
Conversion efficiency	• Recovery efficiency of between 63-80 wt% of feedstocks (dependent on level of contamination).[30]

4.4.2 Legal

Table 22 Activated clay treatment - legal overview

Focus area	Activated clay treatment
Impact of legislation related to the shipping and exportation/ importation of used oil and process outputs (i.e., standards, requirements and insurance)	• International consolidation of feedstocks will require prior consent agreements for transboundary movement along with insurance related to hazardous waste shipments. • The exportation of processed oil products must align with local and international trade regulations and will likely necessitate strict product testing.
Impact of international conventions and agreements	• The transboundary consolidation of feedstocks will require Basel and Waigani Convention licensing and approval. • The removal of contaminants must be ensured prior to product exportation no avoid regulation.
Existing waste control measures	• Processing operations must comply with local waste control measures regarding atmospheric emissions. Emissions from re-refinery plants are minimal due to the capture and internal recycling of gas oils. • Disposal of residuals and spent clays must comply with local waste control measures to minimise leachate damage.

[30] Giovanna, F. D., et al. "Compendium of used oil regeneration technologies." *United Nations Industrial Development Organization and International Centre For Science and High Technology, Trieste* (2003).

4.4.3 Economic

Table 23 Activated clay treatment - economic overview

Focus area	Activated clay treatment
Process outputs and their market value	• ACT treatment tends to have lower recovery performance and less consistent final product quality when compared to more sophisticated re-refinery processing.[31]

Capital expenditure (i.e., equipment purchase cost, ancillary services and infrastructure/ civil engineering requirements)	• ACT treatment has the lowest capital investment when compared to other re-refinery technology options, making it viable for small scale applications.
	• Capital costs will depend on the technology provider employed for plant contracting and the availability of existing onsite equipment, although is estimating to be over $10,000,000 USD.[32]
	• Considerable ancillary services (heating, cooling, pneumatics, electricity, water) are required on site.
	• Additional upfront costs include:
	  ○ Planning and feasibility studies;
	  ○ Land acquisition and site preparation;
	  ○ Insurances and taxes during construction; and
	  ○ Equipment inspection and testing.

Transport and installation cost	• Some plant elements are modular, can be shipped in conventional shipping containers and retrofitted to existing refinery systems. This significantly decreases transportation and installation costs. • Full re-refinery plant commissioning requires considerable transportation and installation overheads, approximately 10% of capital costs.[33]
Operational expenditure (i.e., labour, maintenance, replacement parts, utilities, material handling, storage etc.)	• Process operational expenditure is primarily depended on access and proximity to clay suitable for processing. A key consideration of process planning and viability is ensuring access to local sources to avoid the need for international transportation. • With access to suitable clay, operating expenditure is approximately $0.05 to $0.1 USD per L of treated oil.
Technology lifespan	• Re-refinery treatment plants have a lifespan of 20+ years.

4.4.4 Environmental

Table 24 Activated clay treatment - environmental overview

Focus area	Activated clay treatment
Process emissions and by-product requirements	• ACT produces a greater proportion of by-products when compared to mild processing. The most critical is spent clay that requires disposal either to landfill or brick kilns/ cement plants. • Spent clays should be cleaned via solvent treatment prior to disposal to minimise the risk of polluting leachates. • Additional by-products include recovered light gas oils which can be recycled in internal process heating and heavy residual bottoms from distillation and filtration. Residuals are heavy oils which can be blended as asphalt extender.

[31] Sánchez-Alvarracín, Carlos, et al. "Characterization of Used Lubricant Oil in a Latin-American Medium-Size City and Analysis of Options for Its Regeneration." *Recycling* 6.1 (2021): 10.
[32] Hendrickson, Chris, Chris T. Hendrickson, and Tung Au. *Project management for construction: Fundamental concepts for owners, engineers, architects, and builders*. Chris Hendrickson, 1989.
[33] Silla, Harry. *Chemical process engineering: design and economics*. CRC Press, 2003.

Focus area	Activated clay treatment
Water and electricity consumption	• No water is a direct requirement of processing stages. Some systems employ acidic solutions for clay regeneration, which will require water determined by manufacturer specification. • Pumps, mixers, monitoring devices and control systems will require electricity input. Electricity can form a considerable operational cost for the plant and will need to be sourced from a central grid. Estimated between 150 to over 400 kWh.
Risks to environment	• If spent clays are not regenerated prior to disposal, or are allowed to become heavily contaminated during use, they can leach heavy metals and other contaminants. • Wastewater can cause oil contamination to water sources if not appropriately collected and treated prior to disposal.
Risks to human health	• Risks to human health include heated elements and oil fires resulting from leaks. • Vacuum chambers should be designed as pressurised vessels to prevent failure and release of hazardous substances. • Electrical risks associated with live wires and electronic devices. • Health risks from handling potentially toxic spent clay. • Re-refinery plants should be designed with comprehensive monitoring, alarm and emergency shutdown systems to minimise risk to workers and the general public.
Benefits and impacts to environmental and human health	• Producing new lubricant oils from recycled base stock results in considerable savings in crude oil reserves and energy requirements. This results in overall reductions in greenhouse gas emissions and the extension of non-renewable resources. • Recycling used oil into base stock presents less risks of polluting atmospheric emissions when compared to burning.

5 Case Studies

Case studies provide useful insights into the success and challenges of used oil treatment systems currently in operation. Table 25 compares three case studies showcasing different technology options. Two are located in the Pacific region, while the third was chosen from Germany due to the lack of re-refinery operations in the Pacific. Details provided below have been sourced from interviews with technology suppliers and system operators.

Table 25 Used oil treatment options – case study

Focus Area	Case Study 1	Case Study 2	Case Study 3
Location	Solomon Islands	Papua New Guinea (PNG)	Germany
Management option	Pyrolysis	Mild processing followed by fuel blending or reuse	Re-fining (ACT)
Technology type	Single batch pyrolysis system	Centrifugal separation and fuel blending	Distillation and clay treatment
Throughput	Up to 155 L per day	Up to 10,000 L per day	Approximately 10 ML per day
Feedstock	1. Mixed used oil and plastics. 2. Wood used as retort heating fuel.	1. Low contamination/ unmixed used oils. 2. Products mixed with diesel.	1. Mixed used oils. 2. Activated clay.
Products	Pyrolysis liquid fuel (diesel-like properties) and gas oil	Blended diesel (with ability to control blend ratio)	Lubricant base stock and gas oil
By-products and emissions	Ash (2-3% of process input)	Oily wastewater and sludge	Oily wastewater, distillation residual and spent clay
Mobility	Moveable by 2-3 individuals (short distances) or truck	Containerised unit is moveable by truck or freight ship	Stationary re-refinery plant

Focus Area	Case Study 1	Case Study 2	Case Study 3
Footprint	Less than 5 m^2	Standard 20-ft shipping container	450 m^2
Staff and expertise	1-2 locally trained community members	2-3 employees with some technical knowledge required	Unknown number of staff members, although high level processing and technical knowledge is required.
CapEx	$20,000 USD	$ 190,000 USD	No estimate given
OpEx	No estimate given	No estimate given	General system operation is $0.08 USD per L with additional costs required for clay (dependent on source).
Challenges	Reported that large portions of project funding were used to train and upskill local community members on the operation of the pyrolysis system. Coordination was required to determine optimal uses for pyrolysis fuel products (e.g., generator fuel or community cooking oven).	Reported issues with product offtake arrangements, with engine manufacturers expressing hesitation to use blended fuels. Low incentivisation mechanisms to support offtake. Also reported difficulty in securing quality, unmixed feedstocks. Additional education and source separation required to improve product quality.	Lower quality base stock quality when compared to other advanced re-refinery techniques. Requires offtake/ disposal arrangement for spent clay, which has a risk of environmental damage.
Opportunities	Future opportunities exist for a distributed system of pyrolysis units on small-island nations, using locally trained operators and a central training/ coordination team. Modifications to reflux column design can also allow future systems more control of final product characteristics.	Higher environmental standards, enforcement and regulations will help further reduce inappropriate disposal methods and highlight the advantages of used oil processing. Government support or incentivisation can also help strengthen off-take arrangements (e.g., discounted fuel tax).	Additional processing stages, such as hydrofinishing can further improve final product quality. Ability to retrofit clay treatment systems on the back of existing petroleum refineries to significantly decrease capital costs.

Figure 5 Community scale pyrolysis unit (Solomon Islands)[34]

Figure 6 Direct use of pyrolysis gas oils for cooking (Solomon Islands)[34]

[34] Source: Photos and data for Solomon Islands pyrolysis system supplied by NuFuels, NZ.

Figure 7 Graduates from pyrolysis operation training session (Solomon Islands)[34]

Figure 8 Containerised used oil processing and fuel blending unit (PNG)[35]

[35] Source: Photos and data for PNG used oil processing unit supplied by Total Waste Management, PNG

Figure 9 Front-end used oil distillation plant (Germany)[36]

Figure 10 Transportation of back-end activated clay scrubbing unit (Germany)

[36] Source: Photos and data for activated clay treatment plant supplied by Hering VPT, Germany

6 Conclusions

A range of technology options have been presented and compared as part of this review, from highly technical re-refinery treatment to community-based recovery solutions. No single option can be recommended for the region, hence individual contextual considerations need to be understood during the selection of a used oil treatment technology.

When considering large scale processing options (e.g., direct burning with emission controls or re-refinery), it is recommended to:

- Understand legal and operational requirements for the consolidation of feedstocks from across the Pacific region;
- Arrange low-cost freight transportation such as backloading shipping vessels or eligibility under the Moana Taka Partnership[37];
- Investigate options for adapting existing systems to accept used oil (such as operational industrial boilers or power stations that can be retrofitted with improved emission controls); and
- Secure long term financial arrangements or aid funding which can help achieve high upfront costs.

When considering smaller scale processing options (e.g., community pyrolysis units or mild processing), it is recommended to:

- Ensure local communities are trained in the operation and maintenance of treatment processes to decrease on-going operation costs and empower individuals to responsibly manage their wastes;
- Conduct regular third-party testing of process products to ensure confidence in offtake partners;
- Support education and improved used oil collection locations to decrease contamination and mixing of different streams; and
- Arrange partnerships with large scale industrial used oil generators.

Whether systems aim to recover used oil to be burnt or recycled into new lubricating oil, all technology should aim to improve on the environmental benefits compared to used oil disposal. When systems are optimised to the local context, additional financial and social benefits can also occur.

[37] More details available: https://www.sprep.org/publications/moana-taka-partnership-a-guide-for-pacific-island-countries-territories

Appendix A Used oil treatment – technology options comparison

Table 26 Comparison table of potential technology options for the Pacific region indicating favourable outcomes (green), potentially favourable outcomes (yellow) and unfavourable outcomes (orange)

	Focus area	Direct burning in controlled incineration	Pyrolysis	Mild processing followed by fuel blending or reuse	Activated clay treatment
Technological	Alignment with waste hierarchy objectives	Orange	Yellow	Yellow	Green
	Acceptability of variable quality feedstocks	Orange	Green	Orange	Yellow
	Adaptability to variable feedstock supply rates	Orange	Green	Green	Orange
	Process outputs and their associated reuse options	Orange	Yellow	Yellow	Green
	Facility/ technology footprint	Yellow	Yellow	Green	Orange
	Technological and processing complexity	Green	Green	Yellow	Orange
	Scalability	Yellow	Green	Yellow	Green
	Conversion efficiency	Yellow	Green	Green	Yellow
Legal	Impact of legislation to consolidate feedstocks	Yellow	Green	Green	Yellow
	Impact of legislation for product offtake	Orange	Yellow	Yellow	Green
	Existing waste control measures	Orange	Yellow	Green	Yellow
Economic	Process output market value	Orange	Yellow	Green	Green
	Capital expenditure	Yellow	Green	Yellow	Orange
	Transport and installation cost	Yellow	Green	Green	Orange
	Operational expenditure	Green	Yellow	Yellow	Orange
	Technology lifespan	Green	Orange	Yellow	Green
Environmental	Process emissions and by-product requirements	Orange	Green	Yellow	Orange
	Water and electricity consumption	Green	Yellow	Yellow	Orange
	Risks to environment	Orange	Yellow	Yellow	Yellow
	Risks to human health	Yellow	Yellow	Green	Yellow

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