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Conceptual design of solar-powered dryer for use in municipal wastewater treatment facilities

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ABSTRACT

This project has proposed a solar assisted dryer to remove residual water content from mechanically dewatered, solid, non-organic screening waste from the inlet filtration stage at municipal wastewater treatment plants (WWTPs). By harnessing renewable solar energy, the waste dryer aims to reduce the residual waste moisture (post mechanically dewatered), lowering its weight, costs and environmental impacts during disposal. This work is significant as it offers a sustainable solution aligned with increasing global efforts to mitigate environmental harm using renewable energy and provides the initial step to an alternative waste pathway to valorisation.

The project presented a comprehensive design framework encompassing problem identification, problem definition, idea generation and evaluation of a conceptual dryer design tailored for a local WWTP in southeast Queensland. The proposed multi-levelled hybrid system uses forced heated air in a rotary drum dryer to dry and process the waste mixture. Solar energy provides heat through a Parabolic Trough Collector (PTC) array and supplementary electrical power via fixed Photo Voltaic (PV) panel array. Heat transfer occurs via synthetic thermal oil in a liquid-to-air crossflow heat exchanger, while a subterranean, packed granite rock bed Thermal Energy Storage (TES) system provides short-term heat to the chamber during solar unavailability.

Modelling indicates screening waste with an initial 30% residual moisture content of 18.5 kg could be completely dried within 15 minutes based on average air temperature of 67°C and air velocity of 2 m/s saving an estimated $6000 in annual disposal costs alone. Additionally, the TES system could supply 60°C heat for 60 minutes after a 90-minute charging period. These results imply that the proposed dryer design offers a viable and sustainable solution to reduce residual screening waste moisture using renewable solar energy in southeast Queensland.

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1 Introduction

1.1 Research summary

Solid non-organic inlet screening waste from the initial filtration stage at wastewater treatment plants has been investigated finding that this waste type contains high amounts of water increasing its weight. Screening waste is a heterogenous mixture of sanitary textiles, paper, vegetal, and inert fractions which is difficult to separate. In almost all cases, this waste is disposed at landfill contributing to environmental damage and increasing operational costs from the excess moisture content.

This research has focused on Southeast Queensland where standard practice is to mechanical dewater the waste before disposal. Research finds that ~30% residual moisture is still present in the waste mixture. The objective of the solution is to decrease the moisture content of the non-organic materials, thus reducing the overall weight of waste destined for landfill. However, thermal drying is an energy intensive process, but this could become sustainable by using solar energy instead. As such, a solar-assisted dryer design solution is proposed.

A literature review was undertaken exploring screening waste finding potential beyond disposal. Furthermore, a broad investigation in solar energy, technology, fundamental equations and its uses to produce thermal heat and electricity has been outlined. Following this an overview of drying phenomenon and mechanical design has been researched.

In absence of a standardised solar dryer design methodology, this research has adapted a design framework which identifies problem, defines the problem, generates solutions and evaluates design proposals. Various methods including extensive literature review, reverse engineering of similar systems, functional analysis, block diagrams, objective tree, brainstorming, morphological matrix, SWOT, fundamental calculations and weighted decision matrix have been used in an iterative process to present a conceptual design.

Moreover, a local southeast Queensland wastewater treatment plant has been used as a case study to provide realistic limits of the design including local climate conditions, solar irradiation, panel orientation, waste quantity and physical area.

Several conceptual system designs have been presented and evaluated against design criteria. The most suited design is then numerically modelled to provide indicative system performance including drying temperature, heat storage, electrical power and waste drying rates. Furthermore, the proposed system has been analysed providing the basis for proof of concept at the detailed design stage.

A proposed novel multi-levelled hybrid system which uses forced heated air in a rotary drum dryer to dry waste. Solar energy provides thermal heat through a single axis tracking Parabolic Trough Collector (PTC) and electricity via a fixed Photo Voltaic (PV) panel arrays. Heated synthetic oil transfers thermal heat to a liquid-to-air crossflow heat exchanger to heat the drying chamber. A subterranean Thermal Energy Storage (TES) system consisting of a packed granite rock bed provides short-term heat to the chamber during solar unavailability.

Modelling shows that daily screening waste with a residual moisture content of 18.5 kg could be completely dried in around 15 minutes based on average 67°C and 2m/s air velocity. The TES system can provide a discharge heat of 60°C for an hour after charging for 90 minutes.

1.2 Background

Sanitation is vital for public health, preventing diseases and environmental damage. Wastewater, originating from homes, businesses, and industries, undergoes treatment at Wastewater Treatment Plants (WWTPs). The objective is to remove pollutants and pathogens, producing clean water for various uses. Treatment involves serval stages of filtration to remove solids from water but does not treat the waste that is captured. Current research predominantly focuses on the management of the substantial quantity of organic solid waste produced at WWTPs known as sewage sludge or biosolids. However, other larger, non-organic solid filtration waste, such as primary inlet screenings have been broadly overlooked.

Primary screening waste is akin to municipal solid waste (MSW). It comprises of sanitary items, paper, cardboard, vegetation, plastics, hair, and metallic materials. This material poses challenges due to its variable production, diverse composition, high organic content, and elevated moisture levels. Disposing of screening waste is conventionally either landfill or incineration, to date there is little consideration of alternative methods. Despite constituting only, a small fraction (approximately 2%) of the waste generated by WWTPs, the vast global number of WWTPs - estimated to be over 100,000 - results in a substantial volume of unmanaged screening waste. Sending waste to landfills amplifies transportation generated greenhouse gases (GHG) emissions and operational expenses due to the added weight and volume caused by its elevated water content. When disposed, it can assist the release of harmful landfill liquids, known as leachate into the environment. Furthermore, when incinerated, the excessive moisture also hinders combustion, demanding extra energy to fulfil the process. Considering this, sustainable solutions, such as waste recovery and reuse, have been suggested, but this also requires moisture reduction for viability. In all cases, lowering screening waste moisture content is beneficial.

Drying waste is an emerging concept that offers a management strategy to address some of the challenges related to landfill disposal and incineration. In MSW, it also serves as a pre-conditioning step for other renewable options, such as Solid Recovered Fuel (SRF). However, drying methods often conflict with sustainability principles, particularly for large commercial quantities as used within the food industry, where drying processes traditionally demand substantial energy input. To mitigate this energy consumption, renewable sources like solar energy, have successfully assisted drying food products and reducing moisture in wastewater biosolids on a large scale. Moreover, integrating renewable energy, such as solar, either directly or through solar assistance, has the potential to render the drying process sustainable.

1.3 Research Gap

Based on the literature examined, there is little alternative research in the waste management solutions of the initial screening stage other than disposal. As such, solar drying has never been suggested for WWTP screening waste. This research could potentially provide a design approach in response to the gap identified, especially in nations with abundant solar energy resources like Australia. This research will investigate, propose and conceptual design a solution utilising solar drying techniques to reduce residual moisture in screening waste captured at WWTPs.

1.4 Aim

This project will investigate, analyse, identify design opportunities to provide a solar drying solution for solid non-organic waste that is captured during the initial filtering process in municipal WWTPs. The project will present and evaluate a conceptual design solution.

1.5 Objectives

The objective of the solution is to reduce the moisture in the non-organics that are captured in the screening process, thereby either reducing the weight of the waste to be disposed at landfill or enhance its suitability for combustion.

This project will involve initial scoping, definition, and evaluation of current designs and materials, identify any constraints and parameters, and finally proposes conceptual design options that may fulfil the design objectives.

1) Identify the composition, mass and volume of screening waste locally generated within Brisbane, Queensland.

2) Investigate the current wastewater screening processes and solar drying technologies available via a comprehensive literature review.

3) Determine the design parameters, considerations, and limitations.

4) Evaluate design ideas in response to identified criterion.

5) Propose and present a conceptual design solution.

6) Estimate moisture, mass, and volume reductions for screening waste using numerical modelling.

1.6 Expected Outcomes

WWTPs can serve as waste recovery facilities in the Circular Economy (CE), which promotes material reuse to alleviate natural resource strain and enhance environmental sustainability. WWTP are vital for a sustainable future offering clean water, energy, fertilizers, and nutrients (Silva, 2023).

Moreover, the Australian government has committed to the *Environmental Sustainability Policy* as part of the UN 2030 Agenda of Sustainable Development (Queensland Goverment, 2020). The research outcomes may provide Queensland WWTP facility operators with a new perspective on an enhanced and sustainable waste management approach for this waste type in relation to this policy. This research could begin to identify a suitable solar drying design. Benefits or such a design could lower operational expenses, transport emissions, landfill leachate, energy usage and fossil fuel dependency for WWTPs (Arachchige et al., 2019, Tun and Juchelková, 2019).

The outcome(s) of this research may provide Queensland WWTP facility operators a new perspective on sustainable waste management. In addition, it may provide a pathway for future waste to energy research for this waste type within Southeast Queensland and other similar climatic regions.

2 Literature Review

Through an extensive review of the literature there is little research surrounding WWTP screening waste. Thus, this review has focused on current MSW drying methods due to their similarities with screening waste. Although this research is also limited. The drying process, using both solar and non-solar technology, is predominately associated to the commercial food and agricultural industries to preserve produce. Consequently, some of the extensive literature with food drying has needed to be included in this review. Food drying research has focus on optimising ways to dry efficiently to improve the dried product quality and value. In contrast, this research is focused on the reduction of moisture and volume within screening waste, drying quality is not important. But the mature technology and methods used in the food industry, particularly with regards to solar energy provides a context for waste drying. Moreover, the literature finds considerable research has been conducted on drying methods for biosolids. While the composition and volume of biosolids differ significantly from screening waste, the current application of drying on a large scale with a focus on moisture reduction and its deployed use at WWTPs remains relevant to this project. Moreover, this review broadly investigates solar technology and its usage in relation to drying to seek an understanding of how this technology can be applied to a specific waste drying solution in south-east Queensland.

This literature review was developed through the following process: i) determine key words, ii) select database (Scopus and Google Scholar) and further modify keywords to zero in on area of interest, iii) develop a selection criterion with only most relevant research, iv) critically evaluate the value of the research.

2.1 Problem Context & Extent

Wastewater treatment involves several stages of filtration to remove solids from the water but does not treat the captured waste. Wastewater comprises of diverse substances from drains and toilets of homes, business, and industries. Adhikari and Halden (2022) explain that WWTPs are prolific worldwide with an estimated 109,000 WWTPs serving 2.7 billion people in 129 countries worldwide.

This is expected to rise year-on year with increasing urbanisation and population, thus increasing the disposal tonnage of waste generated (Adhikari and Halden, 2022). To date, the most significant endeavour is the management of captured solids from filtration has predominantly focused on organic waste, known as sewage sludge or biosolids. This focus is due to the substantial volume created, amounting to millions of tons annually, which necessitates treatment. Common methods for bio-solids are mechanical dewatering, thermal drying, and aerobic digestion (AD) before disposal (Perazzini et al., 2016). However, changing attitudes to wastewater is being realised whereby WWTPs are seen as a major resource and contributor to the circular economy (CE) but so far this has not been adequately explored (De la Torre-Bayo et al., 2022, Silva, 2023). Despite this change in perspective, the small fraction of filtration waste, known as primary inlet screenings, has been broadly overlooked in relation to sustainability. Current practices, in almost all cases means screening waste is either disposed in landfill or incinerated (Cadavid-Rodriguez et al., 2012). Considering this, the worldwide quantities of sustainably unmanaged screening waste provide an opportunity to present a solution to either better its disposal or consider alternative resource recovery pathways.

There is limited research in the literature surrounding the composition and generated volumes of this waste. Boni and collaborators (2022) found that this had been limited to primary composition and waste components for resource valorisation using anaerobic digestion ((Boni et al., 2022). Whereas, De La Torre-Bayo (2023) has investigated screening waste usage in Refuse Derived Fuel (RDF) (De la Torre-Bayo et al., 2023). The reviewed literature has focused on Europe including France, Spain, England, and Italy, and often in small samples and over a few (<3) WWTPs. Moreover, a larger scale study was noted by Mansour-Geoffrion et al (2014) in the United States of America encompassing 328 WWTPs but only in part. Nevertheless, screening waste data for localised conditions in Brisbane or Australia remain elusive. However, there is a common theme in the literature informs that there are major challenges facing sustainably management due to the screening waste composition, variability of volume generated, heterogeneity, and high moisture content (De La Torre Bayo, 2022, Perazzini, 2016, Cadavid-Rodriguez and Horan, 2011, Boni, 2022).

Therefore, it is necessary to understand these factors and relate the literature to an Australian context to provide a solution.

2.2 Screening Waste Composition

Screening waste composition fractions have been found to be consistent but depend on pre-screening methods, societal habits, sectors served, geographical location, weather, sewer type and length. De La Torre-Bayo and collaborators (2022) examined the characterisation of screening waste captured during initial filtration at a Spanish wastewater treatment plant (WWTPs). The paper provided insight into the composition, properties, daily, weekly, and seasonal variability. The primary fraction consisted of sanitary textiles (52%), fine particulates of <20mm (hair, inert debris, organic matter (26%)), paper/cardboard (12%), plastics (5%) and vegetal matter (5.5%) with minor fluctuations. They found that waste variability changed little over time and described as heterogenous mixture with a large percentage of organic matter content (61.6%) in its composition observing that the plastic and paper distributions akin to Mechanical Biological Treatment (MBT) reject fraction (De La Torre-Bayo, 2022). Whilst Boni and others (2022) categorised this waste as sanitary textiles, vegetal, paper/cardboard, textiles, metal, composites, fines, combustible, and incombustible components. Moreover, compatible waste composition and waste fractions have also been found in United Kingdom with Wild & Horan (2017), and in Italy and France with Boni (2022) research. Cadavid and Horan (2017) further observed the high sanitary textile fraction and noting the waste similarities to MSW (Cadavid and Horan, 2017). Boni (2022) research concluded was found that accurate predictions of screening waste are still not fully defined and suggests composition and volumes factors include type of sewer, length, different origins of wastewater's (residential, industrial etc) and societal habits (Boni, 2022). Furthermore, De la Torre Bayo (2022) research agrees with Boni (2022) findings but adds further factors including geographical location and the time-of-day influences screening waste composition (De la Torre Bayo, 2022).

Both Cadavid and Horan (2012) and De La Torre Bayo (2022) research also note the times when heavy rainfall washes leaves and general rubbish the waste stream when using combined sewer systems increasing the fraction and volume (Cadavid and Horan, 2012, De La Torre Bayo, 2022). However, both Boni (2022) and De La Torre Bayo (2022) find that there is no significant variation in composition over time. In combined sewers increase rainfall will increase screening volumes and some fractions such as vegetal matter and plastics but not sanitary waste. However, overall, the variation of composition is stable.

2.3 Waste Volume

Composition and waste volumes are influenced by screening mesh aperture size, whereby smaller mesh captures increased waste fractions and higher waste volumes. Silva (2023) explains that primary filtration can capture up to 60%-80% organic and non-organic solid waste items during wastewater treatment (Silva, 2023). Furthermore, Mansour-Geoffrion and others (2014) reported solids content of screenings can vary between 10 and 50% in a large scale North American study (Mansour-Geoffrion et al., 2014). De La Torre-Bayo and others (2022) reported that 6- and 3-millimetre apertures capture 0.53 and 3.49 kilograms per year per inhabitant equivalent $(kg\ (year\ IE)^{-1})$ respectively at three French WWTPs in 2009 (De La Torre-Bayo et al., 2022). Whereas Cadavid-Rodriguez and collaborators (2022) reported that standardised 6-millimetre apertures in the United Kingdom was observed to capture up to 20 dry kg/ML, or 2.19 to 8.40 $(kg\ (year\ IE)^{-1})$ (Cadavid-Rodriguez et al, 2012). They further suggested a waste per capita for France, United States of America, and United Kingdom, however, given the age of the study and he variability of waste volumes this is not reliable. Significantly, Boni's and scholars (2022) found that two Italian WWTPs generated 1714 and 13,361 tons of screening waste in 2017 confirming the European range observed in another historical research or 0.78 to 2.62 $(kg\ (year\ IE)^{-1})$ (Boni et al. 2022). Of significance, an approximation in local south-east Queensland conditions of 20 kg/ML dry weather (Wilson & Thomas, 2009). Wet weather conditions can increase the waste volumes. De la Torre-Bayo (2022) notes the "first flush" effect (De La Torre Bayo, 2022). While Cadavid and others (2012) suggesting this can be up to seven times the dry volume captured (Cadavid-Rodriguez et al., 2012). Moreover, bulk density was found to be broad but consistent. Cadavid-Rodriguez and scholars (2012) proposes average density estimated to fall within the range of 600-900 kg/m^3 in Spain (Cadavid-Rodriguez et al., 2012). Whereas Mansour-Geoffrion et al. (2014) reported a broader solids bulk density of screening waste in the range of

510-1100 kg/m^3 across French (510-1000 kg/m^3), British (600-900 kg/m^3), and American research (600-1100 kg/m^3) (Mansour-Geoffrion et al. 2014). Correspondence with a water and sewage utility in south east Queensland (2024) estimated a 240 kg/m^3 bulk density after using a washpactor machine for dewatering and compaction, but density was acknowledged to significantly varying depending on the exit separation (J Adams 2024, pers.comm., 3 March) Although differing methods of waste quantifying is used, and number of screening samples collected, this indicates high variability of waste volumes from capture rates which is specific to locality and population served. Screening mesh aperture size impacts waste volumes which is highly variable from the literature. This demonstrates the significant generation of this waste type. All these scholars identified that composition depends on largely on societal habits, weather patterns, pre-screening methods, filter mesh aperture size and geographical location.

		UKWIR (2000)	Le Hyaric (2009)	Le Hyaric (2009)	MOP 8 (WEF, 2010)	Canler & Perret (2004)	Metcalf & Eddy (2014)
Parameter	**Units**	Literature review and field study	Literature review	Field study	Survey of 328 U.S. WRRFs	Literature review	(Handbook)
Quantity	L/capita·year	3.7 - 11.0	1.3 - 18.8	--	5.6	1.1 - 16.5	--
	kg/capita·year	--	1 - 15	1 - 2.5	4.5	--	--
	L/m^3 wastewater	--	--	--	0.74 - 148	--	4 - 100
	kg/m^3 wastewater	--	--	--	0.01 - 0.3	--	--
% Dry solids	uncompacted	10 - 20%	10 - 30%	15%	10 - 20%	8%	10 - 50%
	compacted	--	20-45%	30%	--	--	
Bulk density	kg/m^3	600 - 900	600 - 1000	510 - 800	600 - 1100	--	600 - 1100
Volatile fraction (f_{VT})	g X_{VSS}/g X_{TSS}	0.80 - 0.90	>0.80	0.77 - 0.88	--	0.86	--
Calorific value	kJ/kg	15 X 10^3	6 - 25 X 10^3	--	--	--	--

Figure 1- Summary of quantities and characteristics of screenings collected (Mansour-Geoffrion et al. 2014).

2.4 Waste Moisture

Screening waste is characterised by high moisture content which increases the weight and volume of the waste during disposal transportation, impedes incineration, contributes to landfill leachate, and devalues reuse. In disposal of screening waste increases transportation expenses and travel frequency due to the increased weight and volume caused by high water content (De la Torre-Bayo et al., 2022).

Whereas, on-site incineration is also impeded by excessive waste moisture, increasing energy consumption to fulfill combustion (Arachchige et al., 2019). Both Cadavid-Rodriguez (2012) and De La Torre-Bayo (2022) observed that initial screening moisture percentages were 70-85% but noted that this was dependant on local climate, the type of filtration screen used and the subsequent dewatering process. Screening waste can be partially dewatered through commercially available mechanical equipment such as screw screen conveyors or sluices, which can both reduce the waste moisture and transport the waste to onsite disposal bins. Such equipment is reported to reduce initial moisture content by up to 35% (Filquip Pty Limited, 2023). Whereas a local water utility company uses a washpactor system which claims a higher moisture removal rate to 40-50% (J Adams 2024, pers.comm., 3 March). Cadavid Roriguez and others (2012) explains whilst this illustrates the effectiveness of currently used screening dewatering equipment, it also highlights that a significant portion of disposal expenses and energy is linked to waste moisture handling (Cadavid-Rodriguez et al.2012). Depending on the combination of equipment used at a given plant will affect the moisture content of waste at the disposal bins and the energy used in the process.

Furthermore, Wid and Horan (2017) observed that dewatered screenings still have high moisture thus unsuitable for landfill. They suggest a minimum 25% dryness to prevent transportation spillage and reduce disposal costs associated with waste mass (Wid and Horan, 2016). Consequently, when buried, this excessive moisture discharges as detrimental landfill leachate into the environment (Arachchige et al., 2019). While Cadavid-Rodiguez and others (2012) note that the high organic fraction within the screenings affects the waste classification resulting in higher disposal costs (Cadavid-Rodiguez et al., 2012). Tun (2018) adds further explaining that the elevated organics in landfilled waste biologically breakdowns over time generating uncontrolled greenhouse gases (GHGs) emissions. (Tun and Juchelková, 2019). Overall, it is found the reduction in moisture is beneficial to the chosen destination of this waste. Drying serves as a pre-treatment method in both disposal and resource recovery.

2.5 Mechanical Dewatering

In solar drying, knowledge of the moisture content currently achieved is instrumental for any design proposal, whereby a solution can complement existing plant process or serve as a substitute. Mechanical dewatering is the process of using mechanical force to remove moisture from paste or slurry type products.

Dewatering is a common practice and is the initial step in the drying of wastewater sludge (Gregor et al., 2013). There are many types of commercially available machinery that produces a dewatered filter cake using methods including filter presses, centrifuges, and belt presses. For screening waste, both Cadavid-Rodriguez (2012) and De La Torre-Bayo (2022) suggest raw moisture percentages of 70-85% depending on the climate, type of screening (i.e. residential, industrial) and the dewatering process (Cadavid-Rodriguez et al., 2012, De La Torre-Bayo, 2022). Furthermore, Gregor and others (2013) investigated screening waste dewatering in response to German law requiring <45% moisture container before disposal, highlighting the common use of wash presses for organic, mass and volume reductions. Their research finds that slow gradual pressing by piston press was able to dewater raw screening samples to 47% dry weight. Moreover, they find their piston force of 0.3MPa dewatered a sample by 45% moisture. However, they also found that at a given point, the increase piston pressure only offers small dewatering gains, noting from 3MPa to 6MPa only 6% of extra water is removed (Gregor et al., 2013). Moreover, a water and sewage utility in Southeast Queensland describes the current use of a Washpactor dewatering device that delivers 40-50% dry solids at 240kg/m^3 (J Adams 2024, pers.comm., 3 March). Similarly, another local water and sewage utility uses a German made Kuhn KWP Wash press to deliver 40-45% dry solids which reports a waste weight reduction of 70% (M Kuliszer 2024, pers.comm., 18 March). Gregor's results are like those of the existing dewatering machines noted by local utility operators, noting that 45% is deemed viable.

Thermally assisted mechanical dewatering (TAMD) is an improved method combining both elevated temperatures and pressure. Solar energy could be used to prove thermal energy. Cellulose is a prominent part of sanitary textiles fraction in screening composition. Mahmoud and others (2008) experimentally modelled cellulose dewatering finding optimum temperature was 90.2°C and pressure 2993 kPa resulting in 64% dry solids. They find large part of the water (55%) is removed by mechanical means at low pressure, further dewatering at high pressure and temperature will only release 9% water (Mahmoud et al., 2008). The varying particle size and material properties of mixed screening waste has not been studied. Moisture removal by mechanical force can provide a predictable moisture content. Solar derived electricity and thermal energy can help to improve this process in dewatering of screenings.

2.6 Disposal and Recovery

Drying reduces waste moisture content, this not only benefits disposal but also assists in waste valorisation for energy recovery. De la Torre Bayo (2022) highlights the paradox in European WWTPs who are identified as and aim to be key contributors to the circular economy with plants looking to generate energy and targeting zero waste. Despite this, large volumes of primary inlet screenings are landfilled with no alternatives (De la Torre Bayo, 2022). Disposal of this waste type is by two main methods, incineration, and landfill. The literature finds that the preferred method of waste management for screening waste is landfill disposal (Boni et al., 2022). Disposal of screening waste leads to increased transportation expenses and frequency due to the significant weight and volume caused by high water content (De la Torre Bayo, 2022). Hamilton (2020) explains that in their investigation of MSW disposal in Victoria, that transport costs were calculated to 0.13-1.35 $AUD/Km/t for biomass, noting a 500 km journey by rigid truck was $672 and articulated truck $96 (Hamilton et al., 2020). Additionally, waste is charged by type, the high moisture of screening waste results in its classification of a specialled waste type that attracts higher disposal fees (Wid and Horan, 2016). Moreover, when MSW or the like is buried, excess moisture ultimately leads to the discharge of detrimental landfill liquids, referred to as leachate, into the environment (Arachchige et al., 2019).

The alternative of waste incineration is the least preferred waste management option and is governed by strict regulations to ensure both environmental and public health is protected. Incineration results in significant reductions in mass (80-85%), volume (95-96%) and moisture content, rendering it a feasible choice for further diminishing non-organic solid waste (Bazregari and Norouzi, 2022, Tun and Juchelková, 2019). However, it raises significant environmental concerns due to toxic emissions (Silva, 2023). Locally, in Queensland, thermal combustion of waste is illegal (Environmental Protection (Waste Management) Regulation 2000).

Both landfilling and incineration represent costly processes with significant carbon footprint (Cadavid-Rodriguez et al., 2012). Tun and others (2020) urges countries with high solar should utilise solar energy for MSW drying to either create SDF or reduce moisture volume for safe transportation and landfill disposal (Tun and Juchelková, 2019). Even without alternatives to disposal, waste drying would be beneficial. Using renewable energy such as solar would help drying to be a sustainable solution.

2.7 Waste to Energy (WtE)

Waste to Energy (WtE) finds fuel resources from waste and uses it to offset conventional energy processes. This is unlike disposal that does not extract any energy from waste. Hamiliton (2020) explains there are five types of waste to energy conversions including pyrolysis, gasification, digestion, combustion, and torrefaction (Hamilton et al., 2020). The literature review has omitted the latter two types since combustion is briefly explained within Solid Derived Fuels (SDF) and torrefaction, a slow type of pyrolysis (<300°C) needs careful temperature control to fulfill the process whereby solar energy variance is anticipated to cause difficulties to be a useful method. In general, gasification of MSW is an emerging solution requiring more investigation. However, gasification of screening waste has not been reviewed in this paper.

2.8 Pyrolysis

An alternative WtE method without emissions is pyrolysis, a high-temperature process (425°C to 600°C) in the absence of oxygen which thermally degrades waste yielding bio-oil, syngas, and char residue for use as either fuel feedstock or as a reduced solid to dispose at landfill. The high heat input requirement has been suggested using solar energy through Concentrated Solar Power (CSP) for waste pyrolysis in regional Victoria, Australia (Hamiliton et al., 2020). Whereby, CSP directly transfers solar energy as heat. Hamiliton and others (2022) found through comparison modelling that CSP and slow pyrolysis offered greater energy in the liquid fuel produced and high energy transfer efficiency utilising screw conveyor to transfer waste and seal the chamber from oxygen (Hamiliton, 2020). Moreover, Fisher and collaborators (2021) research they introduced a solar thermal disinfection system using parabolic solar concentrators and fibre optics to direct Concentrated Solar Power (CSP) for the pyrolysis of faecal waste (Fisher et al., 2021). The small-scale experiment only reached a maximum temperature of 210°C in 90 minutes for a small sample, it does however demonstrate a potential for scalability in both pyrolysis and various heating applications through CSP. (Fisher et al., 2021). Moreover, Al-Ghouti (2021) notes that the quality of the fuel output from pyrolysis depends on the waste input, and for MSW, mechanical preparation and separation of inert components like glass and sand would be required. Moreover, at present, MSW pyrolysis is limited to small-scale due to the heterogenous composition of the waste (Al-Ghouti et al., 2021). In contrast, solar pyrolysis is a challenge due to solar intermittency for continuous operations finding 5-20°C increase per minutes can mean several hours of heating up to the required 500°C (Hamilton et al., 2020). There is no literature on screening waste pyrolysis, its volume is less, and its inert composition is different to MSW (i.e. no glass, e-waste etc). However, its solar variance and long residence time is a challenge. CSP can directly transfer solar heat via fibreoptics instead of using conventional working fluids and the screw conveyor would be able to contain odour and pressure.

2.9 Recovery -Biological (Biogas)

Studies have identified different methods for screening waste valorisation highlighting the importance of exploring how solar energy can support these processes. Sustainable solutions for managing waste screenings have been proposed through resource recovery and reuse (De La Torre-Bayo et al., 2022). Anaerobic Digestion (AD) to produce biogas has been suggested in the literature as a solution for this waste type owning to the high organic content. (Wid and Horan 2017, Boni 2022). Cadavid and Horan (2012) laboratory research found that this method could reduce 466kg of each screening waste tonne to landfill, offset 4.6 tonnes of carbon dioxide emissions and could produce 3.4MWh in renewable energy. Whilst promising for energy recovery it was noted that the heterogenous mixture caused operational problems for the mesophilic biodigester and would require pre-screening of plastic and sanitary textiles (Cadavid-Rodriguez et al., 2012). Moreover, this was also noted in both De La Torre Bayo (2022) research and Wid and Horan (2017) research finding that high sanitary textile content can impede the digestion process suggesting staged screening to separate waste fractions (De La Torre-Bayo, 2022, Wid and Horan, 2017). Furthermore, Tun and others (2018) research into MSW drying improvement in developing countries finds that while AD method is suitable for waste mass reduction to minimise landfill quantities due to its low cost, they also note the requirement of long residence time to fulfill the process (Tun and Juchelková, 2019). The temperature for required AD mesophilic process is a controlled 37°C ±2°C with residence time of up to 20 days (Wid and Horan, 2016, Boni et al., 2022). Further biological methods include waste bio-drying, a process of organic aerobic decomposition promoted by forced aeration producing biological heat to dry the waste. Operating at temperatures between 40 to 70°C with residence time of 7-15 days. This can be achieved by passive solar energy methods, using internal heat in greenhouses without solar collector but increases residence time (50% volume reduction in 12-30 days (Tun and Juchelková, 2019). Also, biological digestion serves only to separate the remaining non-organic solid fraction residue*.* Ragazzi and others (2007) note the benefits of the process of not needing external fuel but equally that large onsite storage volumes may be needed in continuous operations. Significantly, the paper highlights that bio-drying removes the recoverable energy from the waste source (Ragazzi et al., 2007). Biological methods can be used to reduce waste moisture and volume over long residence periods at low cost with support of solar energy for controlled heating However, the reduction in drying times is desirable in continuous plant operations and variable volumes such as screening waste.

2.10 Waste to Value -Solid Recovered Fuel

Alternative fossil fuel energy options like Solid Recovered Fuel (SRF) from waste represent a potential solution. SRF can be used as a substitute for fossil fuels in industrial combustion processes such as kilns and boilers. It reduces landfilled waste while providing an alternative fuel source, decreasing fuel and disposal cost. De la Torre-Bayo et al and collaborators (2023) found in their experimentation of screening waste SRF that the ideal maximum moisture content was <20% (De la Torre Bayo, 2023). As discussed, waste incineration is an environmental concern due the release of toxic emissions. SRF is a filtered waste that meets certain criteria including required heating value, moisture content, and the percentage of contaminants as these cannot be fully removed. Chavando and others (2022) explain in their snapshot review of SRF identify standards noting UNE-EN15357:2012, CEN-EN 15359 and ISO/TC 300-Solid Recovered Fuels (SRF). Australian standards were notably absence in this research despite identifying the Asia Pacific region a high growth market for Waste to Energy (WtE) (Chavando et al., 2022). De La Torre Bayo (2023) investigated SRF for screening waste by evaluation current European SRF standards and analysing waste samples. They explain that SRF is associated with MSW, whereby the composition may include rigid plastics (PVC) which when burnt can lead to the emission of chlorine (Cl) which damages combustion equipment through fouling and corrosion. Additionally, some MSW fractions include mercury (Mg) which can be released as a toxic emission when burnt. The key findings found sanitary textiles plastics possess low Cl content, Mg content was within SRF classification limits <2.08 (mg/MJ) and ash content, influenced by inert fractions was also in range of SRF standards (De La Torre Bayo, 2023).

	Properties				
Uses	**LHV[a] (MJ/kg)**	**Cl (%)**	**Hg (mg/MJ)**	**Ash (%)**	**M[b] or Mp[c] (%)**
Cement plants	15.6–32.4	0.05–3.89	N.S.[d]	5.27–30.60	1.4–35.0
EfW[e]	13.24–32.98	0.10–1.16	0.001–0.209	7.40–23.60	3.8–34.1

Figure 2- Reference range values of Lower Heating Value (LHV) for Solid Recovered Fuel (SRF) (De La Torre-Bayo, 2023)

Solid Recovered Fuel (SRF) is a method to reduce volume and mass of the waste and provide a product of energy value. Notably, Ngamaket and others (2021) explains MSW SRF from solar assisted greenhouse bio-drying in Thailand was valued at $30 (AUD equivalent) per waste tonne. They found the energy standard is adequate for local cement producers, but the high moisture content (30%) rendered this product unsuitable in their pilot scale experiment (Ngamket et al., 2021b). Moreover, Chavando and others (2022) found that ASTM designation of RDF- 4 and RDF-5 for combustion could derive $133 to $174 per tonne (AUD equivalent) in the European market. However, these fuel classification require further processing into powder or pelletised form and requires moisture removal through drying (Chavando et al., 2022). This links with De la Torre Bayo (2022) and Perazzini (2016) research into SRF noting that decreasing screening waste moisture adds value in resource recovery (De La Torre Bayo et al., 2023, Perazzini et al., 2016). Moreover, the separation of the waste into individual fractions can help the drying process (Wid and Horan, 2016). However, Bhatsada and scholars (2023) explain that while both thermal drying and mechanical separation can quickly reduce moisture in MSW for SRF production it is often not cost-effective process (Bhatsada et al., 2023). The literature explains that SRF is a viable valorisation method for this waste type providing both economic and environmental benefits compared to current disposal practices. Renewable solar drying can assist in reducing moisture content to <20% to develop a sustainable fuel source for industry.

2.11 Solid waste drying

Drying reduces moisture to benefit disposal or add value to waste streams. However, drying is typically energy intensive particularly in large industrial operations.

Ortiz-Rodríguez and others (2022) find that the agriculture & food sector dominates industrial drying and is estimated to be responsible for 3% to 7.5% of global energy consumption. Additionally, they identify other industries such as automotive, rubber, cement lignite/coal, paper, textile, sugarcane, and wastewater treatment (biosolids) also use large scale drying finding that thermal heat drying is used with conventional fossil fuels (electricity, gas, coal, diesel) resulting in fast drying times at the expense of high energy consumption (Ortiz-Rodríguez et al., 2022).

Perazzini and collaborators (2016) explain that commonly solid drying uses thermal hot air drying, bio-drying, rotary drying, and tunnel drying methods. They further add that other methods have been investigated including fry-drying, infra-red (IR) heat, thermal jet drying (TJD), microwave energy, pulse combustion drying (PCD) and the direct use of superheated steam (Perazzini et al., 2016). Further to this, Tun and Juchelkova (2019) research reviews the common MSW drying methods in developing countries finding bio drying, thermal and solar drying are used often utilising renewable energy to lower costs. They further explain key considerations for a waste dryer is economic and environmental costs (Tun and Juchelková, 2019). This is significant as local conditions, energy and affordability are factored within the research providing examples of low-cost solutions in line with the waste value. This contrasts with the extensive food drying literature that focus on value through dried product quality. Moreover, this links with Perrazini's (2016) and De La Torre Bayo (2023) idea that waste has little to no environmental or economic value until moisture is removed. Hence, the value-add process of resource recovery, reuse or disposal needs to be identified to determine suitable costs of a dryer. Tun and scholars (2019) further explain that dryer economic factors are waste disposal costs which include transportation and disposal fees and value addition through sale of product or mitigation of conventional fuel purchases Whereas, they inform that environmental cost factors are pollution reduction, GHG avoidance and reduce dependency of fossil fuels (Tun and Juchelková, 2019). These scholar neglect to consider additional equipment may be needed for recovery processes. Various solid drying methods underscore the importance of considering economic and environmental cost in waste drying process. Moisture removal reveals waste value, and a drying solution should be determined by the appropriate dryer intent and its relative cost.

Solid waste drying is complex due to the heterogeneity of the screenings with each fraction type suited to a drying method. Perazzini and scholars (2016) explain that solid waste drying is intricate due to waste materials' diverse properties including size, shape, porosity, surface area, specific heat, and mass (Perazzini et al., 2016). However, common key factor in the literature noted by was hydrophilicity, which describes the way in which moisture interacts with a solid material thus affecting how the moisture is removed during drying. Non -

Hygroscopic materials (organics) can completely lose free moisture through constant drying whereas hygroscopic material (stone, paper, and textiles) having both free and bounded internal moisture cannot. Bounded moisture is difficult to remove requiring a regime of decreasing drying rates to dry the unbounded moisture first followed by the bounded moisture (Ortiz-Rodríguez et al., 2022). Furthermore, these scholars find that these properties significantly influence heat and mass transfer during drying, making each waste type drying solution unique (Tun and Juchelková, 2019, Ortiz-Rodríguez et al., 2022, Perazzini et al., 2016). Perazzini (2016) further adds that the selection of the appropriate drying method for solid waste requires studies considering material characteristics, final product goals, and operational costs (Perazzini et al., 2016). Solid waste drying methods for screening waste is intricate due its diverse properties influencing heat and mass transfer.

2.12 Drying operations

Heterogeneity of the waste can make finding a drying solution challenging. Food drying items are homogenous mixture of solids, the function of drying in this case is to preserve or obtain value through the process. This differs from heterogenous waste whereby drying quality, uniformity and appearance of the dried product is negligible. In food drying, drying occurs often as one product type. Whereas, in waste drying there is a mixture of solids, comprised of varying material properties which influence the drying process. The literature notes the advantages of waste fraction separation such as inert, which can offer faster drying and increased heating efficiency in comparison to bulk mixture drying (Cadavid-Rodriguez et al., 2012, Tun and Juchelková, 2019, De la Torre-Bayo et al., 2023) Tun and others (2019) also suggest the addition of dry organic carbon bulking agents such a leaves, straw and woodchips add porosity promoting heating through the mixture enhancing drying predictability and efficiency (Tun and Juchelková, 2019).   Furthermore, there has been numerous studies on anerobic digestion for screenings. This is a separation process used within Mechanical Biological Treatment (MBT) of MSW whereby organic fraction digestion leaves the inert portion behind. Wid and Horan (2017) found that the high sanitary textiles, such as disposable cotton wipes impede anaerobic digestion and recommends pre-screening for their work on resource recovery. On the other hand, they also noted this causes onsite storage difficulties (Wid and Horan, 2011). However, for the dominant fraction of sanitary textiles has its own composite fractions whereby its separation is challenging. De La Torre Bayo (2022) describes the plastic items within the primary sanitary textiles fraction reporting that they are composed of cellulose and synthetic fibres containing plastics such as high-density polyethylene (HDPE), polyethylene-vinyl acetate (PEVA), polypropylene (PP) and polystyrene (PS) (De la Torre-Bayo et al., 2022). Furthermore, it is found that this fraction is a mixture of hydrophilicity whereby polyethylene, polyethylene-vinyl acetate (PEVA) is hydroscopic whereas polypropylene and polystyrene are non- hydroscopic. As such, without separation this fraction will be dried as a waste mixture. Even in incineration, mass and volume are significantly reduced but it still produces residue that needs to be disposed of. In all cases, inorganics are found to be problematic when drying but the literature offers no solutions in its management.

2.13 Solar Drying

Drying is an energy intensive process, but the use of renewable energy means it can be both a cost effective and sustainable solution for moisture reduction in waste. Currently, the food industry is dominant industrial sector for solar heating systems, whereby it consumes approximately 30% of global energy and contributes to nearly 26% of Greenhouse Gas (GHG) emissions largely derived from fossil fuels (Ortiz-Rodríguez et al., 2022). The literature explains that renewable energy sources such as wind, geothermal, solar and biofuel can provide a complementary approach to supply and offset current drying energy consumption. Solar equipment is described as generally highly reliable and can be maintenance free (Fisher et al., 2021). Additionally, solar energy can be used to produce heat through solar thermal systems such as flat plat collectors, parabolic trough concentrators and evacuated tube collectors (Ortiz-Rodríguez et al., 2022).   Tun and Juchelkova (2019) compared waste drying of MSW in developing countries and found that solar energy is a suitable solution for countries with high solar irradiance. Additionally, they found that solar drying has higher temperatures, shorter drying times, the ability for work with or without external fuel (i.e hybrid), higher costs and a pre-treatment for resource recovery (Tun and Juchelková, 2019). Albeit this research had only been applied to the organic fraction of MSW at laboratory and pilot scale. Despite this, there is indication of the versatility of solar drying which can be tailored to meet drying demands from low-cost, readily available technologies to large scale, multi component systems for a solar waste dryer.

2.14 Solar Energy in Brisbane

Australia is abundant with freely available solar energy. Pordage (2021) explains there has been several large scale, private and government assisted multi-million-dollar solar projects for power generation in Australian WWTPs. This is utility operators’ response to the United Nations Sustainable Development Goals (SDGs). It is reported that South Australian (SA) Water is targeting a zero-cost future using solar power with energy storage to run equipment at WWTPs and feed the excess back into the grid for revenue (Pordage, 2021). Yan and scholars (2013) undertook a yearlong analysis of Photo Voltaic (PV) solar panel and found that Brisbane, located in South-East Queensland at latitude 27 degrees, averaged an annual solar exposure of 20 MJ per square metre (Yan et al., 2013). Furthermore, historical data shows that Brisbane experiences 280 rain free days with the mean daily sunshine of 8.2 hours on average (Bureau of Meterology, 2023). As such, Brisbane is suited to using solar as a renewable energy source.

To maximise the use of solar energy Yan and scholars (2019) explain the optimum tilt angle and orientation for fixed PV panels in Brisbane is 26 degrees facing true north. They noted theoretical performance of PV panels to experimental results is attributed to differences in shadings, reflections, and air flow (Yan, 2019).

2.15 Solar Energy Fundamentals

Solar energy capture requires an understanding of the sun’s position relative to the solar equipment position on the earth’s surface. Knowledge of proper orientation for solar collectors both tracking and non-tracking is an important consideration in any solar system design as solar incidence amounts to the solar energy collected. The following gives a brief outline of parameters of solar energy collection through Kalogirou (2023) textbook, *Solar energy engineering: processes and systems* (Kalogirou, 2023).

Kalogirou (2023) explains the observers position relative to the sun can vary dependant on geographical location and time of day. There are two corrections that need to be made before calculations. *Equations of time* are important to account for the differences between the suns position or *solar time*, and Earth's elliptical orbit and axial tilt. *Longitudinal correction* can be used to adjust these differences. *Day lengths* refer to the duration of daylight, which changes with time of year, at a given location due to change in latitude and axial tilt. This also ties in with *Sunrise* and *Sunset time* which determines the start and end of the day length.

The suns position changes with time and with the seasons, Solar angles are used to determine this position relative to an observed position on earth. *Declination (δ)* is the angle of solar rays and earths equatorial plane; this varies with the earth's tilt between (-23.45 to 23.45 degrees). *Hour Angle (h)* is the time of day as witness at an observer positions. It is the angular distance of sun to the meridian. An example of hour angle is 0° indicating solar noon whereby the angle is coincident with the meridian. *Solar Altitude Angle (α)* is a measurement of height of the sun above the horizon relative to the observer's position. *Solar Azimuth Angle (z)* is the direction of the sun, measured clockwise relative the observer's true north.

For solar energy collection, the *incidence angle* is the measurement of the sun's rays to the surface of a collector or panel. For non- tracking systems, the tilt angles the panel is set at a fixed but optimised position, collecting low solar energy and larger incidence angles. Maximum solar energy will be at $\varphi=0°$. Tracking systems continually move position to follow the sun they maximise the solar collection throughout the day by repositioning to minimise the incident angle. Solar tracking system are classed by their mode of motion through single axis or double axis. Single axis can be directional North-South or East-West tracking or polar axis angled to be parallel to earth's axis. Whereas double axis moves in both azimuth and elevation to always achieve $\varphi=0°$.

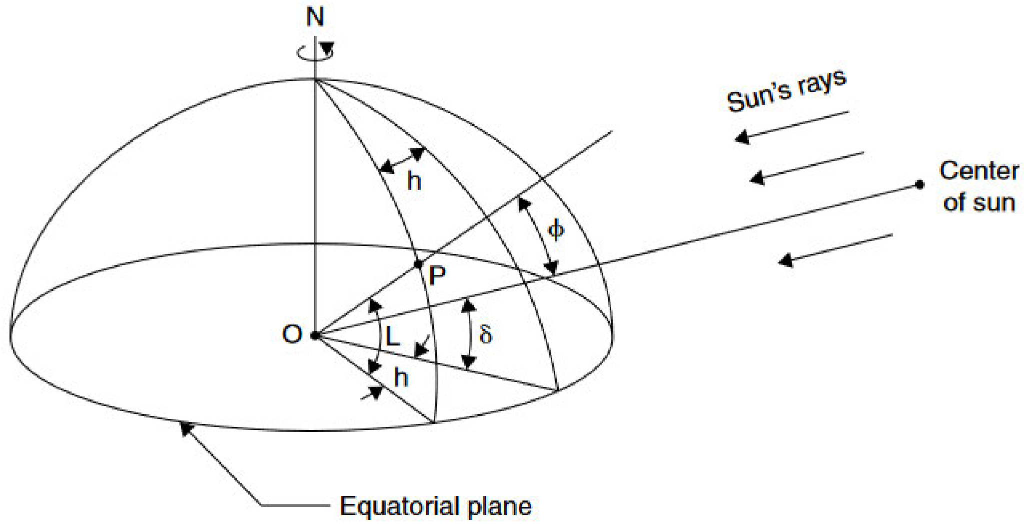


Figure 3- Ptolemaic model of the sun's movement restricted to 2 degrees of freedom for simplicity.
Taken from: *Solar energy engineering: processes and systems* (Kalogirou, 2023)

2.16 Food drying

Solar dryers are typically categorized by air movement mode, insulation exposure, airflow direction, dryer arrangement, solar contribution, and the materials to be dried (Tun and Juchelková, 2019). Mugi and others (2022) explains solar dryers in the food industry primarily use convection as heat transfer mechanism. Moreover, their research identifies two main categories: Natural Convection (NC) is a passive process whereby the movement of air occurs due to differences in air density with a drying chamber. Whereas Forced Convection (FC) is an active process whereby air movement is caused by powered fans (Mugi et al., 2022). According to Ortiz-Rodriguez and others (2022) solar thermal FC is most suited to industrial large scale solar drying for the food industry due to high drying rate. This is further improved when used with TES (Ortiz-Rodríguez et al., 2022). However, the rate of drying is less important for screening waste if it is at the expense of higher energy usage.

Currently, the primary solar thermal technologies utilized in food industry include flat plate collectors (38%), parabolic trough concentrators (20%), evacuated tube collectors (20%), and other available thermal technologies (22%) (Oritz-Rodriguez et al., 2022).

A brief description of the solar drying equipment is briefly discussed.

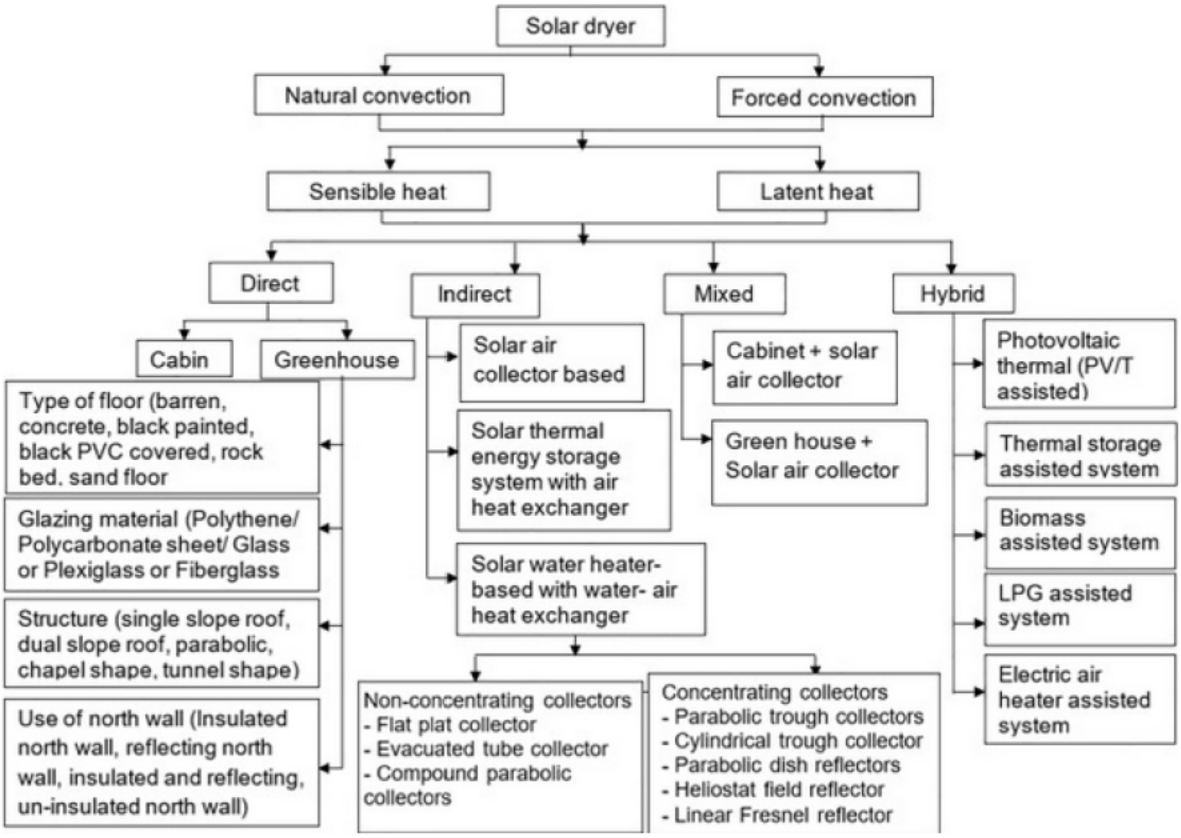


Figure 4 – Solar dryer types. Taken from Mugi and collaborators (2022)

2.16.1 Direct Solar Dryers (DSD) – Passive

Simple, low-cost, and directly uses incident solar radiation energy to dry the product. Open sun drying (OSD) is a commonly used age-old method. DSD improve on OSD by controlling the drying environment based on drying needs (Lingayat, 2021). Direct solar dryers such as greenhouses dry product through solar radiation and convection with internal temperature increase through the trapped heat. Oritz-Rodriguez (2019) explains that 90% of incident solar radiation, irradiated is at a different wavelength that cannot pass back through the greenhouse increasing internal temperature. DSD drying time is dependent and influenced to different proportions on factors including controllable initial product MC, volume, DSD exposure area and the uncontrollable weather conditions/ solar irradiation (Oritz-Rodriguez et al., 2022). DSD range from small to medium-sized drying cabinets or to large greenhouses, product volume is limited to the available surface area. Typically, the dryer temperatures are reported to be 30°C -60°C range (Lingayat et al., 2021).

2.16.2 Indirect Solar Dryers (ISD) - Active

Solar energy is used to with other equipment to heat fluid (air, water, or oil) and transfer heat indirectly by convection into a drying chamber. Two methods are natural convection or forced convection. Convection can be controlled if using forced fluid in the dryer tailoring moisture removal and heat transfer (Lingayat et al., 2021). Auxiliary equipment may include solar collectors, solar water heaters, heat exchangers, water tanks, ducts, pumps, and fans. Suitable for increase drying speed and large drying volumes but are more complex and have higher capital equipment costs to DSD (Oritz-Rodriguez et al., 2022). Furthermore, Tun (2021) explains experimental ISD have been used in the literature to dry food waste finding a 95% MC reduction, 30% weight reduction in 9 hours between temperatures of 22-100 °C (Tun and Juchelková, 2019). This research only offers limited solar drying insight for small scale MSW, however these findings display the potential of this dryer type in a standalone application, for example when no external power is needed. Once again, the implementation of TES allows for improved thermal performance in these dryers (Lingayat et al., 2021)

2.16.3 Mixed Mode Solar Dryers (MSD)

Applies a combination of both DSD direct radiative energy and ISD convective solar energy. An example is a greenhouse type drying chambers with forced air convection. The combination of the two methods increases moisture content removal rate to that of DSD alone (Lingayat et al., 2021).

Its difference to HSD, as MSD is the synergy effect of both DSD and ISD advantages improving drying times despite having not to use convectional energy, thus offering a low-cost solution.

2.16.4 Hybrid Solar Dryers (HSD)

Heated airflow for HSD is derived not only from solar energy but an auxiliary energy source. Typically, conventional energy such as electricity coal and LPG, but this can also be from other renewable energy such as biomass and waste heat This method can be used for high moisture, continuous drying as conventional backup energy is used during the night-time and cloudy days, thus is well suited for commercial applications. Hybrid dryers have a temperature range between 40°C - 80°C

Oritz-Rodriguez and others (2021) explains that HSD are ideal for loads exceeding 1000kg, although this necessitates extensive solar collector areas to ensure an adequate energy supply (Oritz-Rodriguez et al., 2022).

The system is more expensive due to the complexity and can require a specific design to meet the drying needs. However, additional equipment used in forced convection (FC) could use solar photovoltaic (PV) panels and electrical battery storage to operate fans without using conventional electrical power (Lingayat et al., 2021).

2.17 Solar Thermal Collectors

These devices collect and concentrate solar energy for drying. The literature has many differing ways to categories these systems. At high level, these solar collectors come in two main types, non- concentrating and concentrating. Of interest, Sakthivadivel and collaborators (2021) provides a broad overview in the fundamentals of solar energy technologies explaining non-concentrating STC with a temperature range of 100°C whereas concentrating STC can reach temperatures up to 400°C (Sakthivadivel et al., 2021). Higher temperatures can be achieved with centralised receiver towers and heliostat array (>400°C).

2.18 Non-concentrating

Oritz–Rodriguez and others (2022) explain that non-concentrating collectors also known as *Solar Air Collectors (SAC)*, absorbs solar radiative energy which is transferred by convection to heat air. Examples include Flat Plate Collectors

(FPC), Evacuated Tube Collectors (ETC) and Parabolic Trough Collectors (PTC). They report these collectors achieve temperatures of 30-100°C, 50-200°C, and 60-240°C, respectively. They further add that FPC and PTC are suited to locations with high solar irradiance whereas EPC can operate in temperate climates and are not reliant on direct solar irradiance to perform (Oritz-Rodriguez et al., 2022). Fixed collectors are suited for lower drying temperatures and are typically fixed at an angle to maximise daily solar irradiation through the year but can be adjusted for seasonal variations (+/- 10 degrees latitude). This differs from Sakthivadivel's (2021) research which can be explained as the general temperature average for the collectors not representative of the broad range reported in a review paper albeit at small experimental scale. Significantly, this highlights the versatility of solar collection technologies, there customisation to a drying need and the latest studies currently underway within this area.

2.19 Photovoltaic Solar Panels – Electrical energy

For solar assistance, PV panels can provide electrical energy. The photovoltaic (PV) effect found in semiconductor materials (such as silicon) caused by solar energy finds electrons within the material to become excited creating a electrical field and current flow. Electrical output is Direct Current (DC) and requires inverting for Alternating Current (AC) required by normal mains powered equipment. Panels offer versatility in design; they can be connected into large arrays to produce increased electrical power outputs.

Photovoltaic (PV) -thermal collector PVT – 20% of solar radiation is for electricity production whereas the remainder is transferred as heat. PVT is a combination but depends on collector length, cell density, duct depth and heat transfer fluid properties (sakthivadivel)

Kalogirou (2023) presents mathematical modelling of PV solar panel and identifies and explains the relationship between varying factors to allow for calculations (Kalogirou, 2023). Solar incident angle (θ) is the angle between solar rays and normal panel plane. Beta (β) is panel surface tilt angle with respect the horizontal. L is local latitude. This is noted by Yan et al, (2020) at (-27.47) degrees for Brisbane (Yan et al., 2020). N represents the day of the year. Z_s is the projection of normal to the surface on horizontal surface. As previously discussed, Solar declination (δ) id the solar ray's position to equatorial plane, for solar panels, it can be calculated from equation 1.

$$\delta = 23.45 * \left[\frac{360}{365} * (284 + N)\right] \tag{1}$$

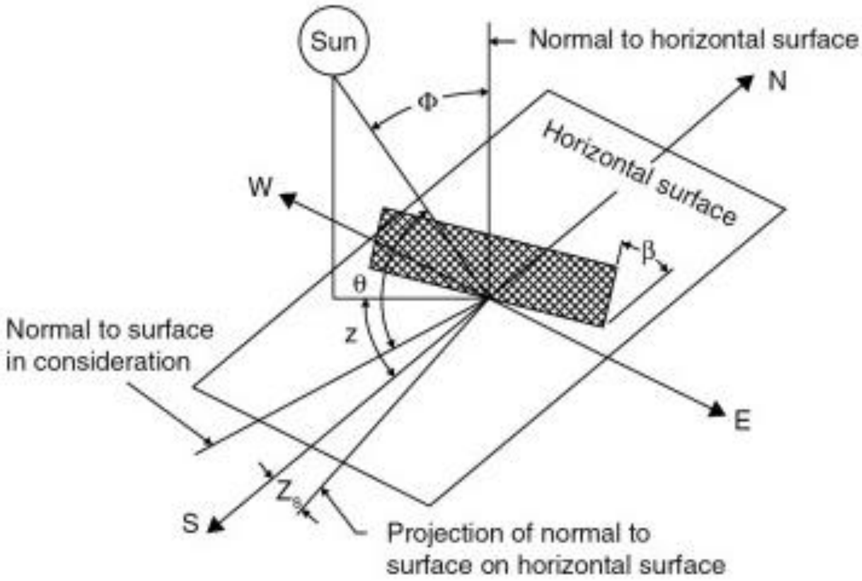


Figure 5- Figure of PV panel

Taken from Solar energy engineering: processes and systems (Kalogirou, 2023)

2.20 Concentrating STC

Concentrating collectors capture direct solar radiation and transfers it to a receiver, optically concentrating through mirrors and lenses by refraction or reflection. This achieves high temperature heat conversion thus higher efficiency for the same collector area to that of non-concentrating solar collectors. Concentrating STC examples include Linear Fresnel Reflectors and Parabolic Trough Collectors (PTC) which can achieve temperatures of 60-250°C and 60-300°C respectively.

PTC are made up of a long reflective mirrors concentrating reflected sunlight to the horizontal absorber tube which is covered with an insulating concentric transparent material to prevent heat losses. Working temperatures >400°C and can operate at high pressures (1.8MPa) with a solar concentration ratio of 30-100 (Hamilton et al., 2020). Linear Fresnel Reflectors use flat mirrors to focus onto stationary linear receivers in contrast to the single point of the PTC. They have working temperatures of 250-500°C with solar concentration varying between 25-100°C for single tracking systems. They can offer the similar performance as PTC but are cheaper due flat mirrors and lightweight construction (Hamiliton et al., 2020). Sustained high temperature systems require solar trackers and both types require clean reflective surfaces (Kalogirou, 2023). Parabolic Dish collector are large reflector dishes or arrays that concentrate solar energy to a single point. Working temperatures are reported as 3000°C with solar concentration of 10,000. They are disadvantaged by significant capital cost and large land requirements.

During Full axis tracking, the angle of incidence, θ must be minimised ideally to zero to continually face the sun, maximising the solar energy collected. For single axis tracking E-W polar and N-S horizontal are most consistent obtaining similar results as full tracking with N-S horizontal suffering poor performance in winter months shown in figure 6. Consistency of solar collection is desirable for the design, E-W tracking is also advantageous due to low shadowing when using in collector rows in large solar farm arrays for power generation. This could be used in the scale up of this conceptual design where collector rows are used in increase power or solar energy through increased collector area.

Tracking Mode	Solar Energy Received (kWh/m^2)			Percentage to Full Tracking		
	E	SS	WS	E	SS	WS
Full tracking	8.43	10.60	5.70	100	100	100
E–W polar	8.43	9.73	5.23	100	91.7	91.7
N–S horizontal	7.51	10.36	4.47	89.1	97.7	60.9
E–W horizontal	6.22	7.85	4.91	73.8	74.0	86.2

E = equinoxes, SS = summer solstice, WS = winter solstice.

Figure 6- Comparison of Energy received for various modes of tracking (Kalogirou. 2023)

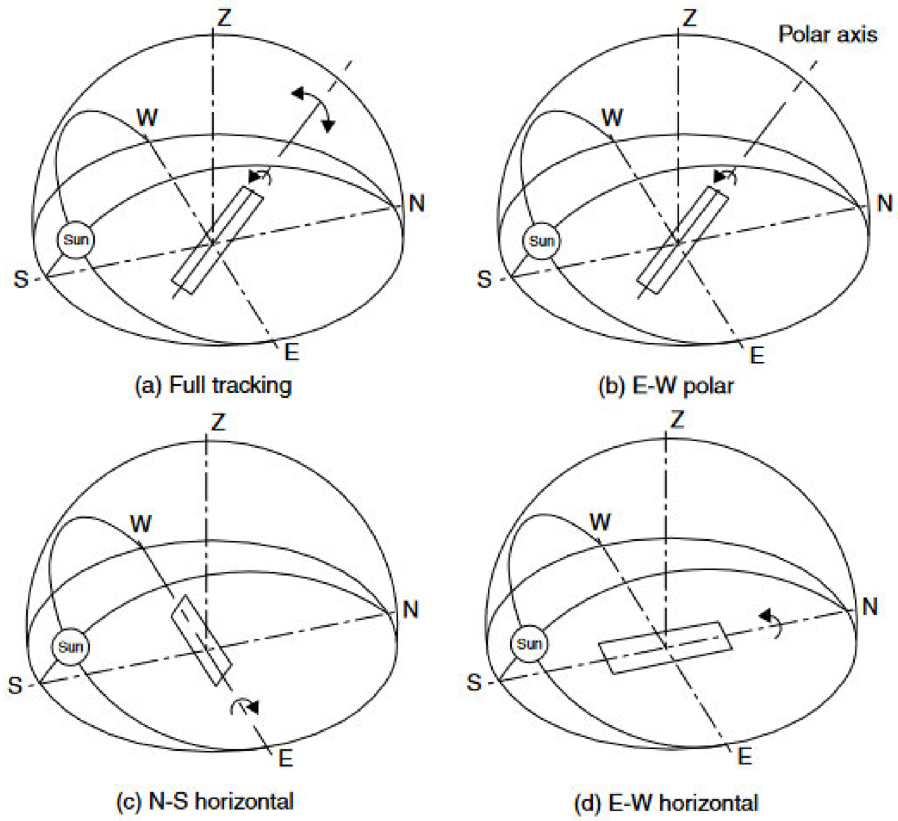


Figure 7- Single axis solar collector tracking diagram (Kalogirou, 2023)

2.21 Solar drying

Renewable solar energy is not always available and cannot supply the energy needed in continuous waste stream generated in industrial operations. Solar energy is highly dependent on weather conditions and can only be used directly during the day (Pawale et al., 2015). This presents a challenge for continuous industrial operations such as screening waste. Dryers can be designed to use solar energy in various ways, such as fully renewable (direct and indirect) solar energy or hybrid type with conventional energy backup (electricity, coal, LPG) or used with or without Thermal Energy Storage (TES) technology. Furthermore, these scholars explain that several hybrid systems have been proposed for both food and biomass drying allowing for the dryer to operate continuously regardless of solar conditions. They further add whilst waste drying offers many benefits it also must balance between energy consumption and value obtained particularly for large scale industrial use factoring thermal efficiencies, energy savings and environmental impacts (Ortiz-Rodríguez et al., 2022).

Typically, non-concentrating collectors are smaller, but both types can be scaled up as needed. Conversely, space limitations may restrict collector size and therefore system capacity (Ortiz-Rodríguez et al., 2022)

2.22 Thermal Energy Storage (TES) Literature

Thermal energy storage can offset the problems of intermittent solar energy and increase drying duration after sunset. This thermal energy is either Sensible Heat Storage (SHS) or Latent Heat Storage (LHS). Sensible Heat Storage (SHS) is cost-effective method for storing solar energy in natural materials like water, oil, rocks and sand or man-made materials such as aluminium, cast iron, brick, concrete by raising their temperature. It can be used for unlimited number of cycles without significant degradation (Hassan et al., 2023) and SHS is preferable where space is abundant. However, Ekka and Kumar (2023) research find the heating capacity of TES is dependent on the materials specific heat, the temperature difference produced, and material quantity (Ekka and Kumar, 2023). Oritz-Rodiguez and others (2021) also note the used of water storage system for low temperature applications (<100°C) due to ease of design, operation, and maintenance. For high temperatures thermal oils or molten salts are often used. CSP can be used to directly transfer solar energy to molten salt and cheaply store energy reporting 60MW at 30-60 $USD/kWh (Hamiliton et al., 2020). The literature notes that good external thermal insulation and methods to prevent internal stratification are needed for efficiency (Oritz-Rodiguez et al., 2021).

Latent Heat Storage (LHS) releases energy isothermally from Phase Change Materials (PCM) during various phase changes. This includes solid-solid, solid-liquid (latent heat of fusion), liquid-vapor (latent heat of vaporization), and solid-gas transitions. LHS can provide constant temperature through controlled heat release. Latent heat may be economically restrictive, experiences cyclic degradation and could potentially leak. (Hassan et al., 2019). In food applications, paraffin wax is a commonly used as an organic PCM because it is non-toxic and relatively low cost (Ekka and Kumar, 2023). Unlike the food industry, waste drying exposure to contamination and overall product quality is not a factor in drying output.

Relevant to this research and local conditions, Hassan and others (2019) assessed modelled drying performance of a hybrid v-groove double pass SAH with a conical shaped rock bed TES system in Brisbane. After 6-hours charging the TES stored 15.6kWh which provided 33% recovered energy during sunset discharge. They found inlet temperature and air flow rate significantly influenced recovered energy (Hassan et al., 2019). However, Oritz- Rodriguez and collaborators (2021) explain that TES in industrial food drying is insignificant, but has it uses in specific applications (Oritz- Rodriguez et al., 2021). This conclusion is due to two reasons: 1) the perspective of the research of continuous industrial operations to produce high value dried food products and 2) current challenges in application. Mugi and scholars (2022) explain that natural sensible heat storage materials are preferred over latent heat storage due to the expense and specialised chemicals involved. However, they note the challenges in natural materials having low energy densities thus need large volumes with high mass, uncertainty in design calculations, non-constant energy release, commonly used water storage can cause tank erosion at high temperatures and materials thermal performance can change over time (Mugi et al., 2022). Conversely, these potential benefits of TES are explained by Ekka and Kumar (2023) noting that TES assists in drying temperature stability, improves dryer performance, reduces energy losses and can work as a medium to restrict very high temperature where drying precision is needed (Ekka and Kumar, 2023). Despite the highlighted challenges, TES has the potential to provides many benefits against solar energy inconsistencies and provide more efficient usage of energy to the waste drying process.

2.23 Fans

Fans produce a pressure difference by electrically powered rotation of fan blades causing in the movement of air. It increases the kinetic energy and flow velocity of the air volume passing through it. Fans force air movement in the drying chamber to increase convective heat transfer. Convective dryer fans can be 20% of the energy used.

Oritz-Rodriguez and scholars (2021) explain that fan correction factors should be used as mass flow rate of air changes with temperature affecting fan power and electricity consumption. For varying temperature of solar dryer, fan must operate over a range of mass flow rates and be sufficiently rated (Oritz-Rodriguez et al., 2021).

Hassan and others (2023) noted during convective heat transfer TES benefits from increased air velocity, but this requires increased fan power due to the pressure drop across rock bed and SAH thus reducing energy efficiency. Furthermore, the mass flow rates of 0.030, 0.040 and 0.050 kg/s needed 1.53, 2.85 and 4.22-kW power respectively. (Hassan et al., 2023).

2.24 Solar drying in waste drying

The use of solar energy for waste drying is not a new idea. In the reviewed literature, only one paper was found to discuss solar assisted drying of MSW with the intention to reduce waste moisture content and eliminate odours. Pawale (2015) presented a conceptual design for a hybrid electrical solar-assisted dryer featuring a solar absorption plate in conjunction with an auxiliary electrical coil (Pawale et al., 2015). The research noted the limitations of solar during nighttime and cloudy days offsetting this problem with electricity. However, this was only a conceptual design for domestic purposes, lacking detailed specifications and research. Moreover, within the context of MSW, Tun and Juchelkova (2019) found that thermal drying is the quickest method, reducing moisture content to 100% within a temperature range of 60 to 200°C. Their work further found that MSW solar drying indicates operational temperatures around 59 ± 37°C with drying times of 7 to 9 hours, achieving a 30% to 40% moisture reduction for solar collector type design (Tun and Juchelková, 2019). However, it should be noted that this was observed from three experimental scale cases for food waste excluding other composites of MSW. Moreover, Ngamket and others (2021) developed a novel solar greenhouse bio-drying system to enhance aerobic microbial activity for MSW degradation. It was found that passive mode greenhouse maintained high temperature (65°C) day and night, while active mode greenhouse reduced the highest moisture content (60% to 26%) respectively making this mode suited for SRF production (<30% MC)

(Ngamket et al., 2021a). As such, solar drying for screening waste has not been explored until now.

Currently, in WWTP, drying beds are used for biosolids to reduce water content, achieved through natural drainage and solar energy heating in greenhouses (Perazzini et al., 2016, Gomes et al., 2023). Similar approaches have been employed for MSW, known as bio-drying, utilizing the high organic fraction for moisture reduction and waste energy retention (Ngamket et al., 2021b).

Cadavid-Rodriguez (2012) and De La Torre-Bayo (2023) suggest applying this method to screening waste due to its substantial organic content (80%-94%) (Cadavid-Rodriguez et al., 2012; De La Torre-Bayo et al. 2023). Bio-drying operates at 40°C to 70°C with a residence time of 7 to 15 days, although this is slower than alternative drying methods (Tun and Juchelková, 2019). However, this approach does not address the small non-organic fraction of screening waste. Nonetheless, solar energy could be used to indirectly encourage bio-drying or be integrated into a staged drying system design.

2.25 Dryer Design

Screening waste drying to date has not been considered, a dryer solution would need to demonstrate feasibility before any consideration of capital investment. Ortiz-Rodríguez and collaborators (2022) find in their reserch into food drying that there are two main solar dryer design technologies to consider: A simple, low-power, cost-effective choice with lower efficiency and a shorter lifespan or a larger dryer with high efficiency, greater durability, but at a higher cost (Ortiz-Rodríguez et al., 2022). However, despite these findings, Ekka and Kumar (2023) note that large-scale solar dryers used in commercial food drying applications face a major obstacle in the form of a substantial initial investment cost, which is the primary challenge (Ekka and Kumar, 2023). However, despite these scholars focus on dried product quality, this design should consider high capital equipment costs which are a factor in any dryer solution.

2.26 Waste to Value

It is anticipated that a solar dryer should be cost-effective because the waste it dries does not hold value for facility operators when compared to the current operational costs of disposal.

Ortiz-Rodríguez and collaborators (2022) explain that a waste dryer design should aim to maximize the load capacity, minimize drying duration, optimize drying quality (uniformity), and utilize versatile materials capable of withstanding high temperatures, weather exposure, and varying humidity levels, all while ensuring a favourable cost-to-useful design life ratio (Ortiz-Rodríguez et al., 2022). Furthermore, key waste dryer selection factors include material type, size, feed rate, drying heat source, dried product quality, construction cost, and ongoing operational expenses (Tun and Juchelková, 2019). Moreover, the research indicates that dryer costs should encompass environmental benefits like reduced fossil fuel dependency, lower landfill and transportation expenses, greenhouse gas reduction, and potential energy and material recovery (Tun and Juchelková, 2019, Arachchige et al., 2019). There are several factors to consider in design, with a drying solution targeting drying to a given outcome. Notably, capital investment of a dryer should be balanced against the value it delivers and potential opportunities it provides for this abundant waste stream.

2.27 Design Methods

Solar dryer design lacks clear methodology. The literature finds many scholars studying small-scale dryers for the food industry which are typically they are used for specific purposes and are simplistic designs. Often work of this kind is trial and error experimentation and practical experience rather than a structured scientific design approach (Ferreira et al., 2014, Ortiz-Rodríguez et al., 2022). Moreover, Gomes and others (2023) found that unique environmental conditions make direct design comparisons impractical and suggested the use of SWOT analysis to evaluate designs (Gomes et al., 2023). However, this is limited to specific scenarios and does not offer a comprehensive design methodology.

Methodological mechanical design process has been suggested by numerous scholars (Rastani et al., 2007, Cross, 2017). This provides a standardised framework for design to take place through understanding the problem, defining the boundaries and evaluating solutions in a series of logical steps to develop a design. However, Cross (2017) notes that these steps should be used as a guide only and not needed to be rigidity adhered too (Cross, 2017).

Initially a problem definition is developed with justified hierarchical objectives and constraints allowing the designer where to focus their efforts. Objective trees provide a graphical diagram which can effectively illustrate commonalities and connections in this context (Rastani et al., 2007). Following this process, multiple design solutions can be generated which will respond to the problem, these need to be evaluated in terms of the most suited response to the hierarchy of objectives through weighting scores. Functional constraints are likely to require some reasonable assumptions and may become more apparent during the objective tree formulation. Thus, it can be said that design process is iterative in nature with a design solution evolving over time when the designer acquires further knowledge.

For example, waste composition and volume will allow estimated drying times and moisture reduction to be identified. This will allow for product quality, heat source(s) and feed rate factors to be determined. Once again, these factors vary for different WWTPs, this research should be able to quantify the waste tonnage to landfill. Understanding the composition of screening waste is essential for designing efficient solar drying systems.

It is envisaged that economic expenses and costs will be a key influencing factor to design implementation. However, this will not be a focus within this initial research. In any case, whilst it is important to have an overview of solar dryers are currently being used and developed, it should not restrict design creativity for the screening waste application.

2.28 Literature Review Conclusion

The escalating urbanisation and population growth necessitate efficient wastewater treatment to sustain public health standards. This must be achieved while embracing sustainable practices due to limited natural resources including fuel and water. Although screening waste constitutes a small fraction of overall wastewater treatment plant WWTP disposal tonnage and costs, its cumulative impact is substantial. Presently, screening waste management predominantly relies on landfill or incineration, with only limited alternatives including SRF and biogas explored in Europe.

The literature finds managing this waste type sustainably is hindered by its composition, variable volume, heterogeneity, and high moisture content. While biological treatment methods have been proposed to reduce mass and volume, their practicality is limited by long residence times, large storage requirements, and energy removal. However, Solid Recovered Fuel (SRF) emerges as a viable option, offering both economic and environmental advantages over current disposal practices. Screening waste composition was found to consists of sanitary textiles (52%), fine particulates of <20mm (hair, inert debris, organic matter (26%)), paper/cardboard (12%), plastics (5%) and vegetal matter (5.5%) with minor fluctuations.

Moisture reduction is crucial for landfill and resource recovery applications, with a target moisture rate <30% from an initial 70-85%. Mechanical dewatering processes are commonly employed, reducing moisture content to around 45% before disposal. Screw conveyors compaction is effective in increasing waste density 240kg/m^3, maintaining an odourless and internal pressurised environment.

In contrast to the dominant food drying literature cited, waste drying does not need to factor drying quality, but the heterogeneity of the waste makes drying a challenge. Inorganics are found to be problematic and are suggested to be separated but offer no alternatives. It has been suggested that the separation of grit and inserts is needed to prevent wear to mechanical machine parts. Additionally, waste fraction separation can increase drying rate.   In general, screening waste can be idealised primarily as hygroscopic (textiles, paper), meaning that there is residual moisture to remove. It is suggested that high drying temperature and high airflow, and low relative humidity following a secondary decreasing drying rate regime is recommended to completely dry these materials. For non-hygroscopic material only a high constant temperature if required.

Thermal drying emerges as the most suitable method despite its energy intensity. Renewable solar energy presents a promising avenue for drying screening waste, particularly in regions with abundant solar energy, like Brisbane which averages 27 Mega-Joules per square metre. Moreover, two -thirds of time with rain-free (cloudless) skies offering eight hours of mean solar irradiance. For fixed panel system (PV and PV-T) optimised angle is suggested a 26-degree incline to true north.

Hybrid solar solutions, coupled with sensible heat storage systems, offer potential benefits in mitigating energy inconsistencies and optimizing drying processes. Sustainable sensible heat storage (SHS) TES is recommended. This can utilise low-cost materials providing space is not limited. Water storage (<100°C) and Thermal Oil (>100°C) can be used. Good insulation and design against thermal stratification is needed. MSW Solar drying found operational temperatures of 59 ± 37°C. However, the feasibility of solar drying solutions must be thoroughly evaluated before any capital investment.

In conclusion, the drying of screening waste using solar energy represents a novel approach that warrants further exploration. While challenges exist, such as waste heterogeneity and energy requirements, the potential economic and environmental benefits make it a promising avenue for sustainable screening waste management practices.

2.29 Literature Review Key Findings

It is required to translate the findings into specifications that can be used as a start point in the design.

From the literature it finds the following key points.

- Common practice to wash screening to remove organic matter.

- Inlet screenings are up to 85% moisture, while current dewatering removes 40-50% moisture.

- Hybrid Solar Dryer is the most suited to dry continuously stream due to the intermittency of solar energy.

- Waste fractions are primarily hygroscopic which requires constant high temperatures and low Relative Humidity (RH) to dry out.

- Screening waste was successfully dried out from 30% to 4.5% moisture at 105°C in 48 hours in lab conditions excluding inert fraction.

- Dewatering reduces space between the materials pores squeezing out moisture.

- Thermal drying increases materials temperature reducing liquid density and surface tension and promotes water absorption resistance (hydrophobization)

In the absence of Australian screening waste composition this design will model the average data from De La Torre-Bayo (2022) for a Spanish WWTP which was found have similar fractions in other European studies shown in Table 1. As a result, it may not precisely match Australian WWTP screening waste. Nevertheless, this data will suffice for the conceptual design stage.

Annual Fractions (Averaged)	Initial Moisture (%)	Sanitary Textiles (%)	Paper & Cardboard (%)	Vegetal (%)	Plastics (%)	Other (%)
	77	52	12	6	5	26

Table 1- Averaged screening waste composition values from De La Torre-Bayo's experimental research. (De La Torre Bayo, 2022)

2.30 Literature Gap

It has been identified that there is little research into the waste management solutions of screening waste at WWTP. Current practice of mechanically washing and dewatering has found to be effective in the reduction of waste moisture and volume. However, it has been identified that residual moisture of ~37% remains in the waste mixture. Consequently, this has increased the weight of the waste costing more in disposal, potential to damage the environment due to landfill leachate and hinders the wastes' ability to be valorised such as generation of Solid Derived Fuels (SDF).

Solar thermal drying of waste is still an emerging concept, there is little research on solar drying of mixed waste in general. In the research found, it finds that this is limited to food wastes and laboratory scale experiments.

Australia and in particular the southeast Queensland region is abundant in solar energy. There is great potential for this resources to be used in a drying application. As far as the author is aware, solar drying of screening waste from WWTPs has not been suggested until now.

Moreover, a standardised design methodology has not been found. Solar dryers for the food industry are generally small and design to meet a specific function. Large industrial food dryers require strict temperature control and continuous operation to produce a uniform, high quality and valuable dried product. This is at odds with solar energy which can be unpredictable and limited to daylight hours. For waste drying, the dried product holds no value thus an energy intensive thermal drying solution is an unwanted cost for industry. But as discovered, solar energy could reduce such cost and potentially provide an alternative pathway for this waste stream. This research may assist in the future development of other conceptual solar assisted dryers' designs focusing on waste drying.

This research aims to develop a conceptual dryer design utilising solar energy to reduce moisture in solid non-organic screening waste (post mechanically dewatered) captured at WWTP primary inlets in Southeast Queensland.

A comprehensive literature review has identified current WWTP screening processes and solar drying technologies to inform suitable design parameters for the region. The objective of the solar assisted dryer design is to decrease moisture in screening waste, thereby reducing waste weight for landfill disposal, and enhancing its suitability for combustion or resource recovery.

In the absence of specific data for this novel solution, this research will undertake a structured design process to develop a waste dryer solution. This will include the determination the design parameters, considerations, limitations. Furthermore, this paper will critically formulate and evaluate design ideas in response to identified criterion to develop a potential dryer solution. A concept design proposal will be presented with theoretical performance data for local southeast Queensland conditions.

2.31 Problem Definition

There are two main solar dryer design technologies to consider: A simple, low-power, cost-effective choice with lower efficiency and a shorter lifespan or a larger dryer with high efficiency, greater durability, and a higher cost (Ortiz-Rodríguez et al., 2022). However, Ekka and Kumar note that large-scale solar dryers used in commercial applications face a major obstacle in the form of a substantial initial investment cost, which is the primary challenge (Ekka and Kumar, 2023). A desirable factor in the formation of problem definition would be consulting expertise, through the correspondence with wastewater facility operators in Brisbane, such as Urban Utilities, Unity Water, and the like, to gain further insight into the WWTP screening stage. It is anticipated that a solar dryer should be cost-effective because the waste it dries does not hold significant financial value for facility operators when compared to the current disposal methods.

The ongoing development of a problem definition can be aided with justified hierarchical design objectives and constraints. Furthermore, an objective tree, a graphical diagram, can effectively illustrate commonalities and connections in this context (Rastani et al., 2007). Multiple designs can be evaluated in terms of the most suited response to the hierarchy of objectives through weighting scores. Functional constraints are likely to require some reasonable assumptions and may become more apparent during the objective tree formulation.

Key MSW dryer selection factors include material type, size, feed rate, heat source, product quality, construction cost, and operational expenses (Tun and Juchelková, 2019). In addition, manufacturing expenses, the substances to be dried, maintenance costs and material sizes (Bazregari and Norouzi, 2022).

However, considering these factors, economic expense and costs will not be within this research. Waste composition and volume will allow estimated drying times and moisture reduction to be identified. This will allow for product quality, heat source(s) and feed rate factors to be determined. Moreover, dryer costs should encompass environmental benefits like reduced fossil fuel dependency, lower landfill and transportation expenses, greenhouse gas reduction, and potential energy and material recovery (Tun and Juchelková, 2019, Arachchige et al., 2019). Once again, these factors vary for different WWTPs, this research should be able to quantify the waste tonnage to landfill. Understanding the composition of screening waste is essential for designing efficient solar drying systems. Currently, the primary solar thermal technologies utilized in food industry include flat plate collectors (38%), parabolic trough concentrators (20%), evacuated tube collectors (20%), and other available thermal technologies (22%) (Ortiz-Rodríguez et al., 2022). In any case, whilst it is important to have an overview of solar dryers are currently being used and developed, it should not restrict design creativity for the screening waste application.

Generally, a design should aim to maximize the load capacity, minimize drying duration, optimize drying quality (uniformity), and utilize versatile materials capable of withstanding high temperatures, weather exposure, and varying humidity levels, all while ensuring a favourable cost-to-useful design life ratio (Ortiz-Rodríguez et al., 2022).

2.32 Research Question

The research question will focus on the characteristics of screening waste and current solar technologies that can be used for a drying solution.

"How can a solar assisted dryer further reduce residual moisture in post mechanically dewatered screening waste considering the waste characteristics, current solar technology and waste processing practices of a local WWTP in Brisbane, Queensland?"

3 Methodology

3.1 Research Design

The methodology shall provide a structed design framework to collate and analyse the determined dryer design parameters, considerations, and limitations. Furthermore, suitable methods will be used to critically evaluate the design to present a conceptual design solution.

The methodology process will be explained and justified in this section.

3.2 Specific Objectives

The research aims to answer the following specific research objectives.

a) Identify the composition, mass, and volume of screening waste. Where possible identify locally generated screening waste within Brisbane, Queensland.

b) Investigate the current wastewater screening processes and solar drying technologies available via a comprehensive literature review.

c) Determine the design parameters, considerations, and limitations of a solar assisted dryer.

d) Undertake a structured design process to develop a dryer solution.

e) Critically evaluate design ideas in response to identified criterion.

f) Propose and present a conceptual design solution.

g) Estimate dryer performance including the moisture, mass, and volume reductions for screening waste using numerical modelling.

The specific objectives a), b) and c) (partial) have been addressed in the literature review. Objectives c) to g) will be focus of the design methods employed in the methodology.

3.3 Methodology Context

Goundar (2012) explains the difference between research methodology and research methods. Research methodology set an appropriate framework and procedures for the investigation of a problem. In contrast, research methods are the practical execution and processes of finding solutions. As such, a methodological framework ensures research is conducted effectively while the methods are the practical means of finding research conclusions (Goundar, 2012). Therefore, it is important to find a systematic framework to undertake this or future designs.

Solar drying design methodology has been found to be illusive in the literature. Solar dryers are predominantly associated with the food industry. As such, individualised, small scale, economical solar food dryers have been studied for specific drying requirements. These dryers are often simplistic structure of the design does not warrant a design methodology to be employed or has not needed to be documented. Moreover, limited solar waste dryers have a focus on the support of biological digestion. In this case, trial and error experimentation has been employed. The literature finds that designs are based on functional requirements for a given product type such as food items or for a specific task relating to the industry (i.e. food drying, waste drying etc). Ferreira and scholars (2014) explain in their work in solid waste drying in the industrial sector, that solar dryers are widely using in food drying applications, found that the designs are not standardised and limited to small scale dryers. They find that in contrast to Goundar (2012) methodology ideas, solar dryer design is based on experience and not scientific methodology as they are not widely commercialised nor typically used on an industrial scale (Ferreira et al., 2014). Even though this research was conducted a decade ago, it is still accurate of reflection of industrial solar dryers to date. Despite this indication, Ferreira and collaborators work also did not employ or suggest a structured design approach. Furthermore, Oritz-Rodiguez and others (2022) state in their recent review paper for medium to large scale agro-industrial solar drying finds that current solar dryer design is customised to the users' requirements whereby each constituent is designed separately instead of a whole system. Typically, they identify there are conventional solar dryer design used (i.e. cabinet, greenhouse etc) but they note that there is still little design and operation considerations for an integrated system, notably for large-scale industrial applications. (Oritz-Rodriguez et al., 2022).

Additionally, the evaluation of solar dryers is not developed. Gomes and collaborators (2018) found in their research into WWTPs solar dryers that there was no standardised methodology for comparing dryers. They concluded that the unique environmental conditions and drying elements finds that direct comparisons of dryers for both system and thermal efficiency is unsuitable. They further suggest the use on Strength, Weaknesses, Opportunities and Threats (SWOT) analysis to find a suitable design (Gomes et al., 2023). However, this methodology approach is limited. Within their research it is applied to greenhouse dryers of defined geometry with known attributes. The SWOT method is not detailed enough for a drying system design, although its use could apply to individual elements of a dryer instead within this current research. Overall, it can be concluded that there is no specific or standard design methodology in solar dryer design. This research will be required to develop a framework in which to design a solar assisted dryer.

3.4 Case Study

So far, the problem has been broadly defined primarily from the literature. There has been limited correspondence with local WWTP utility operators, but they acknowledge that the screening waste management process could be optimised but current dewatering is sufficient (J Adams 2024, pers.comm., 18 March, M Kuliszer, pers.comm., 18 March). It is noted by numerous researchers that there are many possible combinations for a solar dryer design (Gomes et al., 2023, Ortiz-Rodríguez et al., 2022). Typically, they are used on a small scale. It is found that dryers are select to fulfill a purpose for a specific requirement, so a generic design approach is not utilised. As such, to simplify the design space a test site has been selected so as the design can take into consideration the following item thus reducing the variability of assumptions required.

- Location / position for solar design in conjunction with Bureau of Meteorology (BOM) historical climate data.
- Available area for a solar dryer giving size and space requirements.
- Estimation of waste volume generated providing dryer size, storage capacity and feed rates.
- Local WWTP dewatering and standard operations.
- Consideration of methods of integration to existing operations

Figure 8 shows Murrumba Down Sewage Treatment Plant (STP) which is operated by Unity Water and located 32 kilometres north of Brisbane. In 2018, an educational virtual tour video was produced by Unity Water and estimated that 17ML of raw sewage is processed daily (Unitywater, 2018). Using the approximate guide of 20kg/ML from Cadavid-Rodriguez (2012) it is expected that a daily (24 hour) minimum of 340kg of screening waste is generated. This is assumed that raw screening waste (77% MC) is dewatered at 40% to give waste a 32% MC prior to disposal. This is approximately 128 kg of daily screening water mass remaining. The solar dryer design is idealised to remove this moisture content after dewatering.

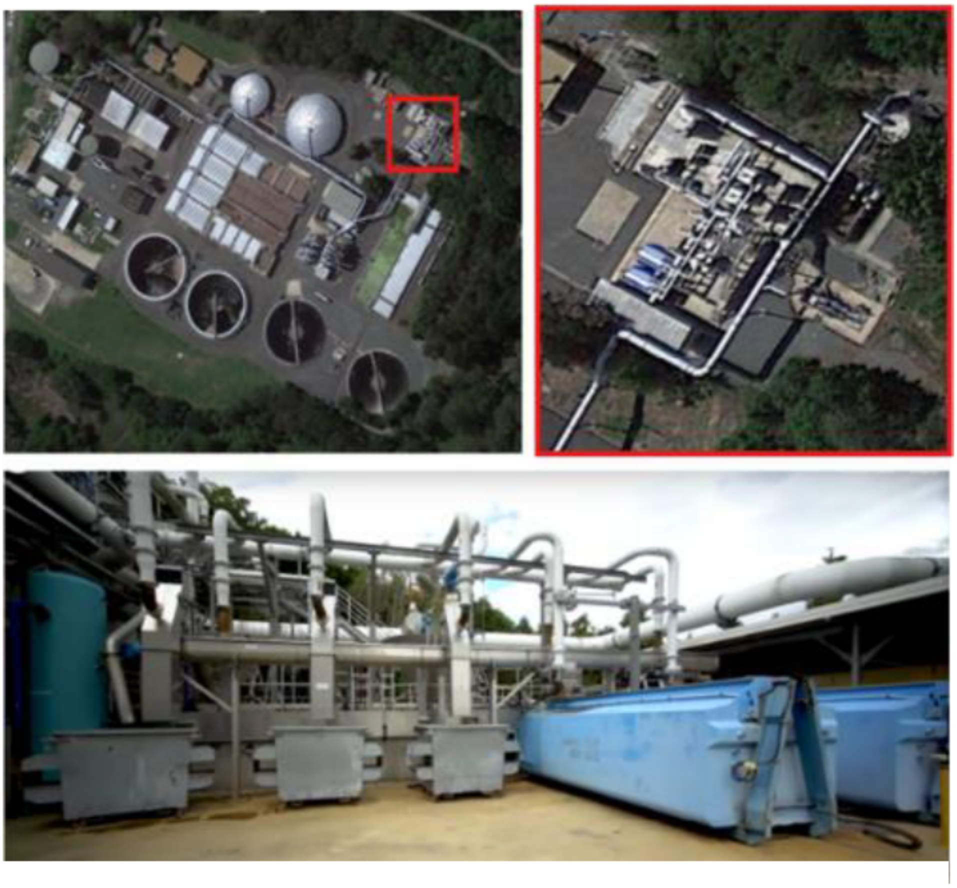


Figure 8 - Inlet screening area located at Unity Water's Murrumba Down STP.

Aerial photos sourced from Google Maps and lower photo from (Unitywater, 2018)

3.5 Methods

The design solution is on the authors understanding of the literature and interpretation of the customer requirements. These are to be presented in this paper in a logical manner with justifiable assumptions and simplifications based on research observations. Furthermore, unspecified data is to be clarified using simple fundamental principles and mathematical equations.

The author has referred to standardised or prescriptive design frameworks to develop the overall design. *Engineering Design Methods -Strategies for Product Design* (Cross, 2017) has been used in development of suitable approach. While Cross (2017) explains that critics believe that rational design methods hinder creativity, they find that systematic design approach broadens solutions space, improves design decisions, and complements design creativity. Equally, Cross (2017) encourages the use of rational methods and the principles to guide the design as a framework, not as a strict set of rules requiring adherence (Cross, 2017).

Rational Methods suggested by (Cross, 2017)

- Clarifying objectives -Objective tree.
- Establishing functions -Function analysis
- Setting characteristics -QFD
- Generating alternatives -Morphological chart
- Evaluating Alternatives – Weighted Objectives

Further literature has been reviewed. Rastani at collaborators (2007) provide a useful explanation of the systematic stages in mechanical engineering design process for capstone students used at an American academic maritime academy. These researchers recommend the use of the objective tree diagram (weighted & non-weighted), QFD method, brainstorming, morphological and decision matrix (2007). Despite this paper aimed at a full design group project, the systematic steps detailed are like the proposed framework presented by Cross (2017) both are useful for this research methodology. Furthermore, this methodology is one of the limited practically applied by Elgendi and others (2022) who present design procedures for a conceptual design of a passive pyramid solar still – a device that converts saltwater into freshwater (Elgendi et al., 2022). Their design method provides a similar framework to that outlined by Rastani and scholars (2007). This paper's relevance to this research is significant as it exemplifies the practical implementation of the suggested method for conceptual design by both Rastani and others (2007) and Cross (2017).

For this report, the engineering design process for mechanical systems has been adapted from Rastani and scholars research (2007). The adaptation includes four distinct stages: Problem definition, Establishing functions, Conceptual design, and Evaluation.

1. Problem Definition
Gathering Data on customer needs. ○ Literature review ○ Reverse Engineering ○ Define requirements and assumptions.
Organise with hierarchy of needs. ○ Objective tree formulation
Establish Relative importance. ○ Weighted Objective Tree ○ Identifying Constraints/ limits ○ Setting requirements
2. Establishing functions
Functional Analysis Method (FAM) ○ Black box ○ Block diagram
Quality Function Deployment (QFD) ○ House of Quality (HoQ) matrix.
3. Conceptual Design
Generating Design Alternatives ○ Brainstorming ○ Morphological matrix
4. Evaluation of Design Concept Alternatives
○ Evaluation of solar technologies -SWOT ○ Design calculations. ○ Weighted decision matrix

Table 2- Solar Assisted dryer concept methodology. Adapted from Rastani and collaborators (2007)

To aid in the design process, a flow chart has been developed to provide visual representation of this process. Of note, it the concurrent activities and the process loops indicating the evolution of the design in response to more information discovered.

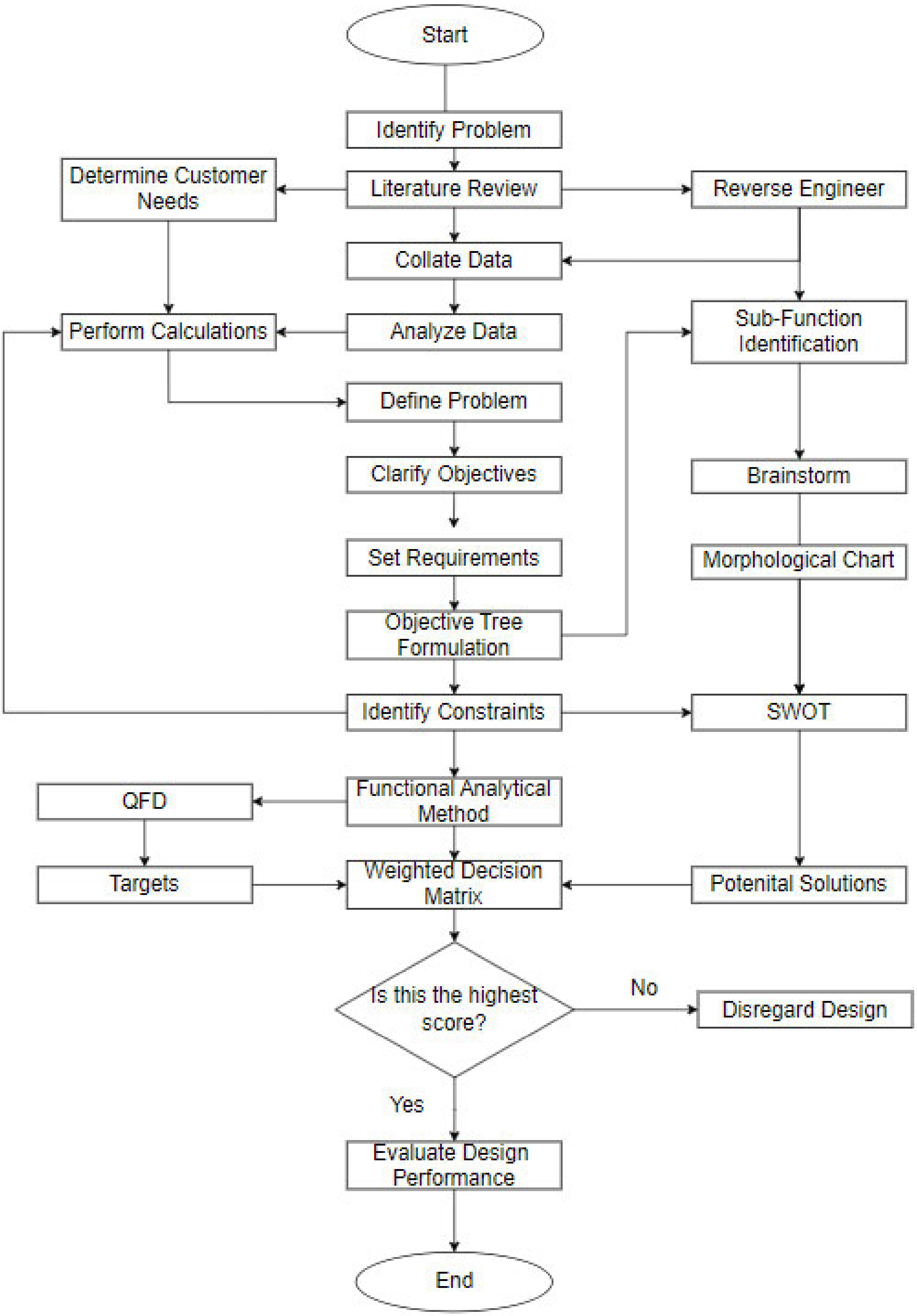


Figure 9- Flow chart of Design sequence. Adapted from Elgendi and collaborators (2020) conceptual design of a solar sill (Elgendi et al., 2020)

3.6 Design Project Definition

Rastani and others (2007) emphasises that early in a design project, there is limited knowledge about the solution. As the project advances, the designer gains a better understanding of the technologies and alternative solutions. The key aim of the design process is to obtain early insights into the evolving product, as changes are less expensive during the initial phases (Rastani et al., 2007). The literature review conclusions have been summarised previously. This provides context to problem definition in which a design should respond.

3.7 Reverse Engineering

Rastani and collaborators (2007) suggest the use of reverse engineering. Through observation of commonalities in design features and the analysis of functions, this research will be better placed to provide a suitable design solution. This process can be used for the current systems in use at WWTPs for both screening waste including dewatering, drying techniques, washing and compaction. Moreover, sewage sludge can also be included as there are known commercialised solar dryers and its key function is the same as screening waste: to remove excess moisture.

The black box functional analysis method suggested by Cross (2017) can be used to identify system functions. However, Tang and collaborators (2010) explored the functional reverse engineering for re-creation design which can be applied to either a system, parts, or components. They explain to enable re-creative design it must be conducted in a transparent box model to identify the inner design intent. That is, overall function is comprised of aggregation of sub-functions with different relations including the objects, actions, inputs, and outputs flows of a system (Tang et al., 2010).

They suggest three stages.

- Identification of product, parts, or product to be reversed engineered.
- Observing or disassembly of original product work and mapping physical model to functions model
- Re-creating the new product based on identified function model.

(Tang et al., 2010)

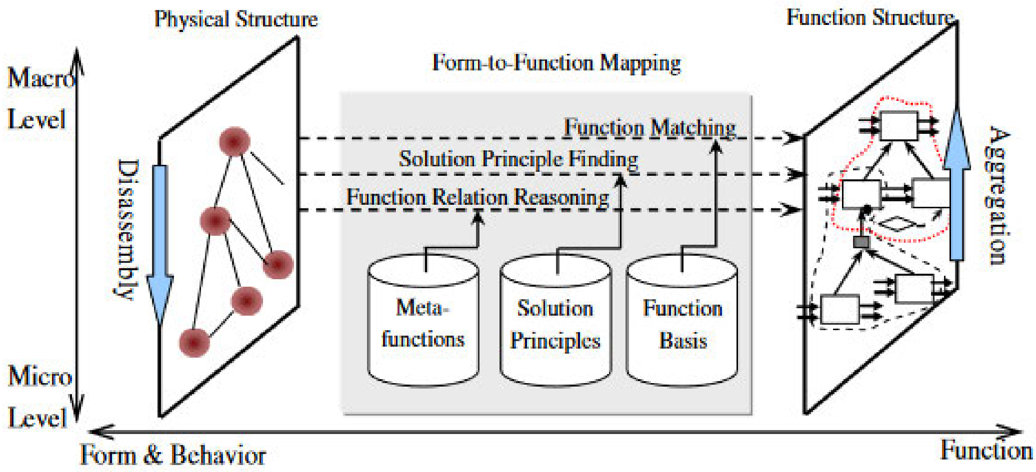


Figure 10- Form to function mapping as suggest for re-creation design (Tang et al., 2010)

While Tang and collaborators (2010) used this method to optimise an existing design, this research will adapt this method and use it to identify functional links in existing screening and sludge dewatering systems. The intent here is that the identification of the chosen product functions may further expanded the design space for the solar dryer. Moreover, the identified functions will allow for design *benchmarking* – which is common practice when creating products in a competitive market. Whilst the design intent is not for commercial gain, it must still compete with the existing products. Therefore, it must have equal of higher function equally to be an attractive alternative for used within the industry.

The following products will undergo the reverse engineering process. These have been identified by local wastewater operators to be in used in South-East Queensland (J Adams 2024, pers.comm., 18 March, M Kuliszer, pers.comm., 18 March). The exception is HUBER technologies products, they have been selected as a large wastewater engineering company which has many commercial products including solar sludge drying solutions.

- HUBER Technologies – Solar drying, thermal drying, and mechanical dewatering
- Washpactor screening dewatering machine – Washing and dewatering screening waste
- KUHN - Washing and dewatering screening waste.

3.8 Design Calculations

A collated set of features and objectives will be produced. Simple calculations will need to be completed to provide details and specification of the design. Mohana and others (2020) explains that fundamental calculations of physical laws are required to make appropriate design selections (Mohana et al., 2020). Moreover, justified assumptions based on the literature must be translated into clear design requirements. It is then important to link this data to design objectives through tangible physical quantities.

So far, the design has not yet been fully specified. As such the method of dryer evaluation will remains broad until a conceptual design is chosen. Several textbooks and papers have been identified that will be able to assist in the calculations necessary to determine parameters of dryer performance.

The main textbooks and research papers are used for reference of this design are as follows.

- *Solar energy engineering: processes and systems* (Kalogirou, 2023) and *Renewable Energy Resources* (Twidell and Weir, 2015) will allow for the calculations of solar collectors and identification of useful energy for electricity and thermal heat.

- *Solar Engineering of Thermal Processes* (Duffie and Beckman, 2013) provides greater detail into thermal energy and heat transfer dervived from solar collectors.

- *Engineering Fundamentals: An introduction to engineering* (Moaveni, 2010) provides the basic engineering mathematics and physical natural law of physics.

- *Drying Phenomena: Theory and Applications* (Dincer and Zamfirescu, 2016) textbook provides the nesscary background on drying in different context includes energy and exergy theory.

- *Autonomous solar thermal system design for indirect dehydration of Aguaymanto* (Camayo Lapa et al., 2021) presents and details the process of evaluating an indirect dryer.

The calculations will use both Microsoft Excel and MATLAB software packages build the equation models to predict performance of the dryer's functional elements. AutoCAD is used to mark-up aerial photographs to estimate areas for solar arrays.

3.9 Organisation of Design Needs

3.9.1 Objective tree

Cross (2017) explains that initially designers are often given a problem that requires a solution, often with vague detail to a product need. As such, a designer must determine set aims for a design to progress toward. One such method is the objective tree which can provide clear statement of objectives so that all stakeholders are aware (Cross, 2017). This can be achieved within an *objective tree* which forms the basis for weighted objective tree.

It is important to recognise the identified objectives in a hierarchically ranking of design needs. Cross (2017) further explains that the accuracy of ranking levels is not the primary aim. Instead, this process is used to encourage broad thinking, establish the relationships among objectives and identify which objectives are needed to be focused on to meet the design requirements (Cross, 2017). For this design, this method helps to widen the design space and given the limited time, focuses the solar dryers' objectives more concisely.

3.10 Relative importance

3.10.1 Weighted objective tree

Further development can use a *weighted objective tree* to prioritise criteria by importance through comparison of several options. The method of weighting is a comparison of importance for each function within each hierarchal level. Each level is equated to a total of one, this is then continued for each level. The highest value reveals the most important combination of functions. This method is intended to provide guidance on objective priorities. For this research, this method can serve as a clear record of justifications in the authors steps, allowing critical judgment on needs and concentration of the design development. However, the determination of numerical value and its assignment can be subjective. There are several techniques that will be used to minimise bias, ensuring rigorous analysis and consideration of factors.

- *Literature Review* - the literature can assist in determination of industry standards and best practices. Moreover, it can identify solar technology suited to objectives (i.e. high chamber temperature (>100°C) will need solar collector type that can provide this heat).

- *Stakeholder Consultation* – correspondence with local wastewater operators can offer valuable insights to the determination of weightings based on their industry experience and knowledge of operations.

3.10.2 Identify limits and constraints.

Understanding design restrictions is crucial, as objectives and constraints are closely linked (Rastani et al., 2007). While objectives explore design possibilities, constraints limit these explorations. Cross (2017) explains that constraints should be quantifiable as they encompass various aspects such as customer requirements, compatibility issues, adherence to standard practices (e.g., codes, laws, regulations), and physical laws of nature (Cross, 2017).

As an example for this design, one critical constraint is odour control, mandated by legislative requirements. Therefore, the design must either fully contain odours or manage emissions from the process. Failure to meet this mandatory requirement signifies a failure in solving the problem at hand. Clearly defined dryer functions at this early stage will prevent overlooking critical factors such as the example discussed. Additionally, the design should not introduce new problems. For instance, while a solar-assisted incinerator could reduce waste volume and mass, it would contravene Queensland's state laws on waste incineration and WWTP emissions, thus presenting a functional but counterproductive solution. This research will utilise the objective tree method which can aid in identifying mandatory constraints and delineating the design space appropriately.

3.11 Establishing Functions

3.11.1 Functional Analysis Method (FAM)

Functions allow to identify the interconnecting requirements of system. This allows for a broader understanding of the design considerations but also may expand the design space allowing for innovative ideas. Tang and others (2010) explain that often it is not feasible to generate an optimal function structure directly from a design brief. They explain that functional design is the initial step in crafting the final function representation, addressing the challenge of defining a vague problem with a clear solution (Tang et al, 2010).

Moreover, Viola and collaborators (2012) explain that FAM is a crucial system engineering tool for innovative product design, ensuring comprehensive requirement analysis, alternative exploration, and component identification, reducing the risk of missing important options (Viola et al., 2012). Moreover, Cross (2017) explains the steps in FAM design: i) Overall function, ii) Dissemination of overall function into sub-functions, iii) Develop system block diagram for sub-function relationships and boundaries, iv) Analysis of elements that can perform the sub-functions (Cross, 2017).

The solar dryer system involves various essential tasks to complete its function, that is to remove moisture from waste. This can be represented by a functional diagram known as a black box whereby the broad overall system function is considered as a series of inputs and outputs. Further development into a transparent box considers the numerous sub-functions to achieve the overall function. These sub-functions are represented by nouns or verbs in a block diagram (i.e. raise, lift, move, heat etc) and are outlined to visualise their composition and connections within a high-level transparent box model. The functional design boundary, encompassing inputs and outputs, is external to the box, symbolising the system's limits. There is recognition of the flow of energy, materials, and information within the system, as highlighted by Cross (2017).

Moreover, this method provides an opportunity to identify the individual steps with the process thus can explore alternatives ideas to meet a given functions. For example, the desired function of moisture reduction is found to be achieved in different ways, such as thermal drying and mechanical compaction. However, further exploration of moisture reduction also finds that biological decomposition also reduces waste moisture content thus providing another solution to meet this requirement.

In the final analysis stage, creativity is prioritised over critical evaluation encouraging exploration of new alternatives and perspectives for the given functions. This promotes idea generation useful to find potential design solutions.

3.11.2 Quality Function Deployment (QFD)

Viola (2012) explains that the Quality Function Deployment (QFD) is a structured design approach and is a common industrial practice. It attempts to translates often ambiguous customers' requirements into measurable engineering parameters preventing misinterpretation of the design (Viola et al., 2012). One tool for QFD is the *House of Quality (HoQ*) which is a graphical matrix that illustrates the correlation between customer requirements and technical requirements (Rastani et al., 2007). The weightings serve as a method of importance, where it can be compared against other requirements. This allows analysis of how well a design aligns with the requirements thus identifying design feature priorities (Viola et al., 2012, Rastani et al., 2007).

Elgendi and others (2022) used the HoQ to identify and prioritise the most significant customer requirements of having automatic control for feed water into the solar sill. Equally, it was found this also made the design eco-friendlier to that of its competitors and allowed for the identification of optimum operation thus this feature was included into all design alternative (Elgendi et al., 2022). This approach allows a methodological and documented approach determine needs of the industry against quantifiable engineering characteristics. In this case, customer design requirements have been interpreted. Nonetheless, the method provides a collection of data to develop the concept design. For this research, it can also be benchmarked against existing screening waste dewatering systems. Moreover, the procedure can be modified through various iterations of the design by revisiting this step.

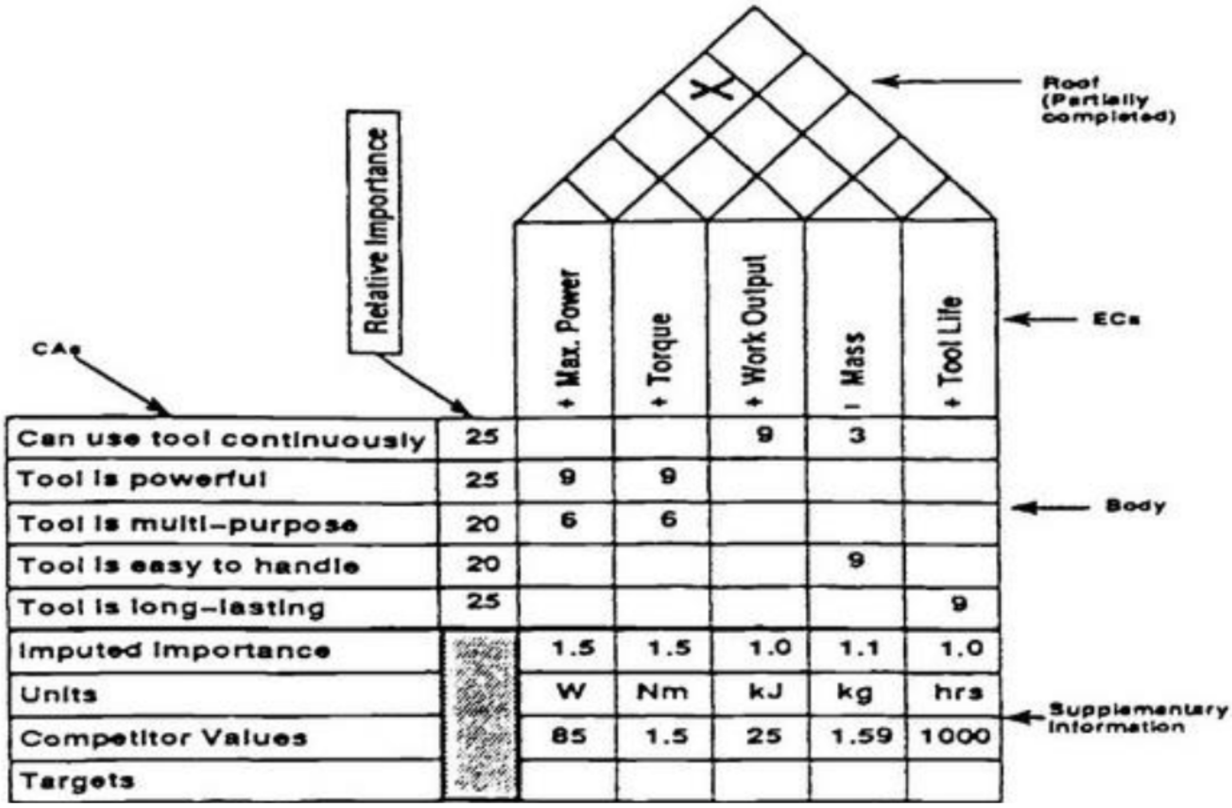


Figure 11 - House of Quality for a design of cordless drill (Cross, 2017)

3.12 Conceptual Design

3.12.1 Creativity

Rastani and others (2007) explain the ideas are generated to support the identified functions and it is essential to generate multiple concepts for each function. At this stage, detailed elaboration is not necessary to foster creativity as creative thinking can be impeded by mental barriers that hinder problem recognition and the generation of solutions. Common obstacles to creative thinking include:

- Analytical and conventional thinking (stereotyping).
- Judgmental thinking (jumping to conclusions).
- Distractions.
- Intellectual barriers (lack of knowledge and information).

(Rastani et al., 2007).

Further explanation from numerous scholars states a good process of exploring ideas can involve brainstorming to generate a multitude of solutions, eliminate all constraint, build upon other ideas, and avoid dismissing any generated ideas (Rastani et al., 2007, Cross, 2017, Pierobom and Andrade, 2020). Typically, this process is used for multiple designers, but it can still be effectively used by an individual. As a follow on from brainstorming ideas, a morphological matrix can be used which combines individual concepts that meet all functional requirements. It is a qualitative technique used to structure and assess relationships within a problem. It is a systematic approach for analysing the structure of generated ideas (Pierobom and Andrade, 2020).

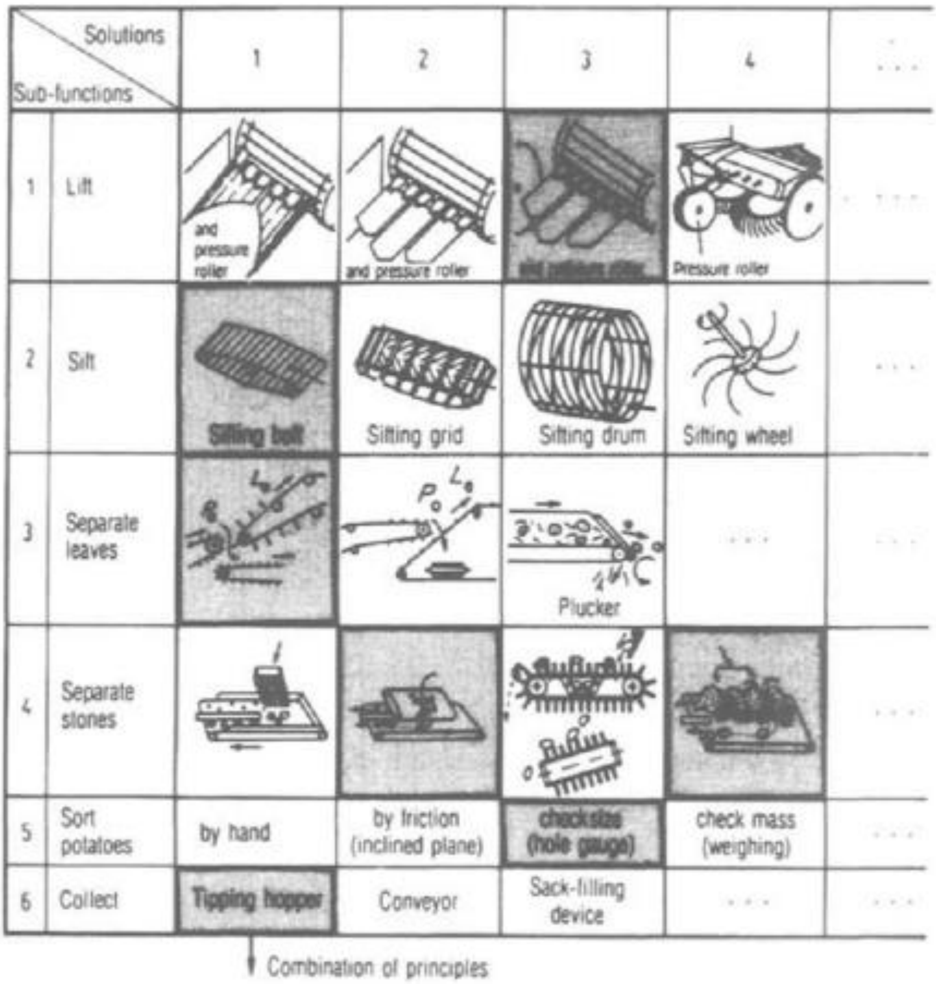


Figure 12- Morphological matrix (Cross, 2017)

These methods for creativity will encourage the generation of many alternative design solutions based on functional requirements which may not have been initially realised or considered.

3.12.2 Evaluation of Solar Technologies -SWOT

The design can use many different combinations of elements to achieve waste drying.

At this stage it must consider the influencing factors to solar collection. Table 3 has been developed from the literature review and is used to select solar collector technology based on several generalised factors including fluid type, temperature, cost, tracking, and ancillary equipment needed.

The use of SWOT analysis can further identify other factors in each of the solar collectors. Gomes and collaborators (2018) used this for the selection of a greenhouse solar dryer comparison identifying this method as a generic aid to guide design selection due to the high number of variables needed to be considered. Variables identified were different drying systems including their basic differences, environmental and local conditions (Gomes et al., 2018). The identification of these variables for a dryer design will allow informed decisions to be made.

Solar Collector Type	Absorber Type	Fluid Type	Temperature Range (°C)	Conc. Ratio	Output	Cost ($)	Tracking	Aux equipment
Flat Plate collector (FPC)	Flat	Air or Liquid	40-85	1	Heated Air	Low	Fixed	Fan
PV/T Liquid Collector	Flat	Liquid	30-80	1	Heated Liquid and Electricity	Med	Fixed	Pump and Inverter
PV/T Air Collector	Flat	Air	30-65	1	Heated Air and Electricity	Med	Fixed	Fan and Inverter
Evacuated Tube Collector (ETC)	Flat	Air or Liquid	50-150	1	Heated Liquid/Air	Med	Fixed	Fan or pump

Compound Parabolic Collector (CPC)	Tube	Air or Liquid	60-300	5-15	Heated Liquid/Air	Med	Fixed	Fan or pump
Parabolic Trough Collector (PTC)	Tube	Liquid	60-300	10-85	Heated Liquid	High	Single Axis	Pump, Tracking control
Linear Fresnel Collector	Tube	Liquid	60-250	10-40	Heated Liquid	High	Single Axis	pump and/or tracking control
Parabolic Dish Collector	Point	Liquid	100-500	600-2000	Heated Liquid/Air	High	Dual Axis	Pump, tracking control

Table 3- Solar collector data. Adapted from Kalogirou (2023)

3.13 Evaluation

3.13.1 Weighted decision matrix

The next step is to evaluate the generated design alternatives in response the design requirements. Design criterion is typically not equal, a weighted decision matrix can be used to prioritise the criterion against one another in hierarchical order. This approach involves translating objectives into measurable parameters and then converting these parameters into values on a point scale based on a weighted decision matrix. These values are used to assess and rate design alternatives concerning each of these objectives. Rastani and collaborators (2007) recommends a 5-point scale whilst Pierobom and Andrade suggest a 3 - point scale since objective knowledge is limited (Pierobom and Andrade, 2020, Rastani et al., 2007). However, Pierobom and Andrade suggestion is related to function opposed to performance. In this research, a 5-point scale (ranging from 0 in 4) will be employed. This scale is suitable for situations where the level of knowledge about the objective is relatively limited and consists of five grades that reflect varying levels of performance as per table 4. The multiplication of design response to the criteria weight will give a total design score. From this the highest weight score would be the most suited design in relation to defined objectives.

3.14 Design Performance Calculations

Eleven-point scale	Meaning	Five-point scale	Meaning
0	totally useless solution	0	inadequate
1	inadequate solution		
2	very poor solution	1	weak
3	poor solution		
4	tolerable solution		
5	adequate solution	2	satisfactory
6	satisfactory solution		
7	good solution	3	good
8	very good solution		
9	excellent solution	4	excellent
10	perfect or ideal solution		

Table 4 – Evaluation Scale table for 5-point and 11-point scale. Viewed at Cross (2017)

This evaluation is intended to provide an estimation of dryer capacity to determine suitability based on calculations including sizing of collector area, dryer volume, expected performance. Fundamentally, the use of the energy and mass continuity equation will be developed and used Whereby the energy of a systems control volume is transferred either by heat transfer Q, work W, and mass flow m.

$$E_{in} - E_{out} = (Q_{in} - Q_{out}) + (W_{in} - W_{out}) + \left(E_{mass,in} - E_{mass,out}\right) = \Delta E_{system} \qquad (2)$$

Rabha and others (2017) used these equations develop equations to link mass flow $\dot{m}$, to heat transfer Q, amongst others for energy and exergy analysis of a SAH dryer.

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{3}$$

$$\dot{Q}_{in} - \dot{Q}_{out} = \dot{m}\,(\Delta h) \tag{4}$$

(Rabha et al., 2017)

Drying is a complex phenomenon, particularly for mixed heterogenous waste therefore the calculations in this research will be limited to approximations. Further experimental studies will be needed to fully model the drying regime. Moreover, it provides a starting point for follow on work in the next design step: detailed design.

Analytical methods can be used to model solar dryer performance behaviour. Scholars have suggested many equations to model drying rate, system efficiency, product moisture removal, solar collector efficiency, generated heat energy, energy and exergy efficiency, energetic improvement potential among others (Bazregari and Norouzi, 2022, Ekka and Kumar, 2023). Mohana (2020) notes the equations used for solar dryers for food applications including combined solar drying phenomena (Conduction, convection, and radiation), drying kinetics, thermal efficiency, overall system, and cost analysis (Mohana et al., 2020). However, these have been used in conjunction with experimental scale data providing necessary data to fulfill the calculations.

Given the variation in dryer types and combinations, a suggested dryer performance model within the food industry is energy and exergy analysis (Rabha et al., 2017, Ahmadi et al., 2021). More relevant to this research Bezregazi and Nouruzi (2022) presented analytical methods based for energy and exergy on MSW drying data. However, their methods are found to be complex using Engineering Equation Solver (EES) to validate the modelled data. Ekka and Kumar (2023) find that this method to represent realistic modelling on the thermodynamic process. They used this to measure the performance of a solar air heater (SAH) for ghost chilli and ginger in conjunction with experimental results (Ekka and Kumar, 2023). This provides several key equation for the SAH. The basic principles can be applied using Dincer & Zamfirecu (2016) *textbook Drying Phenomena: Theory and Applications - Energy and Exergy Analyses of drying processes and systems* (Dincer and Zamfirescu, 2016). For this research, it is intended to use Microsoft Excel to perform energy and exergy calculations.

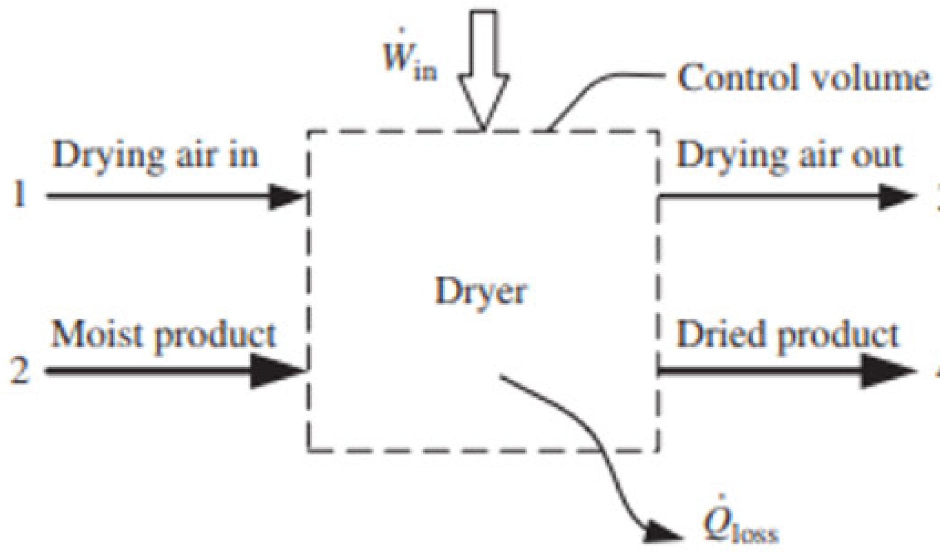


Figure 13- Energy and Exergy representation based on energy law (Dincer & Zamfirecu, 2016)

Alternatively, Camayo and others (2021) provides approximate calculations for a conceptual forced convection solar thermal dryer design used for the indirect drying of aguaymanto. Their considerations were solar energy, construction materials and cost. This research provides an example of dryer design at the conceptual stage.

They were able to indicate numerous values including.

- Drying Factor (Water/m^2 per day)
- Energy requirements for water evaporation (initial and final water quantities)
- Estimated collection area (m^2)

- Calculation of air flow required.

(Camayo Lapa et al., 2021).

Typically, it has been found that the heat transfer can be modelled in various ways. The type of drying, features and exposure to heat transfer effects will affect the evaluation calculations. The following presents the general fundamental calculations for each heat transfer type.

3.14.1 Convection

Forced air convection extensively used in food drying and has been modelled in different ways. In general, this can be modelled using Newtons' Law of heat transfer.

$$\dot{Q} = hA(T_s - T_f) \tag{5}$$

Where heat transfer coefficient h, depend on many factors including flow regime, boundary thickness and fluid properties quantified by dimensionless groups including Biot, Reynolds, Prandtl number and so on. Moreover, this can be used with the knowledge of air humidity and temperature in the case of solar crop dryers (Twidell and Weir, 2015).

3.14.2 Radiation

Radiation is another component of drying whereby direct sunlight heats materials. This is used in solar thermal collectors to heat a working fluid typically air or water. Direct radiation can be used in both passive and active means in greenhouse drying (Gomes et al, 2023)

$$q = \varepsilon\sigma(T_s^4 - T_a^4) \tag{6}$$

Where emissivity of the surface ε, Stefan-Boltzmann constant $5.669x10^{-8}W/m^2K^4$, Surface temperature T_s, Parallel surface temperature T_a. This can be linearised,

$$h_r = \varepsilon\sigma(T_s + T_a)(T_s^2 + T_a^2) \tag{7}$$

Heat exchanged by two parallel bodies of area A.

$$\dot{Q} = h_r A(T_s - T_a) \tag{8}$$

Dincer & Zamfirecu) (2016) explains that practically there is a combined process of convection and radiation in heat transfer processes which presents the following.

$$\dot{Q}_{tot} = \dot{Q}_{conv} + \dot{Q}_{rad} = (h_c + h_r)A(T_s - T_a) \tag{9}$$

(Dincer & Zamfirecu, 2016)

3.14.3 Conduction

Heat transfer by conduction is achieve through direct contact with solid materials it can be approximated with the following equation.

$$\dot{Q} = -k\frac{A}{L}(T_2 - T_1) \tag{10}$$

Where, thermal conductivity k is influenced by material properties and defined as heat flow per unit area per unit time (W/m K). Area A is the surface area and length L, I the thickness of the solid material. Heat will transfer through the material from the heated surface T_1 to T_2

3.14.4 Solar collectors

Once again depending on the equipment used, there will be different equations to model. Initially, it is important to know the availability of the sun’s energy as this is the primary energy source.

- Sun path diagram can be used to plot solar position – expected energy available.
- Solar collector area will determine the energy that can be used for the dryer.
- Heat transfer between solar collector and heating fluid (i.e water/air)
- Fundamental Aspects Heat Transfer - Drying Phenomena: *Theory and Applications* (Dincer & Zamfirecu, 2016)
- Identify the times when external heat source is required. TES and conventional energy.

3.14.5 Thermal Energy Storage (TES) Equations

The TES will be charged with solar energy during daylight hours. This is then used to provide energy to the dryer when solar irradiance is minimal or absent. TES is split into two types: Sensible and Latent heat storage and can use both natural and synthetic storage materials. The following equations can be used to modelled as heat input during these times.

3.14.6 Sensible Heat Storage (Solids and liquids)

$$Q_s = \rho V C_P (T_{max} - T_{min}) = \ m C_p \, (T_{max} - T_{min}) \tag{11}$$

Q_s is sorted heat, m is mass of material, C_P is the specific heat of storage material. T_{max} and T_{min} are initial and maximum temperatures of the storage material (Ekka and Kumar, 2023).

3.14.7 Packed Rock bed TES

A packed rock bed is a common TES SHS. The behaviour of the TES system uses complex equations both one-dimensionally and three-dimensional. The author has attempted to model the behaviour of the TES system via development of the energy equation by Ekka and Kumar (2023) and acknowledges the limitations.

$$Q_s = m_{air}C_{p_{air}} (T_{air} - T_{amb}) = m_{rock}c_{p,rock}(T_{rock} - T_{rock,initlal}) - Q_{loss} \quad (12)$$

For simplicity, it shall be assumed that the heat loss Q_{loss} through conductive, radiative and convective means is small and can be neglected. There will be a change in rock temperature over time shown in equation (12).

$$\Delta T_{rock} = \frac{dT_{rock}}{dt} * dt \quad (13)$$

Assuming no losses to external environment, the transfer of heat of the air to the storage media is equal to the heat gain.

$$(T_{air,in} - T_{air,out}) \approx (T_{rock}(t) - T_{air}) \quad (14)$$

The mass flow of the air and the specific heat will be assumed constant.

$$Q_s = m_{air}c_{p,air}(T_{rock}(t) - T_{air}) \quad (15)$$

The energy storage balance will be the product of temperature over time and the material properties of the storage media. Without a heat source there will be a heat loss thus the minus sign preceding the Q_s term in equation 15.

$$-Q_s = m_{rock}c_{p,rock}\left(\frac{dT_{rock}}{dt}\right) \quad (16)$$

Equation (15) can be rewritten to substitute in storage heat of the rock and rearranged for change in temperature over time shown in (17).

$$m_{rock}c_{p,rock}\left(\frac{dT_{rock}}{dt}\right) = -[m_{air}c_{p,air}(T_{rock}(t) - T_{air})] \quad (17)$$

$$\frac{dT_{rock}}{dt} = -\frac{m_{air}c_{p,air}}{m_{rock}c_{p,rock}}(T_{rock}(t) - T_{air}) \tag{18}$$

The differential equation (17) is solved using the general equation with

$$b = \frac{m_{air}c_{p,air}}{m_{rock}c_{p,rock}}$$

$$T_{rock}(t) = T_{air} + (T_{rock,} - T_{air})e^{-b(t)} \tag{19}$$

Charging the TES will use heated air to increase the temperature of the rocks.

$$T_{rock,charge}(t) = T_{air} + (T_{rock,} - T_{air})e^{-b(t)} \tag{20}$$

Discharging the TES will assume the inlet air is at ambient temperature and is heated as it passes through the rock bed. The air flow will have the same mass flow and specific heat for simplification.

$$T_{rock,dicharge}(t) = T_{ambinet} + (T_{rock,} - T_{ambinet})e^{-b(t)} \tag{21}$$

3.14.8 Packed Rock Bed -TES Energy

Tiskatine and collaborators (2017) explain that the energy stored in a packed bed thermal storage is given by the following equation. This is the energy per kilogram in Joules of rocks whereby specific heat of rocks $C_{p,r}$ in J/kg.K, rock density ρ_r in kg/ m^3, porosity ε, volume of vessel V in m^3 and temperatures of initial and final air flow in °C.

$$E_{rocks} = \rho_r C_{p,r} (1 - \varepsilon) V (T_f - T_i)$$

(Tiskatine et al., 2017)

This equation assumes the rock storage vessel is filled entirely with only the void fraction $1-\varepsilon$ available for air movement. An increase in vessel volume and temperature difference will affect the energy output of the rocks with all other variables remaining constant.

Park and others (2014) researched heat transfer of a rock cavern TES system they identified granite rock density ρ_r, porosity ε, and specific heat $C_{p,r}$ to be 2700 kg/ m^3 and 0.862 kJ/kg.K respectively (Park et al., 2014).

3.14.9 Latent heat

Latent heat storage (Solid – Liquid, Liquid- Gas)

$$Q = m[a_m \Delta h_m + C_{sp}(T_m - T_i) + C_{lp}(T_f - T_m)]$$

Where a_m is PCM fraction melted, Δh_m is the latent heat of fusion. C_{sp} and C_{lp} are storage material and latent material specific heat values (Ekka and Kumar., 2023).

3.15 Limitations of method

Complex design often encompasses multi -discipline teams to work on separate parts or functions. This is a limit to this current research design approach as it can only offer an initial high-level concept based on the authors perceptions. Moreover, this methodology has been developed to support creativity in a systematic and repeatable design framework. The structured process should also provide impartial evaluation. Ultimately, the creativity of design ideas will be limited to the author's abilities and the evaluation may be susceptible to the author's perceptions.

System economic costs such as construction, operation, and value derived is unable to be modelled within this research design. Some base calculations may be presented at this design stage to evaluate the conceptual dryer. Cost assumptions will be used. For example, a more complex system will likely cost more in both capital investment and operational costs. Future work to the preliminary design stage would have the opportunity to investigate this further.

As previously noted, drying is a complex process, Computation Fluid Dynamics (CFD) is a common approach to model drying. However, user expertise in problem definition and application of modelling techniques is a significant factor to its accuracy of results. The author's inexperience in CFD modelling presents a risk to the accuracy of the data. As such this research will use and present analytical methods. On the other hand, this may still lack specific accuracy given the approximation made. An energy and exergy analysis are proposed as useful approximation of modelling dryer performance. Once again this is limited by the simplification of assumptions due to the complexity of mathematical equations may result inaccuracies.

It should be noted that the current research is focused with the intent to provide a structured framework for a solar assisted waste dryer to be conceptually developed and evaluated to prove the design concept. Further refinement of the design will be progressed to a detailed design stage whereby these models can be further investigated and validated.

4 Conceptual Design

4.1 Composition and Characteristics

The averaged composition of screening waste is idealised from the De La Torre-Bayo's (2022) research reveals a high moisture content of 77%, with distinct fractions including grits/inert (26%), plastics (5%), paper & cardboard (12%), sanitary textiles (52%), and organics (6%). Despite its heterogeneity, the composition fractions have been found to remain steady.

The literature finds that during storm events, the waste volume can increase substantially, reaching up to seven times (140kg/m^3) the usual dry weather screening to sewage density of 20kg/ML. In general, waste densities can range from 510-1100 kg/m^3. Commonly used mechanical dewatering systems deliver dry solids at approximately 40%-50% moisture content removing a large portion of organic fractions through washing. A common wash process removes the grit fraction prior to processing is required to minimise damage to mechanical equipment.

4.2 Drying

The remaining waste can be idealised as a predominantly heterogeneous mixture. This requires constant drying through sustained high temperatures and low relative humidity. The ideal moisture content of the waste is targeted is below <20%.

Waste fraction separation has been suggested to increase drying rates through targeted drying. However, practically it is largely unfeasible as separation of the mixture would take considerable efforts to complete. On the other hand, this depends on the final destination of the dried waste output, for example if it is used for solid recovered fuel (SRF) this may be worthwhile endeavour. Similar SRF derived from MSW found it could be sold to industries for around $30/tonne in Asia.

Current research has been targeting screening waste for this purpose finding that conventional oven drying dried raw dewatered screenings at ~30% moisture (less the inert fraction) for 48 hours at 105°C to reduce moisture content to 4.5% during laboratory scale testing. This forms the basis of this research drying model.

4.3 Volume and Disposal

Bulk densities of dewatered screening in disposal bins aims to reach 240 kg/m^3 but this can vary significantly. Local landfills charge for waste disposal through the measurement of truck weight via weighbridges not volume. Correspondence with a local southeast Queensland council finds that disposal costs for limited regulated waste is approximately $290 per tonne (J Purcell 2024, pers.comm. 27 February) As discovered, residual waste moisture content adds to this weight thus the cost of disposal.

Through calculation for one specific Brisbane WWTP, there is an estimated average daily disposal of around 340kg based on a general industry rule of 20kg/ML (Cadavid-Rodriguez et al., 2012). Increased waste capture during storm events could increase this to 140kg/ML. Variability in volume necessitates either high capacity or storage stage. Moreover, the financial burden on utilities is evidenced by a public educational video estimating $600,000 per year is spent on screening waste disposal by a local southeast Queensland utility service (Unitywater, 2018).

Solar drying systems offer potential cost-saving opportunities to reduce moisture content further for this waste type. Solar energy systems are supported by Australian government incentives promoting solar energy utilisation to address UN sustainable Development Goals (SDGs).

4.4 Solar Technologies

Solar dryer designs are based on specific needs and functions to produce a combination of constituent parts. Typically, in the agro-industrial sector there are a several different drying system designs, including direct solar drying (DSD), indirect solar drying (ISD), mixed-mode solar drying (MSD), and hybrid systems, each have their ideal temperature ranges. They are identified as DSD (30-60°C), ISD (22-60°C), MSD (45-60°C) and Hybrid (40- 80°C).

A hybrid solar dryer has been recommended for continuous drying operations and large loads more than 1000kg (Arias et al., 2023). Whilst initial investigations find that the screening waste generated is under this threshold, it may be a prudent design feature for the provision of backup power to allow continuous operation in the event of solar energy unavailability.

Solar thermal collectors have been identified in the food industry. Widely used technologies include flat plate collectors (38%), parabolic trough concentrators (20%), evacuated tube collectors (20%), and other available thermal technologies (22%). Temperature ranges find that FPC (30-100°C), PTC (30-300°C), EPC (50-200°C) and Linear Fresnel Reflectors (60-250°C).

Notably EPC and PTC where able to achieve these temperature ranges <3m^2 collection area. Moreover, EPC can operate without direct solar irradiation even in cloud/wind.

Photo-voltaic panels can be used to provide electrical energy to plant equipment and can be interconnected to increase electrical outputs. Conventional battery storage can provide electrical power in the absence of irradiation. PVT collectors combine both electrical generation and thermal heat.

Thermal energy storage (TES) systems have been found to compliment solar drying designs improving performance and reducing energy losses. TES offers a range of options, using natural materials and forced air for cost-effectiveness to concentrate solar power (CSP) with molten salts for higher efficiency. Additionally, water heat storage offers economical operation <100°C whereas thermal oils can be used at higher temperatures exceeding 100°C.

4.5 Problem Statement

Currently mechanical dewatering technology is used to remove organics through washing and reduce screening waste moisture prior to its disposal. This has been found to be effective but limited reducing raw moisture content from 77% to ~37%. Thermal drying represents as potential solution to further reduce the residual moisture content but is highly energy intensive. The thermal drying of screening waste using renewable solar energy represents a novel approach to providing this energy and reducing the residual moisture which has to the authors knowledge, not been considered for this waste type.

Current research finds that composition fractions are influenced by social habits but are relatively consistent. Waste volumes are dependent upon the location and population the WWTP serves thus, each site drying requirements differ. The mixture of the waste types, unpredictable surge volumes, and costs are challenges to a drying solution. Moreover, solar intermittency against continuous waste generation is a problem. However, the potential economic and environmental benefits make it a promising avenue for sustainable screening waste management practices.

A dryer concept solution must consider and adequately address these issues to allow a feasible design to be proposed to industry.

4.6 Reverse engineering

Reverse engineering is important to this research in two key ways.

- Firstly, any solar assisted dryer design will need to either integration or have similar performance attributes to currently used to be a viable solution to WWTPs.
- Secondly, provides an overview of functionality the design may not have yet identified.

Cross (2017) explains Pahl and Beitz views on conceptual design which includes the establishment of function structures through diagrams and to identify suitable solutions principles. Moreover, The VDI 2221 model breaks the design problem down through the identification of the overall problem which uncovers the sub-problems to individual problems. Thus, the solution to each individual problem contributes in part to solving the sub and then the overall problem (Cross, 2017). The understanding of current system function and sub-functions allows this research design space to be broadened.

Local WWTPs have identified two different screening dewatering machines currently used. The Jones & Attwood Washpactor and KUHN Washpress.

4.6.1 Washpactor

Washpactor takes a variety of filtered solids via conveyor or launder to feed into a wash tank. An impeller creates turbulence in the water to break up the waste which then overflows with the movement of washwater into a screw compactor. Clean water rinses off the waste material as it is transported and dewatered via compaction simultaneously. Waste material is forced up an inclined chute to allow for additional gravitational drainage, where a compacted plug of material exits the chute and into a disposal bin.

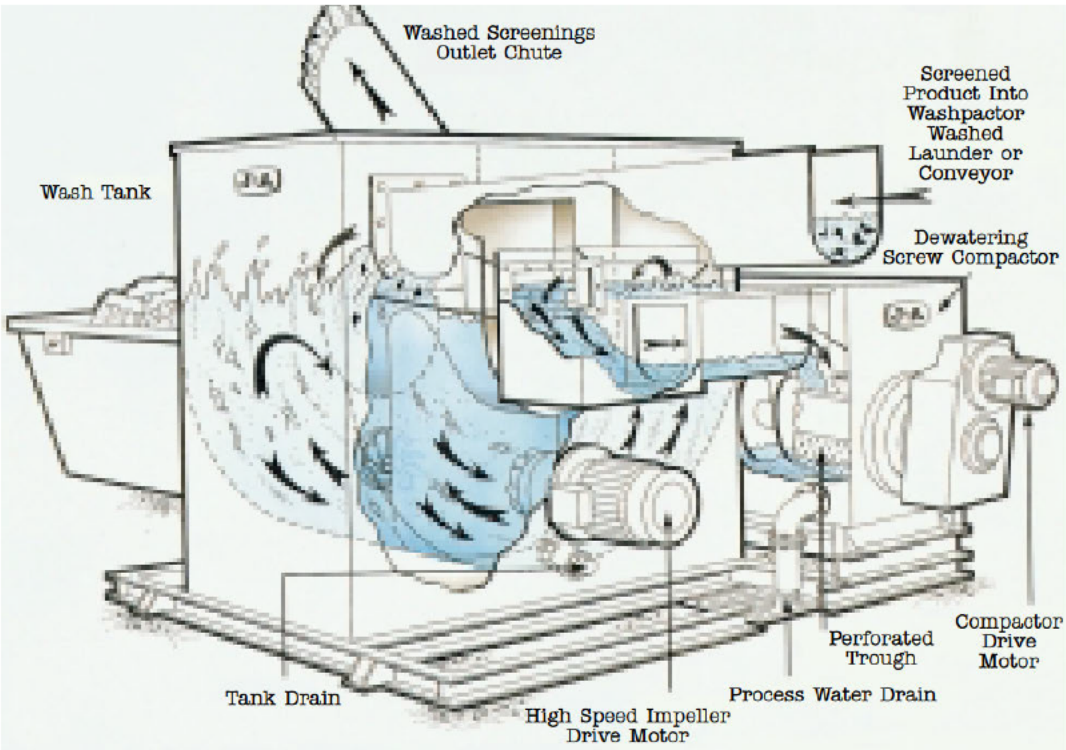


Figure 14- – The Jones and Attwood Washpactor Screening washing system.
Viewed at https://cms.esi.info/Media/documents/eimco_washscreen_ML.pdf

The following observations are found.

- System can be scaled – multiple sizes.
- Removes grit and inserts to protect mechanical components.
- High turbulence in water tank breaks down organic matter different to water jet.
- Washes biological material away using clean water.
- Water transports the waste material through sluices.

The washpactor relies heavily on water movement to transport waste, separate organics, and clean screening material. Waste is agitated by water movement to separate organics from non-organic fractions while it is simultaneously compressed (partially dewatered) and transported to disposal by screw conveyor.

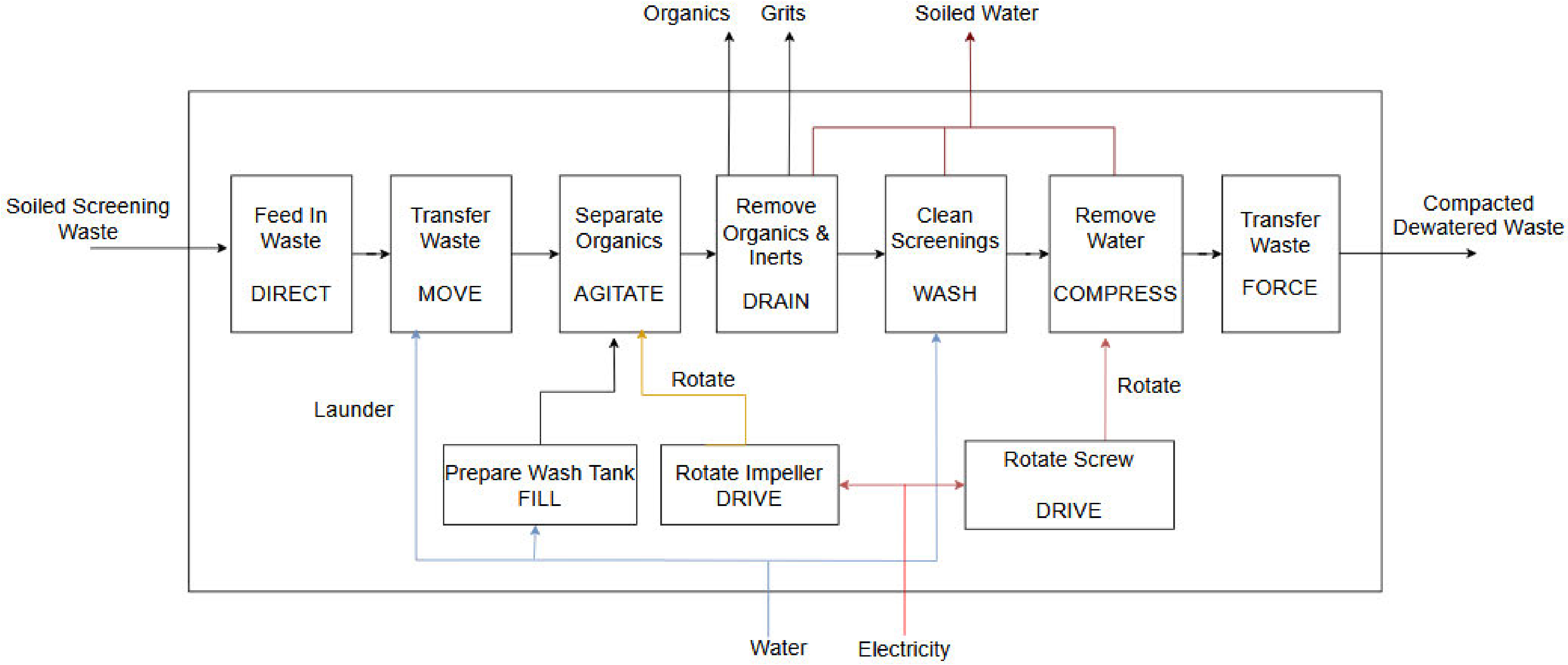


Figure 15-– Washpactor functional block diagram.

4.6.2 Kuhn Washpress (KWP)

Captured screenings are fed into a large hopper which directs the waste into a trough. The trough contains a centralised screw compressor surrounded by a perforated casing to allow solid water and fine particulates to be washed away. The screw action both moves and compresses the moist screening against the outer casing removing excess water. The waste then reaches the end of the screw where it is forced up and a through a inclined chute of decreasing diameter. This back pressure further compacts a dewaters the waste. The addition of more waste forces the waste through the chute where it is finally expelled as a compacted and dewatered plug into a disposal bin.

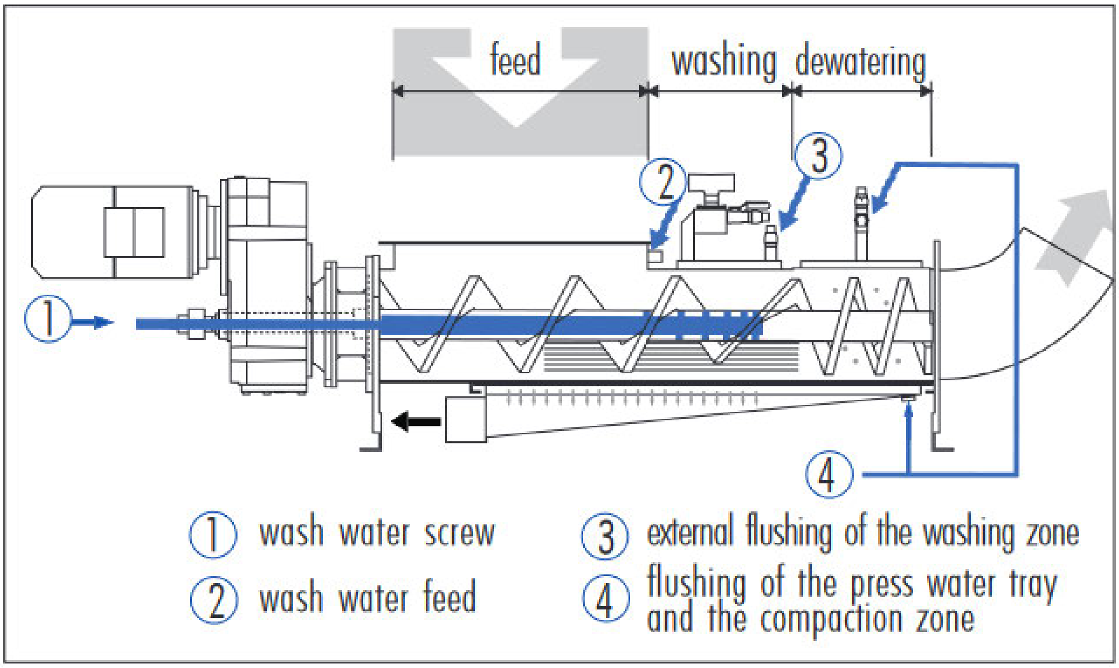


Figure 16- Kuhn Washpress diagram. Viewed at https://3.imimg.com/data3/IR/OX/MY-9357053/kuhn-kwp-wash-press.pdf

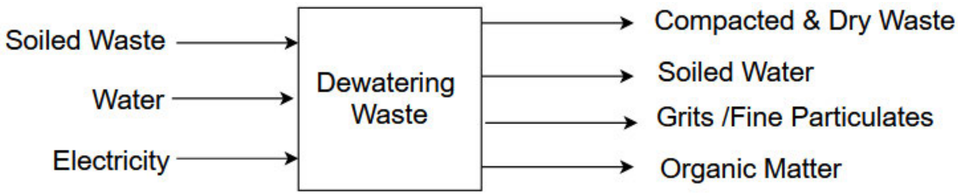


Figure 17- Dewatering high level block diagram of Kuhn Washpress

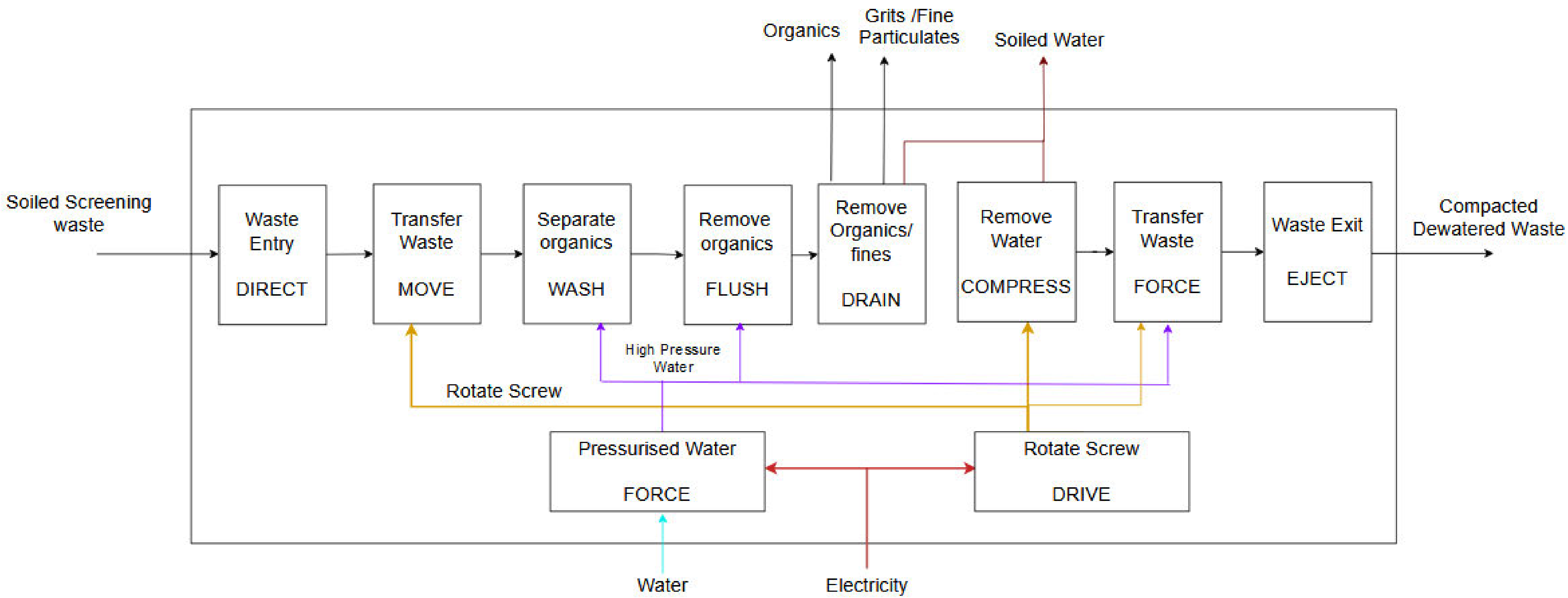


Figure 18- Washpress Functional Block Diagram

Washing away organic fraction is a common process. Note, the use of pressure via the screw conveyor is used to force both movement through the chute and compact the waste reducing waste disposal volume.

The washpress is a simple design using mechanical force to compact and dewater the screening waste. Shaftless screw allows for water to wash from middle outward while dewatering and moving the waste simultaneously. This combined feature increases process throughput.

Other key features of the Washpress were discovered and have been listed below.

- Process both raw sewage and inlet screenings offering versatile.
- Minimal working parts
- Both batch and continuous modes.
- Self-cleaning screen – Wire brush on screw edge
- Washes, compacts, and transports waste
- Variety of sizes
- Motor and gear housing externally located.
- Conveniently located access panels - fully accessible
- Large drainage area along the length
- Robust material – stainless steel, Chromium, and armoured screw
- Large intake hopper for uniform feed.
- High torques via gearing to prevent blockages.
- Modular whirl washing (like washpactor) and shredder add-ons.
- Power output of 2 – 7.5 kW
- Feed Rate 1.4 – 8 m^3/h

4.6.3 Other dewatering technologies

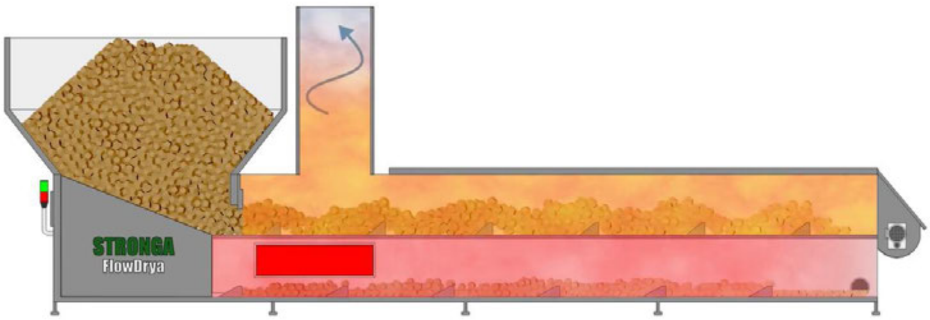
Observations have been taken from HUBER waste technologies for the drying of sewage sludge. From there products, commonalities in the design have been identified.

- Modular and scalable designs
- Integration with other system
- Continuous operation
- Odour- tight
- Low maintenance / Self-cleaning

- Transportation- pumps for liquids. Screw and belt conveyors for dried material.
- Stainless steel and hard-wearing chromium.
- Incline screw press to drain water naturally Q-Press and S-Press
- Screw press usage – very slow to reduce wear (HUBER Screw Press S-Press)
- Double pass though heating chamber to maximise heating times and minimize area
- Maintenance accessible / inspection area.
- Additional shredder process after washing.

4.6.4 Continuous air flow waste dryer

The *Stronga FlowDrya* design is a continuous air flow dryer used to dry wet materials for multiple industries including timber, paper/pulp, agriculture, and waste such as Municipal Solid Waste (MSW). The dryer consists of large flatbed drying chamber divided into two sections. The bottom section is where heated air enters and increasing the temperature, this heat rises to the bottom of the upper-level dryer floor and passes to the upper-level chamber. The dryer uses both convective air and conductive thermal drying to dry the material. Waste is feed into a large hopper and gravity direct the waste to a feed gate which evenly distributes the material on the flat bed. Hydraulic rams move a series of blade faces over designed ramps to tumble the waste and move it along the length of the dryer. This exposes the material to either the heated floor or airflow increasing uniform drying. Saturated air is expelled via an exhaust vent and is used to heat the conductive waste hopper. Numerous sensors detect temperature and relative humidity in the chambers and automatic control adjust inlet air. The heat source can vary and be in the form of heat exchanger module, waste, or residual heat, solar thermal to heat the incoming air.



Viewed at https://stronga.com/wp-content/uploads/2021/06/FlowDrya-UK-2021.pdf

Figure 20- The Stronga FlowDrya continuous flow drying system overview diagram.

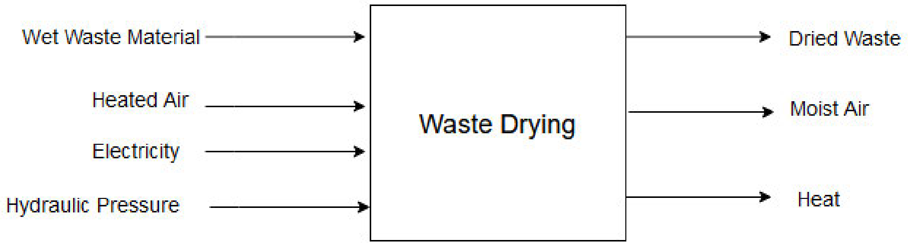


Figure 19- The black box method of the Stronga FlowDrya process.

Key features and functions have been listed below.

- Simplistic drying chamber design - no fans, belts
- Uses both conduction and convection for heat transfer.
- Ability to be used for multiple wet materials.
- Unique agitation design evenly dries material.
- Blade arms move the material slowly down to exit to maximise resident time.
- Heat conduction via expelled heated air heats the awaiting wet waste in the hopper.

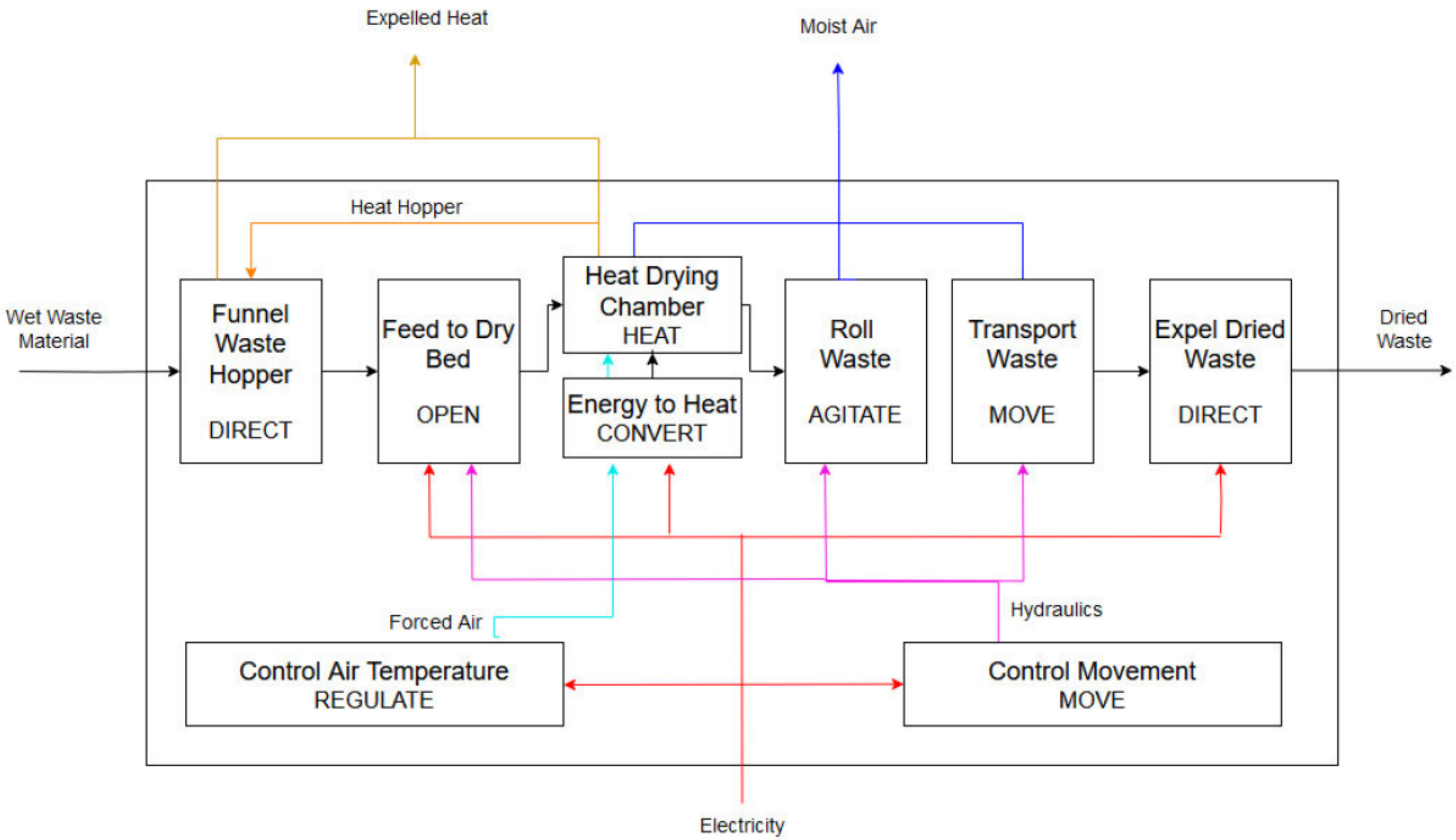


Figure 21- FlowDrya functional block diagram.

Electrical power provides the forced air and hydraulics for the system to operate. The reuse of expelled heat is an advantageous feature aiding to reduce overall energy consumption.

4.7 Links to Solar Assisted Dryer Design

For both the Washpress and the Washpactor, they are found to follow a fundamental and common procedures in both operations. They both wash the screenings to remove organics and reduce odours. Additionally, they both use screws conveyors which both compact the waste to dewater and transport the material through the machine offers reduce process time.

Dewatering by compaction allows both moisture removal and decrease waste volume required in the disposal bins, maximising the space used. Compaction removes moisture through mechanical force. This process is more energy efficient and effective in comparison to fossil fuelled powered thermal drying techniques. Screw conveyors are ideal because they can be shrouded to isolate odours, can facilitate dewatering, and provide a means of material transportation. Moreover, they are simple and robust powered by an electrical motor which can be geared to meet design requirements.

The process of current dewatering could be changed from compression whereby drying could be fulfilled with solar energy through direct solar thermal or indirectly by electric to thermal. However, this process already effectively removes a large amount of moisture and provides a method of encapsulated material transportation which is an important consideration. Solar drying can be incorporated to further reduce the residual waste moisture. Opportunities exist during after the washing stage with thermal heat applied. Compaction is likely to hinder drying so should follow washing or during compaction stage. Moreover, the solar electrical energy produced could aid the plant and equipment currently used.

4.8 Continuous Operation

For continuous operations and large volumes, it finds the process to be a single path through a series of stages. For drying, it is desired to increase the resident time the waste is contained in the drying chamber but equally this should not be excessive to decrease material throughput. Product drying is improved when the material is uniformly spread out, but this also increases the require area for a dryer. To minimise floor area, some dryers can have vertical levels of drying at which different temperature zones are encountered. This is useful to support a regime of decreasing temperature rates drying as with hygroscopic materials. On the other hand, if the material is idealised as non-hygroscopic, the aim is to have high temperature, high airflow, low humidity at a constant rate to dry out effectively.

A key feature is uniform feed control waste input via a hopper. Additionally, this can act as a method of temporary storage. The control of input flow to the dryer is useful as the processing of waste can be halted during times without solar energy such as overnight or during overcast weather. The input feed can be resume or even varied to meet demands.

Waste agitation is another key feature in waste processing used in fraction separation, water removal and drying. Waste agitation is integrated with waste movement to progress the material from one stage to the next.

4.9 Collate Data

The collection of data is an important part of engineering design. Observations, classifications, commonalties, inductive reasoning and calculations can provide a overview of the design limitations and more importantly work towards a design solution (Cross, 2017). The intent is to provide a summation of what has been found to prepare for the creative design process.

4.9.1 Reverse engineering findings

It is common practice to washing and further filter the waste to remove organic matter and grits prior to dewatering. In the two washpactor and washpress design reviewed the wet waste is mechanical dewatered, transported and compacted using screw compressors. This allows for the size of the system to be small and compact finding high torque motors processing the waste in sealed chambers.

So far, it finds that for industrial purposes that the waste is continually moved at varying speeds through a system relating to large and variable flowrates.

Continuous slow movement can increase the resident time of waste for system storage and reduces wear on components. As before, higher torque motor is favoured in comparison to higher speed. This is enabled by sizing dewatering chamber to hold a certain volume of waste but also a front-end storage vessel to provide uniform input to the system. Use in the hopper is a passive means of direction. Most notably in the designs the movement of waste through the system is used to either agitate the waste to promote water removal either by mechanical force in compression using screw conveyors or through conduction and convention heat transfer favouring long and wide conveyors. Waste agitation allows waste surface to be exposed to the heated air to promote heat transfer in drying. Overall, a slower process movement is desirable to increase the resident time but increases dryer size due to increase pathway lengths and potentially the waste storage volumes.

Considering this stacked designs exploit the phenomenon of heated fluid buoyancy allowing heat to rise underneath drying trays or conveyors suited for compact areas. Moreover, in a stacked design multiple height level of a single path increases the resident time of waste in the drying chamber. The designs feed -rate to system movement must be aligned. Front end storage tanks or hoppers can ensure a unform feed rate into the system. Variable motor speeds of the conveyors or screws changes the rate of waste transfer through the system with the length of travel pathway assisting in this timing. This pathway directs the waste stream which can be further filtered to separate and divert some waste components to other areas. The pathway directs the waste and controls its final destinations. Gravity is used to roll the waste and to drain water away using inclines.

Designs using heated fan forced air, the dryer is enclosed to allow the direction of heated airflow to pass over the waste materials and to exhaust moist air naturally. For this design, expelled air requires a scrubber to clean emission odour. The enclosed space promotes the heat retention within the chamber increasing overall temperature. Whereas, in mechanical dewatering compression is achieved by reducing the space in which water resides in the waste forcing moisture out.

4.9.2 Dryer design – Stages

The design itself can be consider as several stages of a single system to meet the outlined objectives. If the design uses the idealisation of each stage is a module that that performs a series of functions, then the design can be used to fit a specific site.

- *Solar Capture*

  The collection and conversion of solar energy into usable energy. Solar collectors, pipes/ducts, motors/fans, controls, sensors, invertors.

- *Energy Storage*

  The storage of collected solar energy for later use supported by traditional energy supply. Tanks, pumps, fans, bypass, storage media, batteries, backup supply, re-heat.

- *Drying chamber*

  The area of the system where heat drying of the waste occurs expelling excessive moisture. Insulation, heating elements, pipes/ducts, exhaust, controls, sensors, fire suppression.

- *Processing*

  Processing facilitates the storage and controlled movement of waste through the stages. Channels, conveyors, screens, motors, hoppers, gates,

- *Preconditioning (optional)*

  The initial process for raw screening waste of high moisture and organic content washing and dewatering prior to drying. Use when waste is not dewatered first. Wash, motor, press, filter.

This design will consider these stages excluding preconditioning. The idealised site at Murrumba Downs has existing washpress mechanical dewatering technology which the design system will expand on.

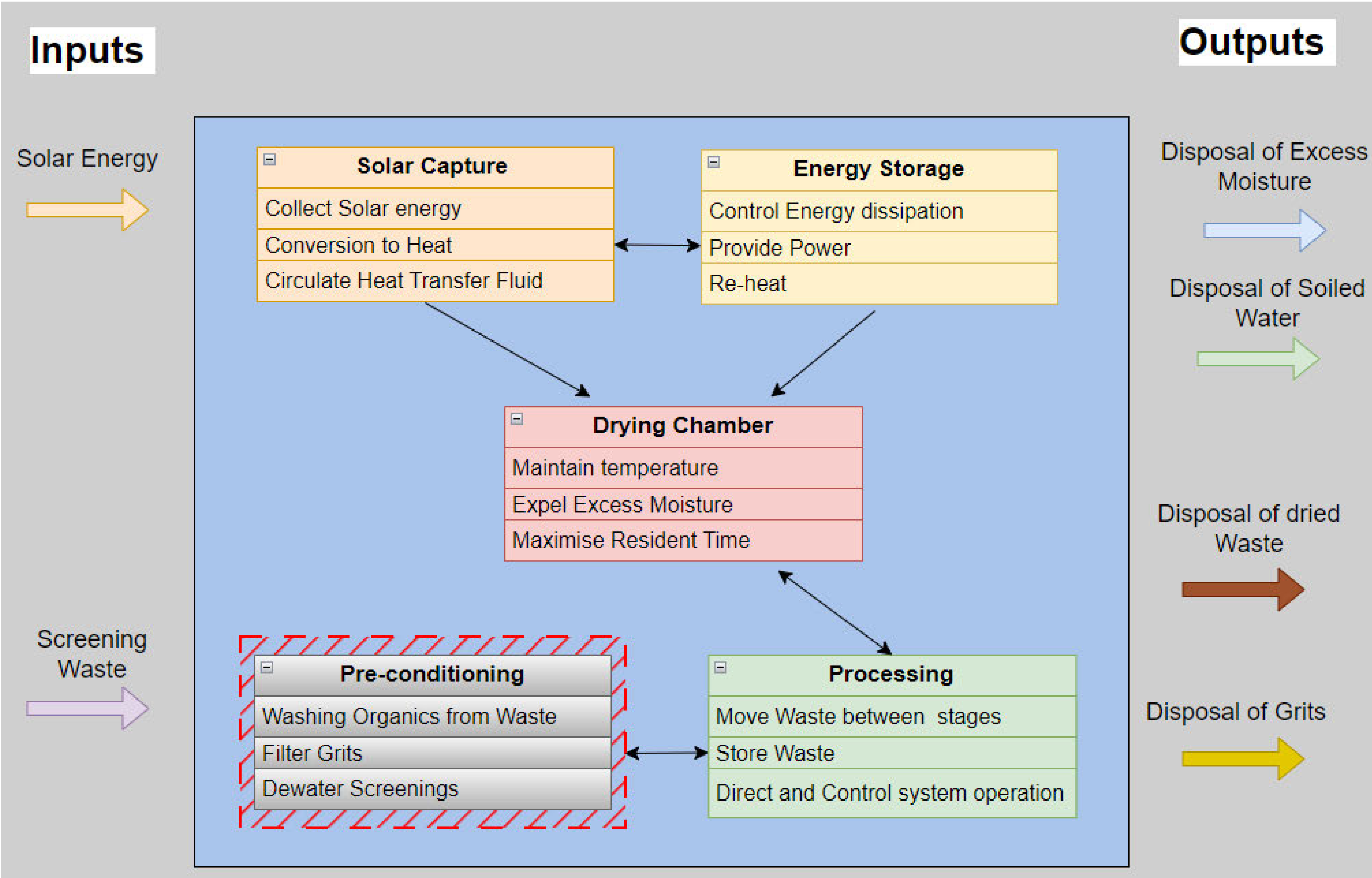


Figure 22- Overall Functional diagram of the solar assisted dryer broken up into five main section detailing the function each stage must perform.

4.10 Define Customer Needs

In the absence of specific data regarding the generation of screening waste in the context of Southeast Queensland certain assumptions have been needed to be made to define the design specifications. The chosen site is the Murrumba Down WWTP Site operated by UnityWater in the Moreton Bay region North of Brisbane. The waste volume averages are taken as the basis of this research's dryer design specifications.

The dryer will process waste as a mixture of both wet and dry material Cadavid-Rodriguez and collaborators (2012) cite Wilson & Thomas (2009) Brisbane research giving the industry general rule of thumb of 20kg/ML dry weather (Cadavid-Rodriguez et al., 2012) The Murrumba Downs WWTP is reported to process 17 ML per day in 2017 (Unitywater, 2018). This results in 340 kg of waste per day. A small design overhead of 3ML (or 60 kg) in addition to the 2017 data has been made which estimates a daily average production of 400kg per day. However, first flush effects from heavy rain can increase organic and plastic fractions in the screenings to around 140kg/m^3 but for short durations suitable front-end storage and variable process speed are considerations to address this.

Water is contained within the waste is made up its mass fractions to reflect this each fractional average moisture content percentage is reduced by this value resulting in Sanitary textiles (41.1%), Paper & Cardboard (41.7%), Vegetal (31.6%), Plastics (22.8%) and other fraction (40.6%). De La Torre Bayo (2022) noted no significant change in waste fractions overnight (De la Torre-Bayo et al., 2022).

The design assumes that existing mechanical dewatering occurs prior to entering the dryer. It is reported that the moisture content of the waste is reduce by 40%. Taking an average initial raw screening waste moisture as 77% (De La Torre Bayo et al., 2022). As such, the new moisture content of the waste is 37% post dewatering. The overall assumption is that the remaining water is distributed equally across each waste fraction as in table 5. This reduces the waste weight to 148kg estimated at 58.6kg (wet) and 89.4kg (dry) weight.

If it is assumed steady conditions and total water removal for a seven-day operation the total generated waste mass is 2.8 tonne with a weekly disposal cost of $812 or $42,224 per annum. The total removal of water using this solution would generate less weight at 2.38 tonne per week with a weekly disposal cost of ~$690 or $35,890 per annum. A saving of $6333 per year. What is not quantified is the reduction in waste transportation cost, transport emissions, water saving and environmental benefits. Of greater significance, is the potential for valorisation deriving value in SRF or generating energy

In the scenario of available Australian markets for SRF, the potential found by Ngamaket and others (2021) research state a value of $30 per tonne which could generate an annual revenue of $3712 for ~124 tonnes of dried screening waste for this site. Moreover, if processed to RDF-4 or RDF-5 as suggested by Chavando and others (2021) the value could be four times greater at $16,492 per year. Energy generation has not been fully defined but the ability to generate energy to support drying, other WWTP process operations or export would be a worthwhile endeavour to reduce costs and impacts.

As such, the dryer shall process up to 148kg of moist waste per day and attempt maximise the removal of ~60kg of daily residual moisture from within the waste

4.10.1 Solar Resource at Local Plant

An idealised constraint will be the available solar collector area at the chosen Murrumba Downs WWTP site. A possible location is adjacent to the existing inlet screening area and between other facilities shown in figure 23. The area has a large pipe passing through it which will be used to demark the boundaries of two areas: area 1 in the yellow box and area 2 in the red box

The area appears to be grassed with several trees, this would provide a convenient location for solar collectors due to the proximity of the existing conveyor and waste disposal bins. Area 1 is approximated as 400 square meters, roughly 16 meters wide and 25 meters in length. Area 2 is approximated a 225 square meters, roughly 15 meters wide and 15 meters in length. These areas will be used as the design site so calculations can be performed and will encompass the conceptual design including solar collectors, process equipment and waste storage.

The area does not account for shadowing effects of nearby buildings and plant equipment. A practical design consideration may be to have the solar collectors located on a platform higher than the surrounding building with process located underneath this would solve both shadowing and area constraints for existing sites.

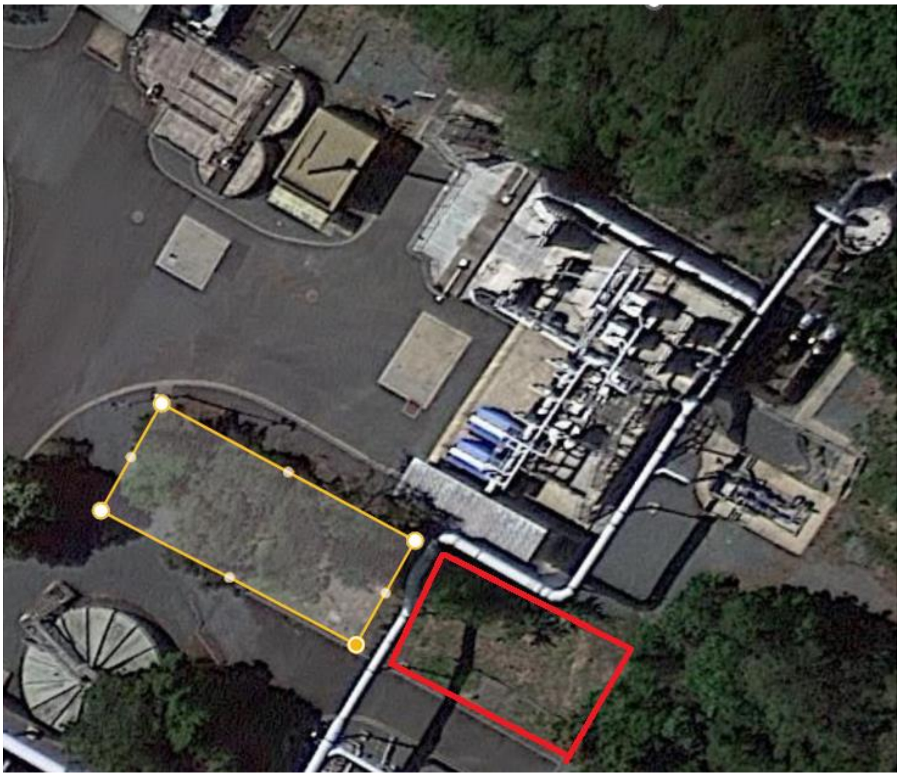


Figure 23- Aerial view of Murrumba Downs STP screening works.
Identified are two areas for the system design. Area 1 is the yellow box at 400m^2 and area 2 is idealised as 225 m^2

4.11 Analyse data

To develop a successful solution a solid understanding of waste and drying is required. Screening waste is a mixture of relative constant mass fractions.

Solid waste drying is difficult due to the mixture of waste types and hydrophilicity. As discussed, the mixture has both hygroscopic and non-hygroscopic materials which require different drying approaches. The waste mixture is idealised as hygroscopic as it includes the bulk fraction of sanitary textiles (cellulose fibres), paper, plastics and grits/inserts. These materials require high drying temperatures and low humidity. Low humidity drying is an important factor to prevent waste moisture absorption. Drying is assisted with forced air flow free moisture removal at ideally a decreasing drying rate until completely dried out. The remaining waste fraction is organics which is a hygroscopic material in screening waste representing only 5% the total waste fraction requiring high drying temperature and vapor pressure for dehydration. The waste is assumed to be hygroscopic for this design requiring high to medium temperatures which is achievable through tracked concentrated solar collector technology (>60°C - 250°C). This contrast with passive greenhouse type dryers whereby temperature limits typically do not extend beyond >60°C.

The only know screening waste drying data is from De Torre Bayo and collaborators (2022) work which successfully dried out from 30% to 4.5% moisture at 105°C in 48 hours in lab conditions excluding inert fraction (De Torre Bayo et al., 2022).

Fraction	Statistical parameter	Physical parameters		
		Moisture (%)	Ash content (% TS)	Volatile matter (% TS)
Sanitary Textiles	**Average value**	81.10	8.10	92.10
	Deviation	2.10	2.60	2.40
	Coefficient of Variation	0.03	0.32	0.03
Paper/ Cardboard	**Average value**	81.70	5.60	94.30
	Deviation	2.00	0.40	0.60
	Coefficient of Variation	0.02	0.07	0.01
Vegetables	**Average value**	71.60	10.40	90.30
	Deviation	3.60	0.90	0.30
	Coefficient of Variation	0.05	0.09	0.00
Plastics	**Average value**	62.80	10.00	89.90
	Deviation	6.30	0.90	1.20
	Coefficient of Variation	0.10	0.09	0.01
Others	**Average value**	80.60	16.50	84.20
	Deviation	7.50	1.80	1.80
	Coefficient of	0.09	0.11	0.02

Figure 24- Average value of non-mechanically dewatered screening waste composition for individual fractions on a dry basis. Table taken from (De La Torre Bayo et al., 2022)

Table 5 finds that 148kg of partially dewatered screening waste is processes each day at the Murrumba Downs WWTP requiring ~60kg of water to be removed from post dewatered screening waste.

Moreover, the unpredictable waste variability and odour emission controls (sealed system) necessitates waste storage. This allows for waste to be uniformly fed into the dryer, maintenance activities, waste redirection which is a useful design feature. As such the volume must be sufficient to meet current demands.

Annual Fractions (Averaged)	Sanitary Textiles (%)	Paper & Cardboard (%)	Vegetal (%)	Plastics (%)	Other (%)	Total Mass (kg)
	52	12	6	5	25	100
Weight per %	208	48	24	20	100	**400**
Average MC %	81.1	81.7	71.6	62.8	80.6	
Wet basis	0.81	0.82	0.72	0.63	0.81	
Wet mass (Kg)	168.7	39.2	17.2	12.6	80.6	318.2
Dry mass (Kg)	39.3	8.8	6.8	7.4	19.4	81.8
Post Dewatering						
Weight per %	77.0	17.8	8.9	7.4	37.0	148
Average MC %	**41.1**	**41.7**	**31.6**	**22.8**	**40.6**	
Wet basis	0.41	0.42	0.32	0.23	0.41	
Wet mass (Kg)	31.6	7.4	2.8	1.7	15.0	58.6
Dry mass (Kg)	45.3	10.4	6.1	5.7	22.0	89.4

Table 5– Idealised moisture content and mass percentages for screening waste at Murrumba Downs WWTP.

Although associated costs of a dryer are not considered in this current research, some base costs can provide a perspective of the indirect costs incur to operators such as transport and disposal fees of screening waste. Murrumba Downs is located within the City of Moreton Bay region with landfill costs for restricted sanitary waste is estimated at $290 per tonne (J Purcell 2024, pers.comm. 27 February). Assuming an average of 400kg per day or 2.8 tonne per week costs arrive at $812 per week or $42,224 annually. Current methods partially dewatered waste by a residual 37% moisture content or 60kg daily water weight contributing to this waste cost estimated at $6,333.60 annually. This is only indirect costs, disposal transportation, fuel, contractor fees, GHG emissions, power consumption, water loss and landfill leakage are but some of the other costs not analysed in this report.

High temperature drying from CSP and PV electricity for plant equipment can be provided by solar power which is abundant is Australia. Electrical power is overall simpler method for both power and heat via resistive heating. It provides a useable energy with little changes needed to incorporate as a hybrid design. Thermal heat is more complex converting from solar energy and transferring the heat via fluids with the reliability of energy storage in the medium itself but offers more in energy efficiency.

4.12 Identifying Constraints and Limits

Solar generation is naturally variable. Average conditions are used in some basic calculations and assumptions within this report. Given the continuous nature of waste generation, the design must factor in backup power in the case of solar unavailability with this provision assuming that this is equal to continue dryer performance as per average solar conditions.

The selected site is indicative of potential sites the design must integrate into with the dryer area constrained by other plant housing and fixtures. Solar collection is only one aspect of the dryer design with processing and storage needed. A stacked or multilevel design including roof or subterrain areas may be a worthwhile consideration. The design limitations are divided into two areas. Area 1 is the largest and will be used to model thermal solar collectors while area 2 will be used for PV solar. The process and storage are to be situated underneath. The elevation of solar collectors is advantageous to minimise shadowing from nearby buildings approximately 3-4 meters tall. However, other structural considerations have not been fully investigated, but if achievable it would offer significant benefits to existing WWTPs.

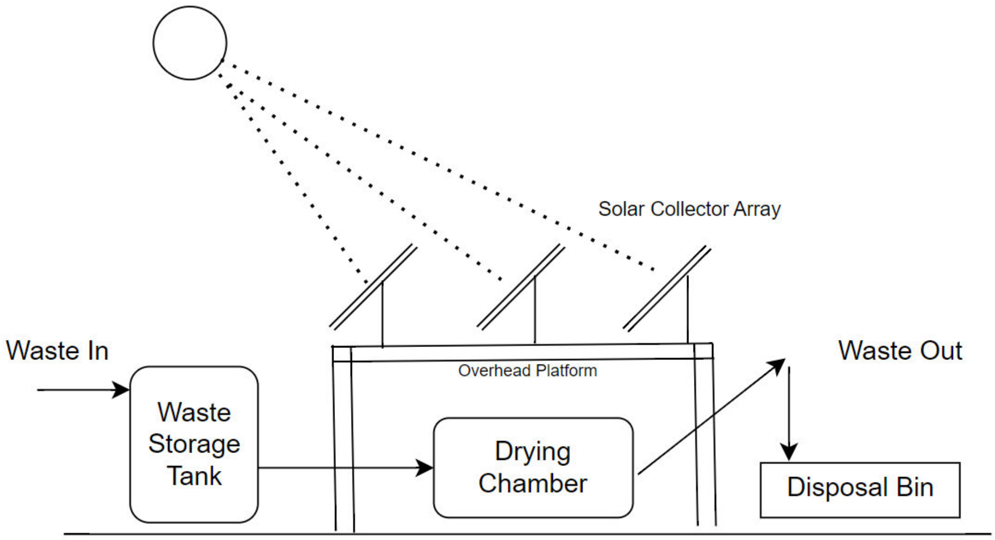


Figure 25- Indicative equipment arrangement to maximise limited space available for a dryer design at Murrumba Downs WWTP.

4.13 Design Calculations

Several basic solar calculations have been undertaken to define the problem, its constraints and possible solution direction for this site.

4.13.1 Solar Availability

Solar energy can be utilised in two ways in this dryer design. Thermal heat using concentrated solar power and electricity generation using solar photovoltaic collectors.

Modelling has been performed based on average days per month (Kalogirou, 2023). Horizontal irradiance (Hh) approximated from figure 26 as a per unit area (square meter) based on ideal conditions and assumptions. Direct irradiance can be calculated and is the key factor in determining solar energy collected thus allowing for a general but direct comparison of fixed and tracked solar collectors at the Murrumba Downs site. Yan and collaborators (2013) explain that there are additional limitations including low irradiance, ambient temperature, shadowing, collector efficiency, air flow and reflections which affects energy generation (Yan et al., 2013). Only shadowing and collector efficiency has been factored into the current solar theoretical modelling for this research. Nevertheless, this provides a general comparison of the collector arrangements for this concept design.

This report has used the Kalogiru (2023) approximation of day number and average days for each month (table 6). Additionally, Twidell & Weir (2015) provide the approximate solar insolation variation with season and latitude received on a horizontal plane H_h. The data models the Murrumba Downs site (27.27° latitude) for the purposes of identifying design constraints regarding the solar resource over an idealised year.

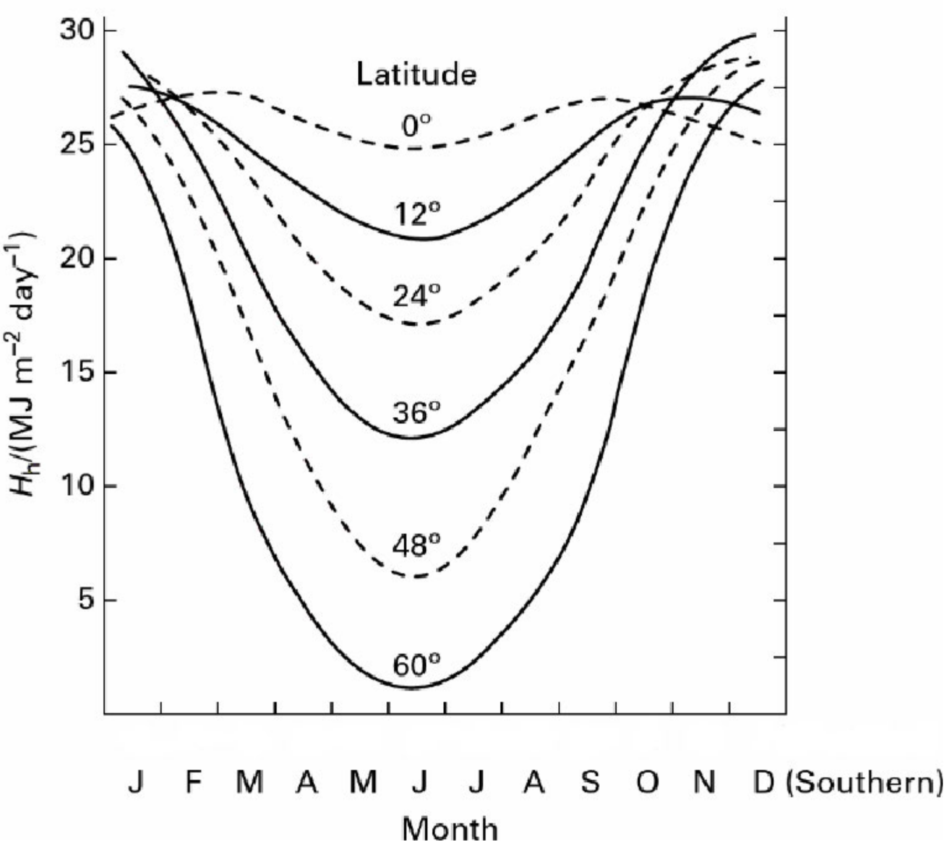


Figure 26- Daily ideal solar insolation variation with season and latitude received on a horizontal plane H_h. Adapted from Twidell & Weir (2015)

H_h is the daily insolation ($\frac{j}{m^2}$ per day) on a horizontal surface and is approximated by month from figure 26. This is converted to W/m^2.

$$G_h^{max} = H_h\left(\frac{2N}{\pi}\right)$$

$$H_h \approx \left(\frac{2N}{\pi}\right) G_h^{max} \tag{22}$$

(Twidell & Weir, 2015)

Month	Day Number	Hour of the Month	Average Day of the Month		
			Date	N	δ (degrees)
January	i	k	17	17	−20.92
February	$31+i$	$744+k$	16	47	−12.95
March	$59+i$	$1416+k$	16	75	−2.42
April	$90+i$	$2160+k$	15	105	9.41
May	$120+i$	$2880+k$	15	135	18.79
June	$151+i$	$3624+k$	11	162	23.09
July	$181+i$	$4344+k$	17	198	21.18
August	$212+i$	$5088+k$	16	228	13.45
September	$243+i$	$5832+k$	15	258	2.22
October	$273+i$	$6552+k$	15	288	−9.60
November	$304+i$	$7296+k$	14	318	−18.91
December	$334+i$	$8016+k$	10	344	−23.05

Table 6- Day number and recommended average day for each month. Adapted from Kalogirou (2023)

Hourly variation of irradiance G_h (W/m^2) which can be approximated product of a local latitude G_h^{max} value and the local time and day number.

$$G_h \approx G_h^{max} sin\left(\frac{\pi t'}{N}\right)$$

$$G_h = \frac{H_h}{\left(\frac{2\pi}{N}\right)} * \sin\left(\frac{\pi t'}{N}\right) \tag{23}$$

(Twidell & Weir, 2015)

Solar concentrators require solar beam irradiance G_b to work. The beam irradiance varies throughout the year for each solar hour and zenith angle. However, atmospheric conditions can change the amount to beam irradiance collected. The beam irradiance is a horizontal irradiance divided by the cosine of the zenith angle θ_z.

$$G_b = \frac{G_h}{Cos\, \theta_z} \tag{24}$$

4.13.2 Fixed Panel

For the fixed panel, angle of incidence β, has been set to 26° facing North based on Yan and scholars (2013) recommendations for PV solar in Brisbane.

Kalogirou (2023) Identifies fixed panel as an average power output allows for a consistent power output throughout the year of between 1.40 to 1.56 kWh/m^2. This has been averaged as 1.48 kWh/m^2 annually. This energy is intended to be used to electrical power dryer equipment as suggested by Lingayat and others (2021)(Lingayat et al., 2021).

Solar PV panels and thermal collectors can be added together in arrays to customise electrical and thermal output of a given site. Cost, complexity and panel density are associated with suitability of such systems.

Table 7 shows the collected energy throughout the year of between 1.73 to 2.43 kWh/m^2 . This is averaged as 2.11 kWh/m^2 annually.

4.13.3 Single axis tracking

As discussed in the literature review for single axis tracking it finds that E-W polar and N-S horizontal are most consistent obtaining similar results as full tracking as shown in figure 6. It finds that N-S horizontal suffers poor performance in winter months. Consistency of solar collection is desirable for the design, E-W tracking is also advantageous due to low shadowing when using in collector rows in large solar farm arrays for power generation. This too could be used in the scale up of this conceptual design where collector rows are used in increase power or solar energy through increased collector area. The tracked system is modelled as a E-W tracking with horizontal N-S axis (figure 7 (d)).

The tracked system requires the value of the beam slope (beta) to be minimized so the panel face is perpendicular to the direct solar irradiation beam (Gb). The model used 180° freedom limits the travel of 90° on both sides, whereby 90° is parallel to due East and -90° is parallel to due West.

Single axis tracking requires the angle between solar beam and the collector to be minimised to maintain a maximum value of beam irradiance.

$$\cos\theta = (A - B)\sin\delta + \left[C \sin\omega + (D + E)\cos\omega\right]\cos\delta \qquad (25)$$

$A = \sin\phi \cos\beta \qquad B = \cos\phi \sin\beta \cos\gamma$

$C = \sin\beta \sin\gamma \qquad D = \cos\phi \cos\beta$

$E = \sin\phi \sin\beta \cos\gamma$

(Twidell and Weir, 2015)

The above equation uses the combination of collector slope β, Azimuth angle γ, solar incidence angle θ, Solar hour ω, declination δ and latitude φ to model solar angle cos θ.

The method of solar tracking is accredited to Dr Byrenn Birch (*MEC4104 – Renewable Energy Technology -University of Southern Queensland)* whereby Microsoft Excel Solver is used to minimise the angle of the sun to collector surface normal $cos\theta \rightarrow 1$ by minimising the collector slope angle β with the differences between the left and right side of the equations found by the Root Mean Square method. Physical limitations of collector movement may impede the solar collection but for the purposes of this design the limitations are $\pm$90° are used for East to West respectively. Realistically, limits of travel may be less due to practical restrictions on tracking frame, nearby buildings and ground elevation. Nevertheless, it has been modelled as ideal to generally compare the methods of tracking and non-tracking.

Table 7 models the Murrumba Downs site and provides monthly averages of expected Direct Solar Irradiation (DNI) under ideal conditions for a single axis tracking collector by modelling each daylight hour for an idealised year. For this analysis, a monthly average, the maximum and minimum irradiance as limits of the design being 883, 1069 and 859 $W/m^2\,K$ respectively.

Month	Monthly Approx $G_h(W/m^2)$	Monthly Average $G_b\,(W/m^2)$	Monthly Max $G_b\,(W/m^2)$	Monthly Min $G_b\,(W/m^2)$
Jan	28	928.24	962.96	909.66
Feb	26	918.66	937.77	907.23
Mar	22	871.71	876.09	869.51
Apr	19	827.67	910.99	887.76
May	17	822.59	1003.17	960.10
Jun	16	865.55	1061.37	997.03
Jul	17	873.70	1068.63	1012.80
Aug	19	894.71	989.13	949.60
Sep	22	851.52	930.76	925.97
Oct	26	948.99	964.91	940.03
Nov	26	874.42	902.75	858.64
Dec	28	921.66	958.70	902.24
Totals	**22.2**	**883**	**1069**	**859**

Table 7- Direct Normal Irradiation (DNI) Monthly average, maximum and minimum values at Murrumba Down WWTP site.

Table 7 has been generated using Microsoft Excel from the data in table 6 and figure 19.

Furthermore, Table 7 and figure 27 show the comparison of the two methods. Summer months have increase solar collection of up to 71% but only ~15% in winter. It finds that there is an overall 42% improvement in collected solar energy with the tracking system considering both the high summer and low winter differences for an ideal case.

It is expected that cost and complexity would be greater than that of the fixed panels. On the other hand, a fixed system is idealised to produce a steady output with minor fluctuations with minor maintenance. Fixed systems may benefit from being closely installed not needing to consider panel movement only shadowing. Increased quantity of panels and higher efficiency would be envisaged to increase costs in this case albeit while keeping complexity low, reducing the advantages of a tracked system.

Month	Power (kWh) per m^2		Power increase (%)
	Tracked	Fixed	
Jan	1.44	2.43	68%
Feb	1.49	2.37	59%
Mar	1.44	2.17	51%
Apr	1.46	1.91	31%
May	1.49	1.73	16%
Jun	1.52	1.74	15%
Jul	1.56	1.79	15%
Aug	1.55	2.00	29%
Sep	1.53	2.06	35%
Oct	1.56	2.43	56%
Nov	1.38	2.27	65%
Dec	1.40	2.40	71%
Annual Average	**1.48**	**2.11**	**42%**

Table 8– Annual Solar modelling of fixed and solar E-W tracking panels.

The solar tracking system on average generate 42% more power than that of fixed systems. However, the tracking system power output reduces to ~15% in winter like the fixed system but increases to ~70% during summer.

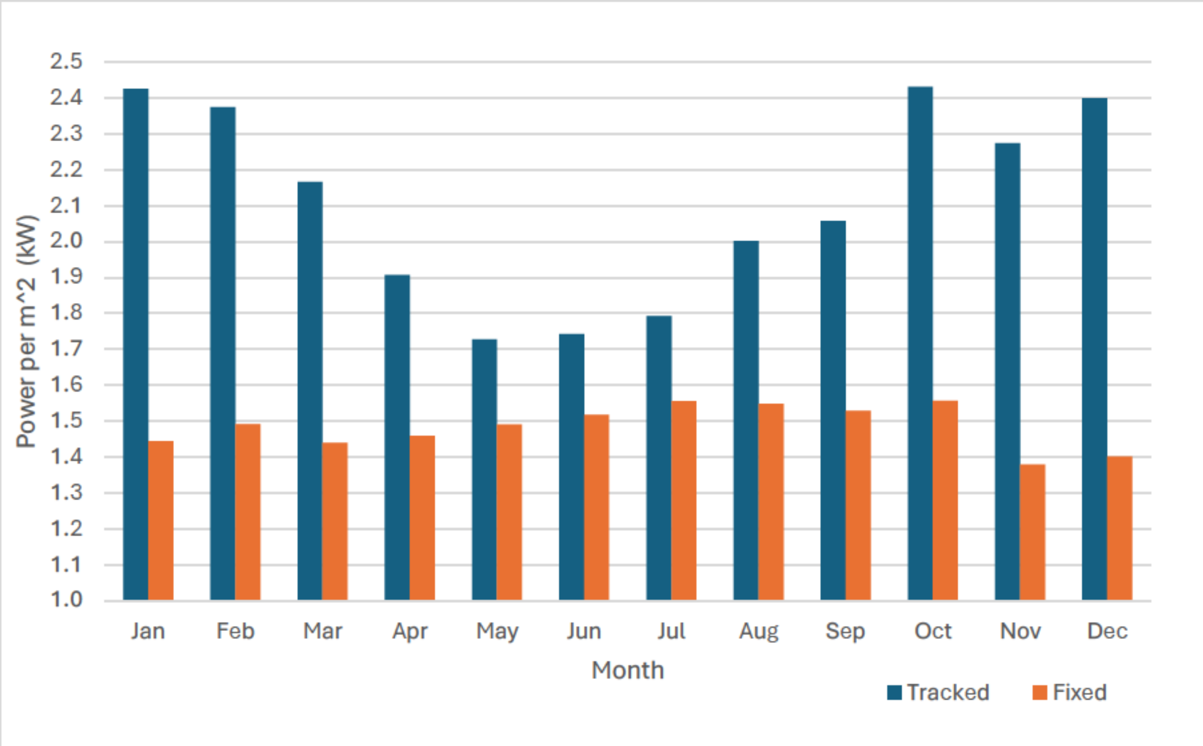


Figure 27-Comparison between single axis tracked and fixed solar tracking over an idealised year.

Figure 27 shows the solar modelling finding that fixed panels facing due north provide a relatively consistent power output. Whereas, tracking solar can maximise direct solar irradiation in the summer months.

4.14 Define Problem - Waste

Screening waste volumes are highly variable and can be up to seven times the average amount in heavy rain depending on the stormwater connection pipework (Cadavid-Rodriguez et al., 2012). The design system for the selected site must be capable of processing a minimum of 148kg of waste per day as a mixture of water and solids. A volumetric flow rate is assumed 18.5kg per hour with an estimated density of ~200kg/m^3 noting the high variability of waste densities from mechanical compaction.

$$\dot{V} = \frac{\dot{m}_{waste}}{\rho_{waste}} = \frac{18.5\ kg/h}{200\ kg/m^3} \rightarrow 0.0925m^3/h$$

4.14.1 Flat bed

The coverage of waste over a flatbed will cover an area length L, and width W, and will be equal to an hour worth of volume V, where 0.0925 m^3 . It can be assumed to increase the capacity of the flat bed to account for variations in waste thickness. A thin spread of waste can decrease the drying time in forced air dryers. Moreover, conductive heat transfer from flatbed to the waste mass can assist thus speeding up the drying process. An assumed 25-millimetre thickness or depth d is initially calculated.

$$V = L * W * d \;\rightarrow\; LW = \frac{V}{d} \tag{26}$$

$$L * W = \frac{0.0925m^3/h}{0.025m} = 3.7 \approx 4m^2/h$$

$$L = \frac{4\,m^2/h}{W} \quad \& \quad W = \frac{4\,m^2/h}{L}$$

The same process can occur for varying thicknesses. A reduction in thickness to 20mm, 15mm and 10mm finds that surface area per hour is 4.63, 6,17 and 9.25 m^2/h. Figure 28 shows these trendlines on the graph. The total flatbed length must accommodate waste generated in an hour and can be separated into a series of flatbed runs as needed. Additionally, multilevel conveyors can be orientated one above the other to reduce dryer length but increasing dryer height.

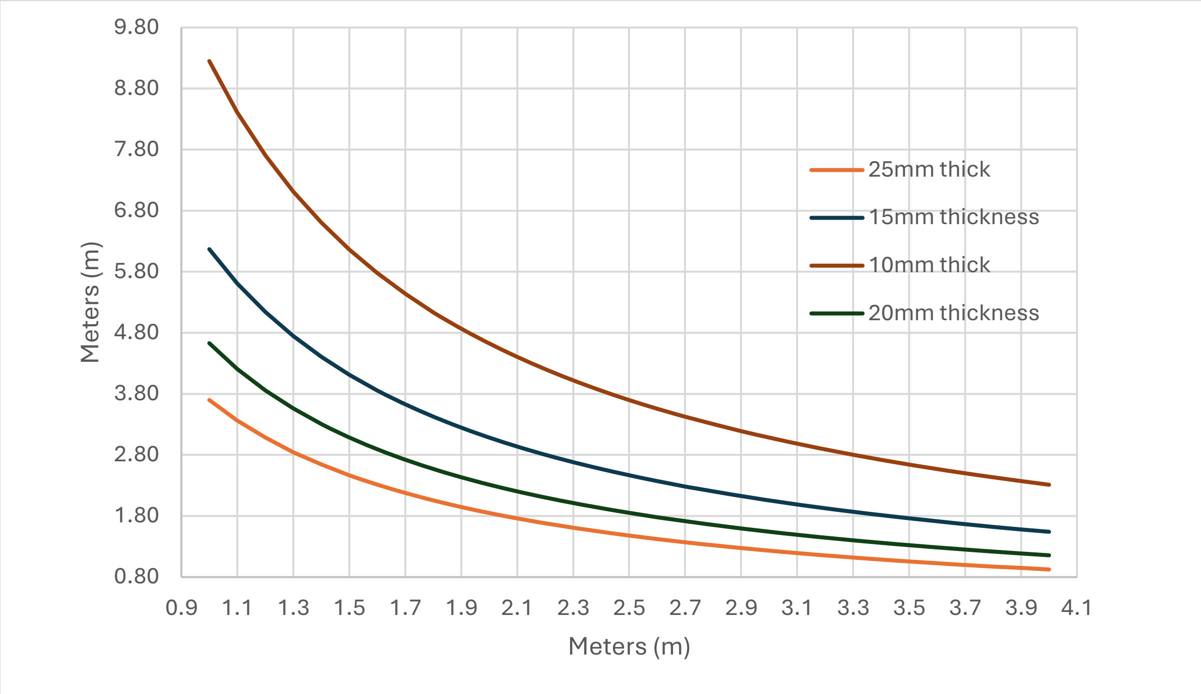


Figure 28- The relationship of width and length of a flatbed conveyor for varying waste depths

Figure 28 shows the relationship between flatbed width and length for a specific waste volumetric flow rate at a specific depth or thickness. Note, the equation for length and width are equal so have not been explicitly labelled in the graph. The graph is used to provide general guidance for the design.

There are numerous considerations that must be undertaken for the flatbed conveyor. It should consider the waste thickness variability but also the energy and material requirements of additional overhead in conveyor dimensions. The specific site may also have limitations on physical size. Moreover, heat transfer may require the waste to be thinly spread. However, given the nature if the waste mixture consistent thickness may be difficult to achieve.

In addition, conveyor standardised widths or lengths could assist in parts and maintenance increasing the reliability of the system.

4.14.2 Rotary drum

A rotary drum is more complex to analyse since waste does not fully adhere to the inner surface of the drum when rotated to a vertical position. It has been assumed that the drum slowly, but slow rotation will decrease dried waste output. Rotary dryers are typically angled on a 3 to 5° tilt (Susanto et al., 2021). Internal spiral guides to progress the waste through the drum.

Moreover, the drum size will limit the capacity of the dryer it is undesirable to have a small diameter drum since this restricts waste it can process.

$$V = 2\pi RL * d \quad \rightarrow \quad R * L = \frac{V}{\pi d} \tag{27}$$

$$R * L = \frac{0.0925\,\frac{m^3}{h}}{0.1571m} \rightarrow 0.589 \approx 0.6m^2/h$$

$$L = \frac{0.6\,m^2/h}{W} \quad \& \quad W = \frac{0.6\,m^2/h}{L}$$

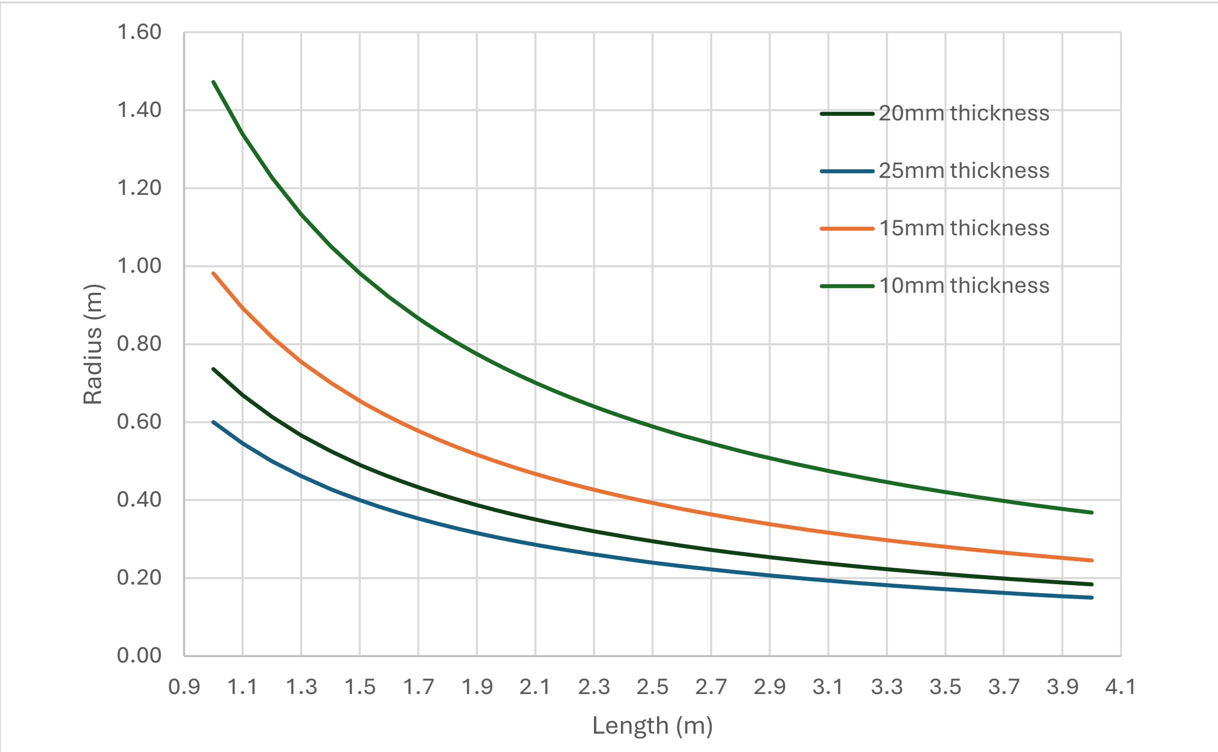


Figure 29- The relationship of drum radius and length of a rotary drum for varying waste depths

Figure 29 shows the relationship between drum radius and drum length for a given waste volumetric flow rate. Typically, at a length of >3 meters there is a small decrease in the radius required. Whereas, under 2 meters there is a larger increase in the drum radius required. A 1.2m diameter drum at length ~2.5m could achieve a waste thickness of 10mm based on the volumetric flow rate and the simple assumptions which do not factor in dynamics of the rotation.

In both cases, a uniform volumetric waste feed is desirable. If waste processing needs to be increased speed of rotation or travel through the dryer can be increased but the cost of decreased moisture reduction. Once again, waste storage should have the capacity to store to prevent this occurrence.

4.15 Clarify Design Objectives

So far, the objectives of the design are not fully defined. Through the understanding of the design functions will allow further solutions to be developed (Cross, 2017). The objectives allow for a clear and define targets to meet with the process documenting the designer steps. Any design must retain its functional purpose to be a viable solution to the given problem. In this design, it is required to "*remove moisture from screening waste*." This requirement can be expanded to gather more specific details "must *remove moisture from 40% to <30% using thermal heat energy to dry screening waste and transport to disposal bins*". As can be seen the expanded objective provides clear and detailed information for potential solution to be developed. Furthermore, following the same example, incineration is a method of moisture removal so is a solution to the problem, but through the research this is not legally permitted setting a constraint to the original objective. Importantly, the design cannot have emissions to meet legislation requirements, so this objective has a high importance to another desirable objective in the list.

As a designer, the objective must be expanded and clearly defined. Hierarchical ranking helps develop a design solution to the objectives. The generated solutions may not meet all objectives but quantify which one have responded to the primary objectives aids the solution ranking against others. A list of dryer requirements has been produced from the previous sections. Table 9 attempts to expand and specify these design requirements so they can be arranged into hierarchical levels. Cross (2017) explains that not all objectives are independent from one another. Some objectives can be considered as sub or lower objectives as a means of achieving a higher-level objective. For example, durability of the design is the sub-function of reliability, therefore reliability is the higher objective the design should achieve through the selection of durable materials. The relationships between the identified functions can be mapped as an objective tree in figure 30.

For the main purpose of the dryer design in to reduce moisture content of screening waste. As can be seen in figure 30, there are many more functions this dryer must do to meet its functionally as a successful design solution. They have been grouped and four main design objectives have been identified for the solar assisted dryer which are high reliability, high performing, functional and add value to the process.

Table 9 – Objective clarification table

Objective	Why do we want to achieve this?	How is this going to be achieved?	What is the problem?
Primary			
Reduce Moisture	Removal of excess water absorbed in the waste to reduce weight prior to disposal or other routes to valorisation	Compaction Heating	Mixed waste is partially dewatered by exiting methods.
Reduce Volume	It is desirable to minimise the waste volume to decrease the amount of disposal transportation required. Maximise energy and financial savings.	Compaction Pressure Moisture reduction	Low waste volume is most efficient to save space in landfill, reducing costs. Less transportation means this process is worthwhile.
Must be reliable	Waste screening is a continuous operation. Downtime would increase waste volumes stored	Simple operation Ease of maintenance Maximise energy -i.e TES, batteries etc	Poor reliability would render the concept of drying waste useless. Integration with conventional energy allows for continuous operation but with little energy savings.
Must be durable	Waste screening is a continuous operation. Downtime would increase waste volumes stored The design will be subject to high temperature and external conditions. May	Robust materials Fit for purpose design Follow material standards for design in anticipated environments (AS, ASTM, ISO).	Durability assists in the reliability of the design. Long lifespan will reduce costs over long term. Ensures the reliability of operation over service life. Strong materials will last longer under the

	include high pressures, moisture and chemical liquids (refrigerant, thermal oils, salts) in a continuous industrial operation over many years.	Identify current materials in service.	conditions reducing repair and renewal costs over the design's lifetime.
Odour Control	Screening waste is filter from raw sewage. Biological components produce a unwanted odour which must be contained required by law.	Washing screenings Fully sealed conveyors / screws. Fume scrubber	Water Treatment plants treat a populations sewage so are generally in close proximity of populated areas. Odours must be contained as a legal requirement
Transport Waste	Waste is continuously produced. It must be directed to the different areas to be processed.	Mechanical means. Launder channels	Method of separation of waste types to effectively manage the generated waste at disposal. i.e grits disposal and general waste disposal
Secondary			
Drying Time	Minimal drying time is advantageous so more waste can be processed	High heating Pressure cooking	A high heat input will reduce the drying time of the waste but must be balance against the energy costs of doing so.
Efficiency	Higher efficiency will improve the dryer's performance making the design a desirable and providing both environmental and cost benefits.	Good planning Fit for purpose design Methods to re-use energy	High efficiency will maximise the utilise energy and reduce dependency on traditional fossil fuels
Dryer Capacity	Design may need to change to meet demands as waste generation is driven by social habits. For example, an increase	Modular design System split into zones or stages.	Waste volumes fluctuate depending on several external factors. Large system capacity

	heating may require more solar collectors, the design should facilitate this option readily.	Physical space to add functions Simple design and operation Provide waste storage	increases costs while minimal capacity is not fit for purpose. The generic concept should allow the idea to be implemented easily to different sites. Waste volumes vary greatly. It provides a means of futureproofing the design
Flexibility	Concept design function to be used at other sites or be adaptable to changes (Varying loads)	Storage Built in capacity Upgradable	Varying waste loads are unknown a change with people's habits or weather patterns. Needs to be site specific.
Modular	Allows design to be flexible to meet site specific requirements	Design in stages or zones Simple interconnection of stages	Site specific requirements are variable. Waste volumes vary with social habits or local population numbers.
Reduction in costs	Design must present a value or benefit to existing methods to ensure the design is a viable product	Maximise energy efficiency Methods of re-use/recycle energy Simple operation	There is little incentive to change current disposal practices. Cost savings using solar assistance may make the concept viable and attractive.
Ease of maintenance	Dryer will be required to operate continuously. Maintenance ensures minimal downtime and reliability. Ease of access allows maintenance to be performed quickly and safely.	Accessible panels Modular design External parts Simple design	Mechanical systems require human intervention for periodic maintenance, cleaning and renewal. Ease of access will facilitate this for reduce downtime, maximise availability and equipment reliability. Reduced costs with capital expenditure (i.e new system purchase).

Energy Storage	Storage of thermal or electrical energy is needed as solar can be intermittent and not available during nighttime. Energy stored can be used during these times or as needed, maximising the renewable energy collected	Chemical Batteries Heated water, molten salt, PCM Heated natural material (rocks, sand etc). Alternative - Pumped hydro	The operation requires a continuous energy source. Solar can only provide energy during daylight and direct irradiance. Energy storage allows for increase stability of energy to the process and maximise its usage before resorting to fossil fuels.
Backup Power	Waste drying and transportation to disposal is a continuous operation. Backup power is required if no solar irradiance of fault occurs to keep the process ongoing.	Connection to traditional fuels (i.e electricity, gas etc) Requires energy bypass controls and sensing	Solar energy collection can be intermittent and unpredictable. Industrial process requires continuous operation with a dependable energy source to be used as needed. Predictability provides assurance.
Integration with existing systems	Current wastewater operations have existing dewatering systems in place. The design must be adaptable to integrate to become viable and beneficial to current operations.	Understand how current wastewater systems are used and the functions they provide. Determine opportunities to follow on the existing process. For example, conveyor to disposal bin could be rerouted to the dryer stage first.	Existing systems provide a level of dewatering and compaction. Each site is specific in its requirements the design provides a additional step in the existing processing. Compatibility with existing system can make the concept a viable design without risking operational failure.

Simplified drying method	There are several heat transfer mechanisms and combinations to be considered. Complex drying may increase design expense and reliability of the system.	Simplified methods are well documented and may provide some data on anticipated drying results.	Less complexities may decrease system cost. Drying is desired to be predictable, repeatable and controlled.
Feed rate	The feed rate determines the amount of screening processed. Processing must keep up with generation.	Storage tank controls flow rate Staged drying	Controllable and predictable output is desirable regardless of the input volume fluctuations. A specified feed rate limits excessive design costs and energy usage.
Energy Savings	Efficient performance will reduce the amount of traditional energy used for a giving.	Thoughtful design. Energy re-use /recycle	Energy savings will be attractive long term design solution supporting the value of waste drying.

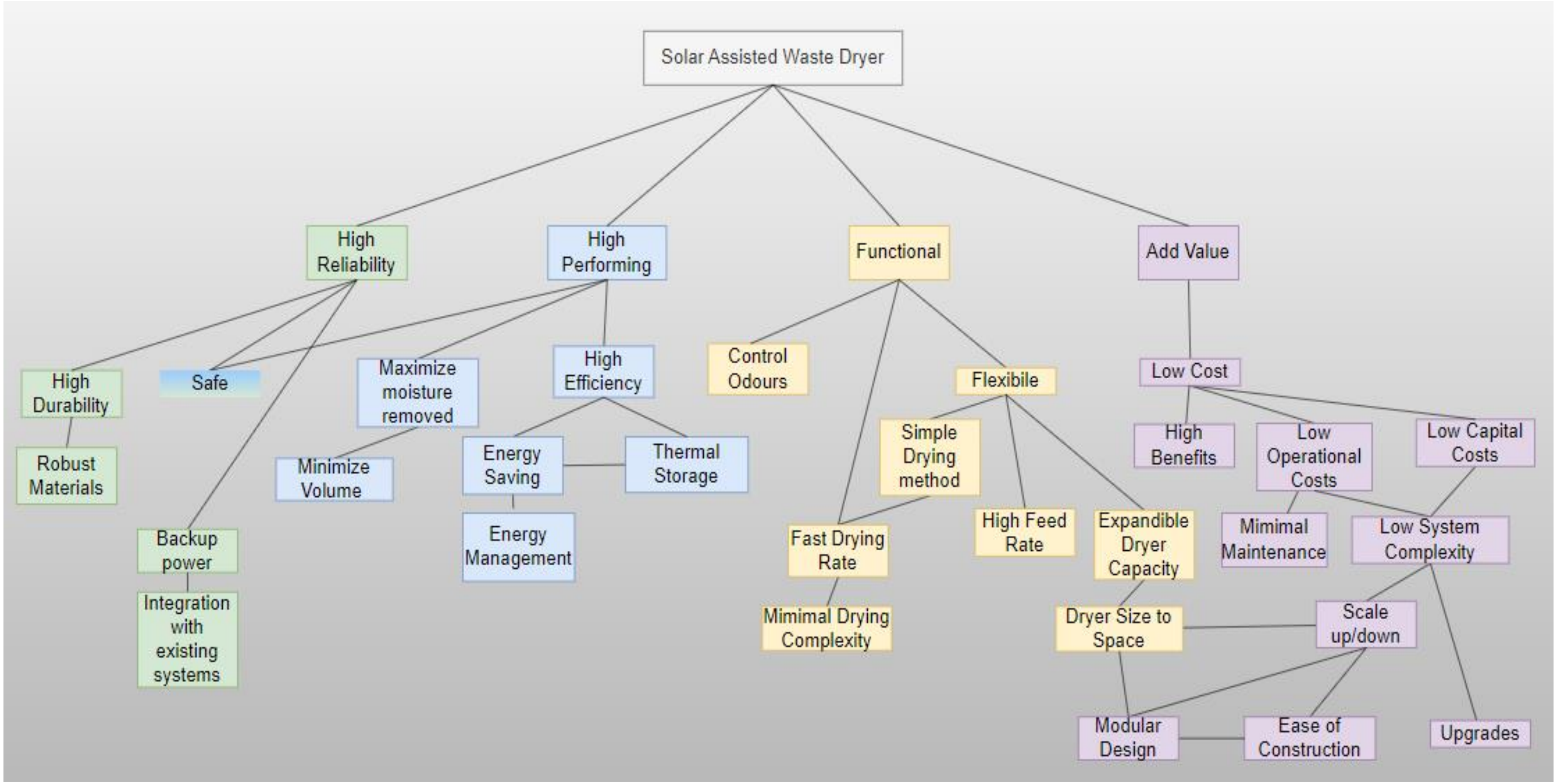


Figure 30- Objective Function Tree and functional inter-relationships

4.16 Setting Design Requirements

The dryer has a key objective to reduce moisture which is achieved through the function of thermal drying. The design shall be developed within a boundary of clear limits known as the design requirements. The requirements set what is to be delivered of a design but does not detail how it will be achieved. For the example, the waste final moisture content must be <30% and the thermal drying temperature must be between 60°C -100°C thus setting the boundary limits of the solution space. In this way, the designer can work towards appropriately providing a design solution to the problem.

Moreover, these requirements set tangible limits for which to evaluate design ideas against one another later in the process. However, Cross (2017) warns of setting the limits too narrowly which is non-inclusive of design ideas. He suggests that requirements should be comparable to other industrial processes and have attributes that are independent of a given solution (Cross, 2017).

The design requirements will be a mixture of engineering and customer wants. Typically, industry stakeholders would define the actual needs of the design. High performing products and desirable attributes requirements may not be feasibly achievable or may be cost prohibited. A consultation process allows the designer or design team to provide realistic visions of the design such a cost estimates and timelines for delivery thus the design brief can be adjusted accordingly.

The design needs to remain functional and should strive to address certain criteria such as safety, legal, environmental and performance constraints. Without these, the design fails in its function regardless of any other attributes. These are mandatory requirements (demands) and shall be achieved above desirable requirements (wishes).

So far, reverse engineering has identified some benchmark limits to use for the dyer design despite having a broad overview. Furthermore, the base functions of existing system provide the independence from a particular solution to expand creativity. On the other hand, the requirements must also to give precise design information. This can be achieved using design ranges. For the dryer design, some restrictions will be physical limitations (height and space) or temperature to achieve drying.

As such, the design requirements should be set over appropriate ranges to meet the identified objective to generate several specific design solutions.

Identified are four main objectives, High Reliability, High Performing, Functional and Add Value.

Objective	Requirement Description	D or W
Functional	Must dry daily waste generated <30% MC per day	D
High Performing	Must dry daily waste generated <5% MC per day	W
Functional	Provide a waste throughput of >18.5kg per hour	D
High Performing	Dry daily waste in <8 hour	W
Functional	Dry daily waste generated in <24 hours	
Functional	Must have storage capacity for >2380kg waste per day	D
Add Value	Provide a disposal compaction of >240kg/m3	W
Reliable	Must maintain an average temperature range of 60°C to 100°C in drying chamber during operation.	D
Reliable	Require minimal maintenance available to operate >95% time.	W
Functional	Must provide drying air temperature of >60°C	D
High Performing	Automated - Require <1 hour worker intervention per day	W
Functional	Fully automated requiring minimal worker interaction	W
Functional	Automatically transport the waste through the system	D
Functional	Must provide maintenance access to serviceable equipment and parts – Motors, pumps, valve etc.	D
Reliable	Easy to repair and service. Standard spare parts	D
Reliable	Must have provisions to automatically fully extinguish and suppress a fire	W
Functional	Must be able to safely	
Reliable	Must safely operate using sensor, detectors, interlocks to prevent harm or damage to workers and equipment.	D

Reliable	Must be fabricated from durable materials. Withstand temperatures -50°C >400°C Withstand pressures <1MPa	D
Add Value	Operate an average >3 hours on stored energy	W
Reliable	Must have energy backup to power dryer completely	D
Functional	Fully contain odours	D
Functional	Fully fit with Area 1 (16m x 25m)	D
Functional	Fully fit within Area 2 (15m x 15m)	D
Functional	Plant and equipment underneath overhead platform cannot be >3m in height.	D
High Performing	Must utilise an average >50% usage of solar PV derived per day	D
Functional	Service life >10 years	D
Functional	Operate as an independent modular dryer	D
Functional	Provide a means for integration with existing waste dewatering equipment.	D

Table 10 – Dryer objective and requirement (Wishes & Demands)

4.17 Design Specifications

Specifications are how the requirements of the system are achieved. These will be specific to each site factoring in physical location, waste processing ability, available space, available solar energy and budget. At this stage, the design specifications are broad and would be further defined in the detailed design, experimentation, comprehensive modelling and industry correspondence. Despite this, an outline of specifications has been attempted based on the collated data.

Drying Time	$Hours$
Drying Temperature	$°C$
Power Consumption	kW
System Cost Estimate	$\$$
Design Lifespan	$Years$
Size Dimensions	M
Energy Capture Capability	kWh
Waste Storage	m^3
Energy Storage	kWh

Table 11- Dryer specifications categories

The drying time is the ability of the dryer to reduce waste moisture <30% while being transported through the system. It shall primarily use renewable solar energy to provide thermal heat and/or solar PV for processing equipment power. The drying time shall at dry waste equal to or greater than the daily waste input feed rate of 148kg per day.

The drying temperature shall be adequate to support the requirements of the drying time with the temperature to be >50°C average across the drying time. A working range of 50 - 200°C is to be considered.

Power consumption relates to the ability of the system to use collected energy well and to minimise the reliance on backup power providing a metric of energy usage. This includes the provision of PV batteries and TES systems. It is expected that the system when operating will use the collected energy to both heat and power without using backup power. In times of solar intermittency, a specification could be to have a minimum backup power of one hour prior to switching to conventional means. Additionally, once solar power is restored the system shall revert to this renewable energy source.

System cost is not fully explored but is envisaged that system cost will be a key factor in implementation. The system cost could be to a set capital and operational expenditure value or provide a return on investment parameter. Moreover, this specification will link with all other listed factors. For example, increase design lifespan may use highly durable and expensive materials. Higher reliability decreases maintenance costs but increases initial design costs.

The design lifespan could specify a certain operational life based on costs. An indicative 10 years would not be unreasonable request for industrial plant equipment. The design would also need to consider maintenance to ensure the level of performance remains consistent over the dryer's life.

Size and dimensions shall fit wholly within the identified zone of the WWTP. A larger drying chamber will need a larger energy source for heating and waste processing. Conversely, larger solar collector area will capture an increased amount of solar energy. However, if the waste generation is small then the dryer system should not be oversized. It is therefore desirable to have the system scaled. First to the waste processing then to the solar collection technology that can be used. Both waste and energy storage must be customised but adequately sized to the expected use of the system.

4.18 Function Analytical Method

An overall black box diagram of the dryer's system design has been produced with interactions between the sub functions. Additional functionality has been shown to display the limits of the design between essential functions and desirable functions. The design in this report considers the screening waste arriving as partially dewatered so does not require the initial filtration, washing, agitation, drying and mechanical compaction. Thermal energy storage, heat recycle, and photovoltaic (PV) electricity are desirable to reduce power consumption but is deemed not essential to fulfilling the objective of reduce waste moisture.

Figure 32 provides a high-level functional diagram for this design noting the boundaries of processing and solar assistance. The sub functions of processing are related to both waste and fluid movement through the dryer. It also stores, rejects and controls the input and outputs of the system. Whereas solar assistance sub functions are concerned with converting solar input to useable system energy be it heat or electricity to power pumps and motors. The figure provides the connection between sub functions to identify the interactions that may occur.

4.18.1- Black Box diagram

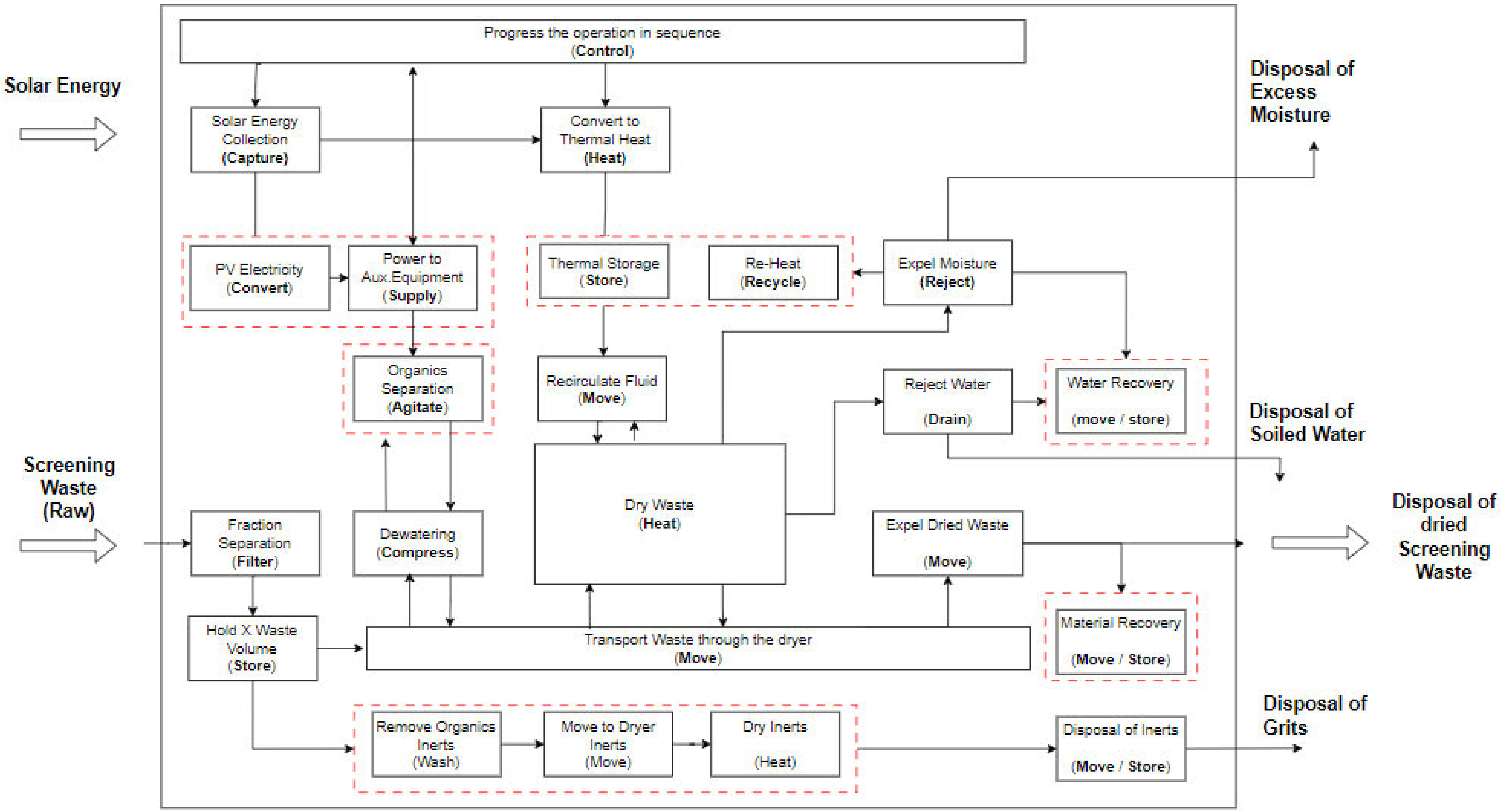


Figure 31- Black box design of solar assisted screening waste dryer. Note, additional functionality within red boxes.

4.18.2 - Solar Dryer Functional Block Diagram

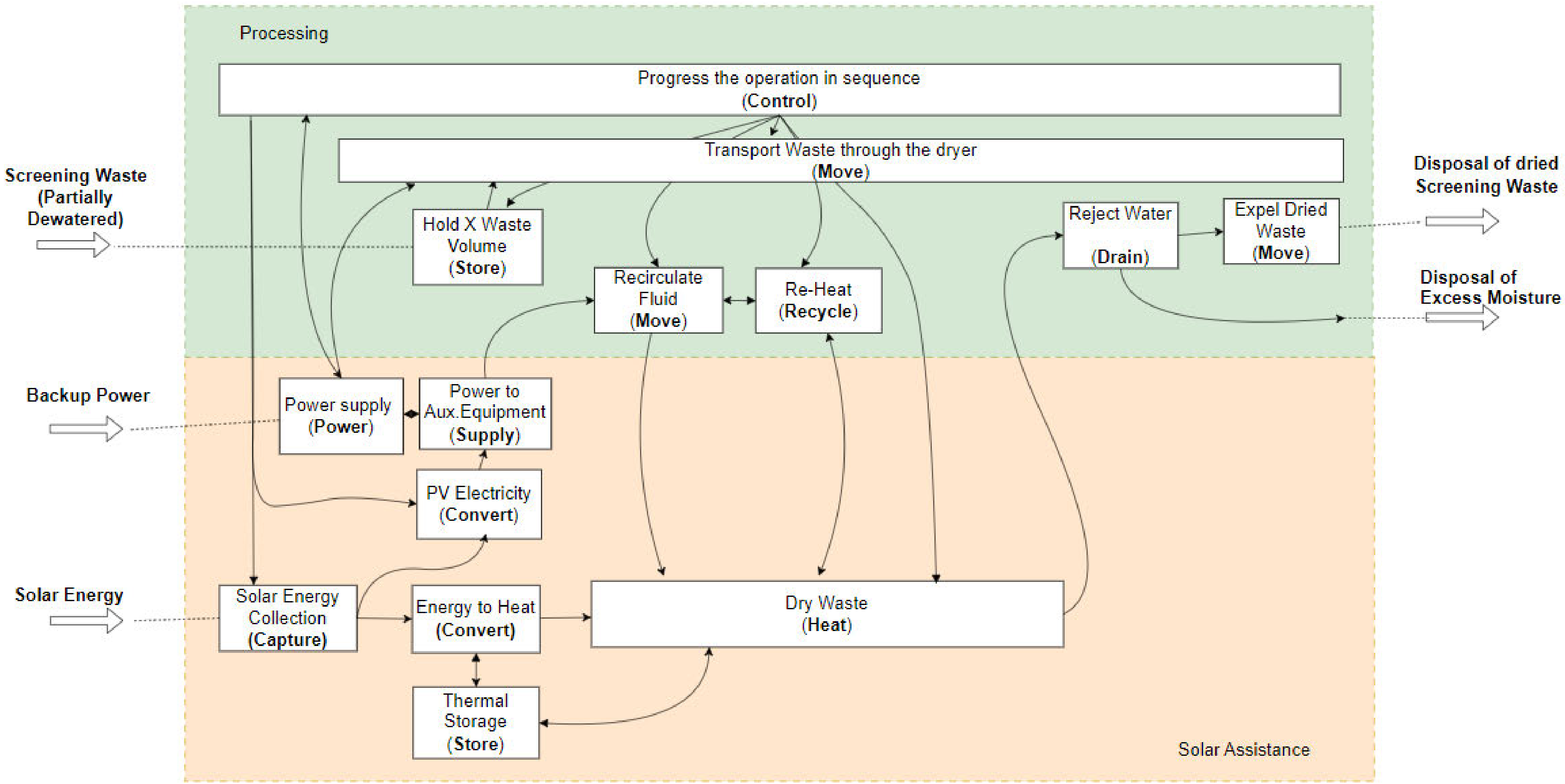


Figure 32—Solar assisted dryer functional block diagram

4.19 Sub Function Identification

So far, several common functions have been found while investigating the current waste dewatering process. Table 12 has been produced identifying the sub function and the means of achieving the function.

Table 12 – Sub-Function identification and means achievement

Essential Sub Function	**Means of Achieving Function**
Filter	Separate waste fractions by means of screens and bars to allow small items to pass through in liquids. Dry materials can be separated by size and weight. Light items using air-blade. Heavy items sink
Store (Waste)	Waste materials can be stored in a container. A hopper makes use of storing and directing material allowing uniform feed rate through physical restrictions. Material in transport is a means of temporary storage. (i.e piping / ducting)
Store (Energy)	Storage of excess thermal and solar energy for on demand later use. Heating of storage hopper from exhaust air Both Latent and sensible heat can store thermal energy. Use of batteries or mechanical system to store electrical energy
Move	Movement of materials is found to be achieved using a continuous motion screw conveyor, repetitive motion blade to push with these motions pushing waste through a channel. Wet waste can use water to launder (push) materials quickly through level or decline channels. Drying air is moved/agitated to create forced flow through fan rotation.
Agitate	Agitate requires the input of force. Water turbulence is used to separate waste fractions through rotation of an impeller. Dry waste agitation is used to tumble and roll waste to expose all surfaces of the material to heat promoting heat transfer.

Dewater (mechanical)	Waste material is squeezed through pressure to removed water. Screw conveyors can achieve this by decreasing the void while progressing the material along. Compaction using electrical motor force, hydraulics, rollers can achieve water removal.
Heat	Heat is achieved through a combination of energy transfer via heat transfer processes typically with a fluid. Forced heated air dries material through convection. Heated liquid in pipes can also radiate heat can conduct heat to other part of the structure.
Capture	Solar energy is captured via collectors. This can be passively – fixed panels or greenhouse type design. Alternatively, this can be achieved actively with tracked control systems and concentrated optics. Materials can be coated black to absorb radiation allowing for heating. Component geometry can increase absorption.
Conversion	Captured energy can be either thermal or electrical. PV solar requires inverter for usable electricity. Thermal conversion is transferred to a fluid such as water, thermal oils
Supply	Commonly, fluids can direct this captured heat to the desired location. Gases needing ductwork and fans. While liquids needing pipes and pumps. Natural ventilation and thermosiphon take advantage of fluid density to transport the fluid. Electrical power uses cables to direct the supply of energy to desired location. CSP can use fibre optics (light + solar energy) to directly transfer this to a desired location
Store	Heat energy can be stored through a charging cycle. Electrical storage is achieved through chemical energy within batteries. Thermal heat can be stored through heated fluid or solid materials Naturally or artificially means
Wash	Screening waste is washed to remove a large proportion of organic matter through rinsing with clean water.
Drain	Effective drainage is important to remove the expelled moisture to prevent reabsorption. Soiled water can be treated and reused.
Control	Automated control is an important feature to sense, measure and adjust the system operation continuously. Temperature, moisture, humidity and

	feed rate can be changed to meet given commands under minimal human input.
Reject	Like drainage, the system must expel moisture and dried materials so it can start over. The system must direct the direct waste or moisture to the desire location.

The above table list the sub functions and their means. Of note and not explicitly expressed in the above examples is safety. It is prudent of any design to be inherently safe or to at least consider safety as an unsafe design fails in its function to be a realistic valid solution.

The control sub function can encompass safety but at this point the exploration of the hazards and the available control measures should be performed. The following table attempts to identify numerous hazard that exist within his design including high temperature heat, electrical power, water/moisture and mechanical compaction equipment. Further hazards or controls measure can be added in the design process.

Table 13 – Functional safety table

Hazard	Presence in the design	Control Measure
Heat	Heated fluid and structure present a risk of injury to workers (Burns and scalds)	Insulated pipes Barriers Temperature controls Fail- safe cut-out Temperature sensors – hotspots Limit temperature generation Expel high temperature water vapour
	High temperature generated into flammable gases or material (fires)	Chamber extraction Sensors and controls Fire suppression Firewalls /barriers Alarms
	Equipment damage through misaligned concentrated solar (if used).	Modular construction to remove isolate a damaged section Redundancy/bypass

	Equipment mechanical damage fatigue, creep, corrosion, thermal shocks	Robust materials for function Use of appropriate standards Facilitate inspections & maintenance

Hazard	Presence in the design	Control Measure
Power	Hybrid design will include sources of external mains power	Electrical standards adhered to Electrical isolations and protection Cabling sized to anticipated power Separation from other services (i.e Water/ Mechanical)
	Mains electrical power accessible	Design ease of access. Alert and alarms Bypass and isolations (E-stops)

Hazard	Presence in the design	Control Measures
Mechanical	Mechanical compaction and transportation	Barriers and isolations Access panel interlocks Sensing Manual isolations (e-stops) Damping/anti vibration
	Mechanical equipment failure	Ease of access to equipment Modular design Redundant/bypass systems Robust design and materials Exposure to high temperatures Automated controls (pumps/fans/motors)
	Sun tracking (if applicable)	Physical travel limits Drive motor thresholds Interlock sensors Barriers/isolation while in operation Manual override Manual positioning

		Damping/anti vibration

Hazard	Presence in the design	Control Measures
Water	Water is extracted to dry material or used as a heat transfer fluid.	Isolation from other services. Pressure relief (boosted water) Heated water vapor -minimise uncontrolled condensation Expel heated vapor away from workers Humidity control to temperature control. Mould/mildew Drain water away quickly and efficiently. Direct water types to correct location (i.e solid water back to treatment)

In summary, separation of mechanical, water, heat and electricity from one another is good practice. Where this is not achievable additional control measures or design can be considered. Human interaction with these sources should be minimised. Automation can provide the safety but requires manual overrides to protect against harm in the event of controller faults or error.

4.20 Brainstorming

Creativity is a key phase to any design. Mental blocks and focus on a single solution can impede creativity. Rastani and others (2007) list common obstacles such as conventional and judgmental thinking, lack of knowledge and distractions hindering creativity (Rastani et al., 2007). Typically, this is undertaken in a group to collate design ideas the intent is to generate large number of design unbounded by practicality to expand on a solution to foster creativity (Cross, 2017)

Brainstorming is a common creative method process to generate and explore many designs idea not initially thought of. Imagination overrides logical reasoning with ideas expanding the solution space to more novel solutions. Many designs will be discarded through the evaluation stage, but the intent of this process is to build or combine on other ideas or methods of achieving the design solution. The evaluation stage is also important as the dismissal of any idea requires reasoning thus better defining the solution space and the overall problem statement.

The design itself can be considered as several stages of a single system to meet the outlined objectives. If the design uses the idealisation of each stage is a module that that performs a series of functions, then the design can be used to fit a specific site. For this activity, the following has been listed giving an overview of each stage. It is required that the statement not be too broad or detailed to allow design idea generation to flow.

One technique used to enlarge the solution space is transformation using verbs to transform the problem – combine, separate, add, subtract, rearrange, substitute, eliminate etc. Additionally, counter planning using an idea thesis against a counter argument (antithesis) is useful for existing solution. The compromise of the two allows for a synthesis of a design.

The design is to be broken down into areas of the design to focus on each rather than a whole system including solar energy, energy storage, drying and processing. Preconditioning is the requirement of processing of capturing, filtering, directing and processing of raw mixed screening waste into the drying system has been excluded from this reports design.

4.20.1 Solar Energy Capture

Fundamentally it is desired to collect and convert the solar energy into thermal heat. Direct methods like greenhouses are simplistic and easy to achieve. Solar concentrators can amplify the solar energy but are more complex. Generally, water or air are the heat transfer fluid to transport heat energy to where it is needed. Natural heat phenomenon convection, conduction and radiation are attempted to be exploited. Appendix I shows the brainstorm sketches.

The brainstorming activity built upon conventional methods of heating from direct sunlight such as greenhouse to indirect methods utilising reflections. Unconventional designs include a magnifying glass to heat a flat plate or ignite gas for a flame or create steam from water vapor, a sawtooth roof absorber/reflector, pressure cooker chamber and a natural ventilation spiral fan. Two more abstract designs look at natural inspiration, leaves of a tree to maximise and collect solar energy or how a sailing boat sail receives solar reflections of the surrounding water.

4.20.2 Energy Storage

Solar energy is intermittent, the ability to store the capture energy in useable form, thermal or electrical is important for this design. Energy storage will maximise the collected energy overnight and during bad weather reducing back up energy costs. This can also provide predictability and control to the heat input into the system an important feature of continuous operation processes. Appendix H shows the brainstorm sketches.

Photo-Voltaic (PV) solar will allow for the generation of electricity which can be stored in a conventional chemical battery which is useful for the running of pumps/fans for force fluid flow. Thermal energy heat storage will likely be most suitable for this design to maintain drying temperatures. The use of latent or sensible heat are conventional approaches and will dissipate over time. Energy conversion to mechanical storage or pumped hydropower retains the energy into a different form but some losses may be experienced. Other ideas include the support of biological methods (composting, aerobic digestion etc) or pyrolysis can produce fuel to support a boiler or generator for the system. However, this increases the complexity of the design.

4.20.3 Drying Methods

The application of thermal heat causes moisture to evaporate from a material. The brainstorm activity took observations from common drying techniques such as clothes drying and cooking. In clothes drying through a washing line, water is evaporated by both radiation and convection. Typically, modern washing machines spin the clothes using centrifugal force to dewater the fabric prior to hanging. Prior to the modern washing machines, compression was used in the form of laundry mangle. Moreover, steam ironing heats and presses the fabric further drying the material. These techniques could be useful in waste drying. Furthermore, cooking uses the application of thermal heat. Common cooking heats food on a conductive hotplate or within an oven which uses a combination of pressure, convection, conduction and radiation. A pressure cooker can reduce cooking times for the same heat input by creating an artificial pressure, equally the creation of a vacuum can also lower dryer temperature. These observations are useful for the solar dryer design. Appendix F shows the brainstorm sketches.

4.21 Morphological Chart

So far, ideas have been developed for each stage and evaluated to the suitability of the design function. This produces a list of sub-functions the system must perform. However, the function remains abstract. For example, the movement of waste can be achieved by many different means such as conveyors or by gravity. There may be numerous methods of achieving each sub-function, a morphological chart allows for this exploration encompassing conventional methods, feasible solutions and new ideas. Differing from other approaches, the chart allows to bridge the gap between ideas by explicitly analysing each individual function. The synthesis of all functional features creates multiple and theoretically feasible system designs solutions which incorporate all key functions necessary to fulfill the design task. Additional to assisting the creativity process, a morphological chart can provide a systematic approach to evaluating the generated design ideas (Pierobom and Andrade, 2020).

Appendix J and K are the first iteration of this process and reveals that some features are not independent of one another. For example, in the exploration of method of heat supply to the dryer all three heat transfer modes can be applied. It is in fact desirable to combine these effect to maximise heat transfer to the drying chamber. Equally with waste movement and storage all the ideas could be used in a single design. At this point, Cross (2017) emphasises the importance of limiting the chart so not to have an unmanageable quantity of design combinations (Cross, 2017). As such, the author has chosen to restrict the breadth of possible features such as control, energy recycling and fluid movement. However, for heat supply and waste movement these remain in the chart, while not independent they can be combined to synergise the design.

For clarity, the author has omitted the full design generation using this method. Instead, four selected design options for processing and solar assistance will be discussed. The design has been developed using the ideas from the initial morphological charts shown in appendix J & K.

4.22 Creating Design Alternatives

4.22.1 Design 1

Design 1 is a forced air rotary dryer and features an incline fine aperture metallic drum which rotates slowly to move and agitate the waste up internally via a spiralled helix. Forced heated air passes over the moist waste and through the drum drying via convection which naturally exhausts to the top of the dryer. The heated air increases the temperature of the metallic drum and the drying chamber assisting dehydration via conduction. Waste is fed into a hopper locating in the drying chamber and a screw conveyor discharges to waste disposal. An additional feature is the return screw conveyor back to the front-end storage tank for reprocessing (too wet) or as a dry bulking agent assisting storage tank drying suggested by Tun & Juchelkova (2019). Exhaust air is partially recirculated as a mixture via electric fan with fresh outside air to a heated coil with the duct. The exhaust remainder is expelled to atmosphere via an air scrubber to eliminate any odours. The dryers shape allows small particles and water to escape through the drum mesh to an inclined trough along the bottom length of the drying chamber. Water is filtered and drained away to treatment by gravity in a gutter. Small fines and grits are sent to disposal. Backup is by mains power

4.22.2 Design 2

Design 2 is also a forced air dryer using multiple level of chain mesh conveyors to increase the resident time within a compact drying chamber. Waste is uniformly fed and thinly spread onto the upper conveyor which slowly moves to maximise waste time in the drying chamber. At the end of the upper conveyor, waste falls onto the next lower conveyor agitating the pile and then travels back towards the front of the dryer. This is continued among a series of conveyor levels. Forced heat air is fed into the dryer at the bottom, heat builds up between the levels and expelled from the top. A large horizontal fan circulates air flow akin to a conventional oven. At the end of the conveyor levels a mechanical gate directs waste into a constricted passageway whereby a hydraulic piston arm forces and compacting the waste through compacting it as it travels out at to disposal as a dense plug.

4.22.3 Design 3

Design 3 is a batch dryer design using fixed panel ETC to heat air. It is known that ETC are not reliant on direct solar irradiation. The batch dryer loads waste carts into a drying chamber whereby side stream forced heated air is applied and exhausted out in a centralised stack. A feature of the batch dryer chamber is pressurisation. The chamber is sealed and heated akin to a conventional oven where the waste is dried over a period of several hours. The design features a circular track which allows for two drying chambers to be used. There is a disposal point which funnels waste to a disposal bin underneath the track. Design 3 is simple in operation with minimal parts.

4.22.4 Design 4

Design 4 uses a hot plate to fry dry moist waste. A mechanical arm pushes and pulls across the hot plate surface to agitate the waste promoting faster drying times. Heat for the plate is by steam achieved by a single axis tracking Linear Fresnel collector array which heats water to superheated temperatures. The speed of drying would be envisaged to be rapid being able to achieve large waste feed rates once hot plate was at high temperatures. An advantage of the design is that water for steam production will be readily available. Backup electrical restrictive heaters could be used when solar energy was unavailable. Pressurised steam would need to be further investigated to determine materials, system safety and other considerations.

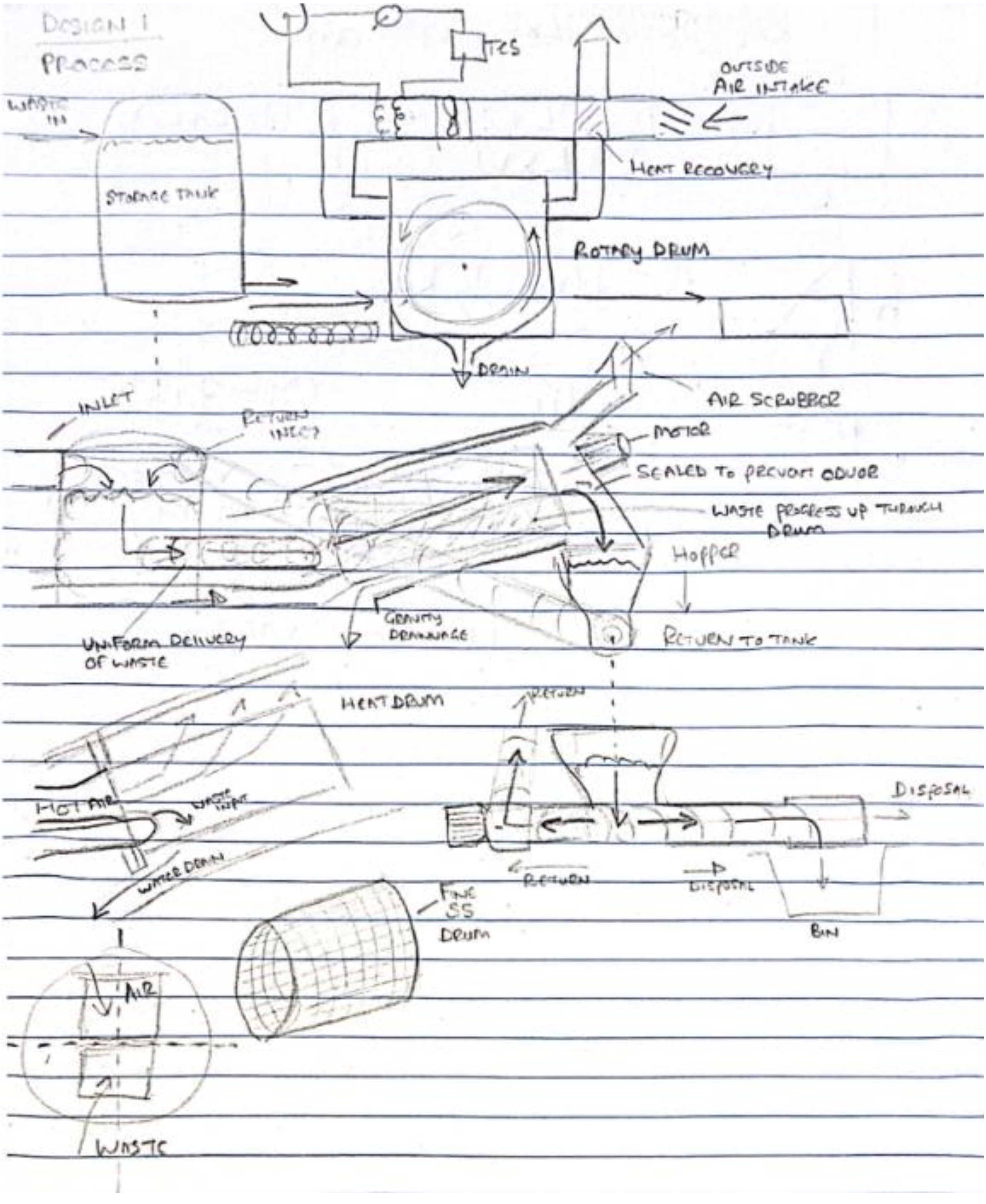


Figure 33- Design 1 (Process) uses an inclined rotatory mesh drum with forced heated airflow.

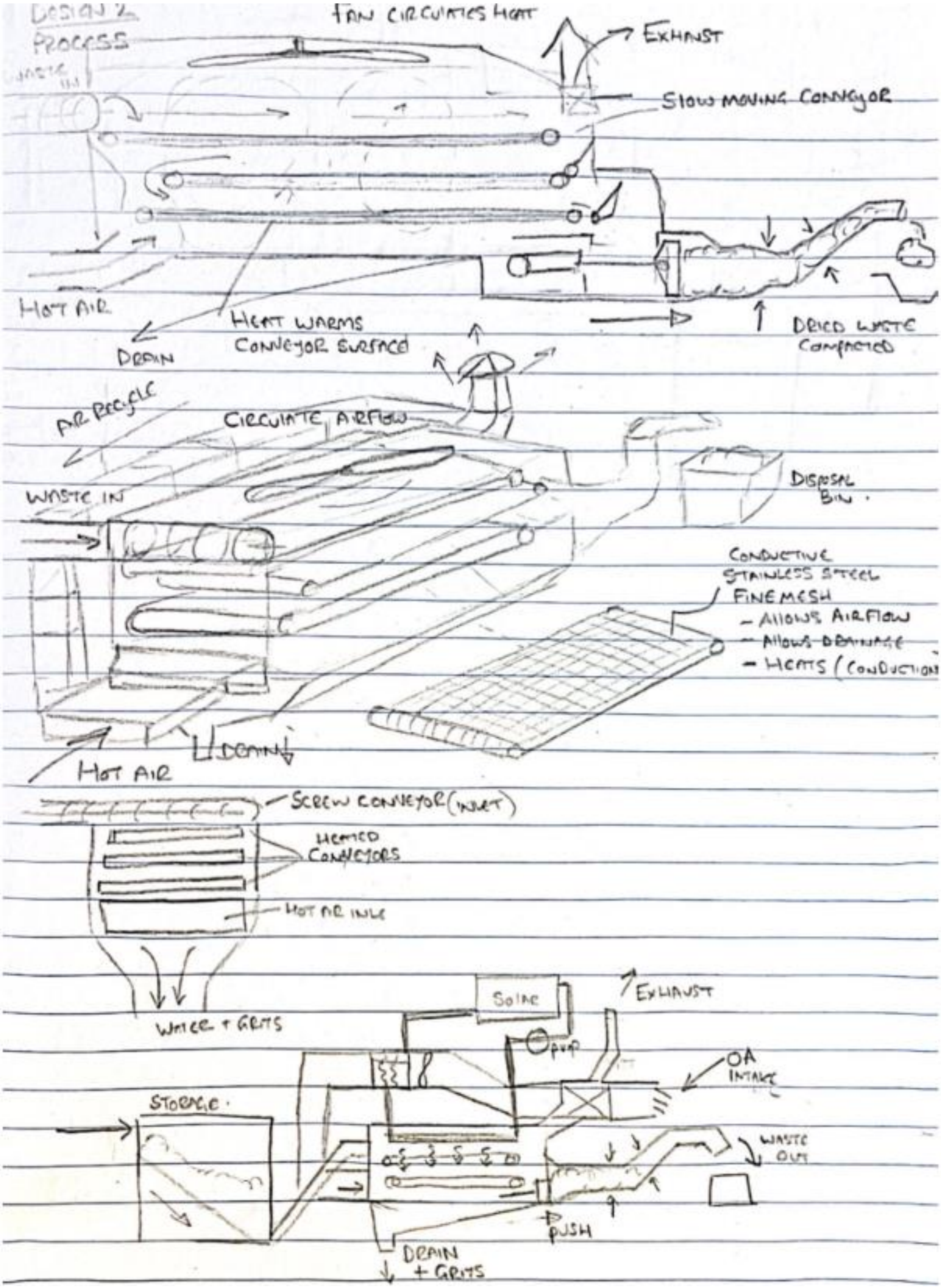


Figure 34- Design 2 (Process) uses flat conductive mesh conveyor with forced heated airflow. The stacked alternating direction conveyors maximise waste resident time within the chamber

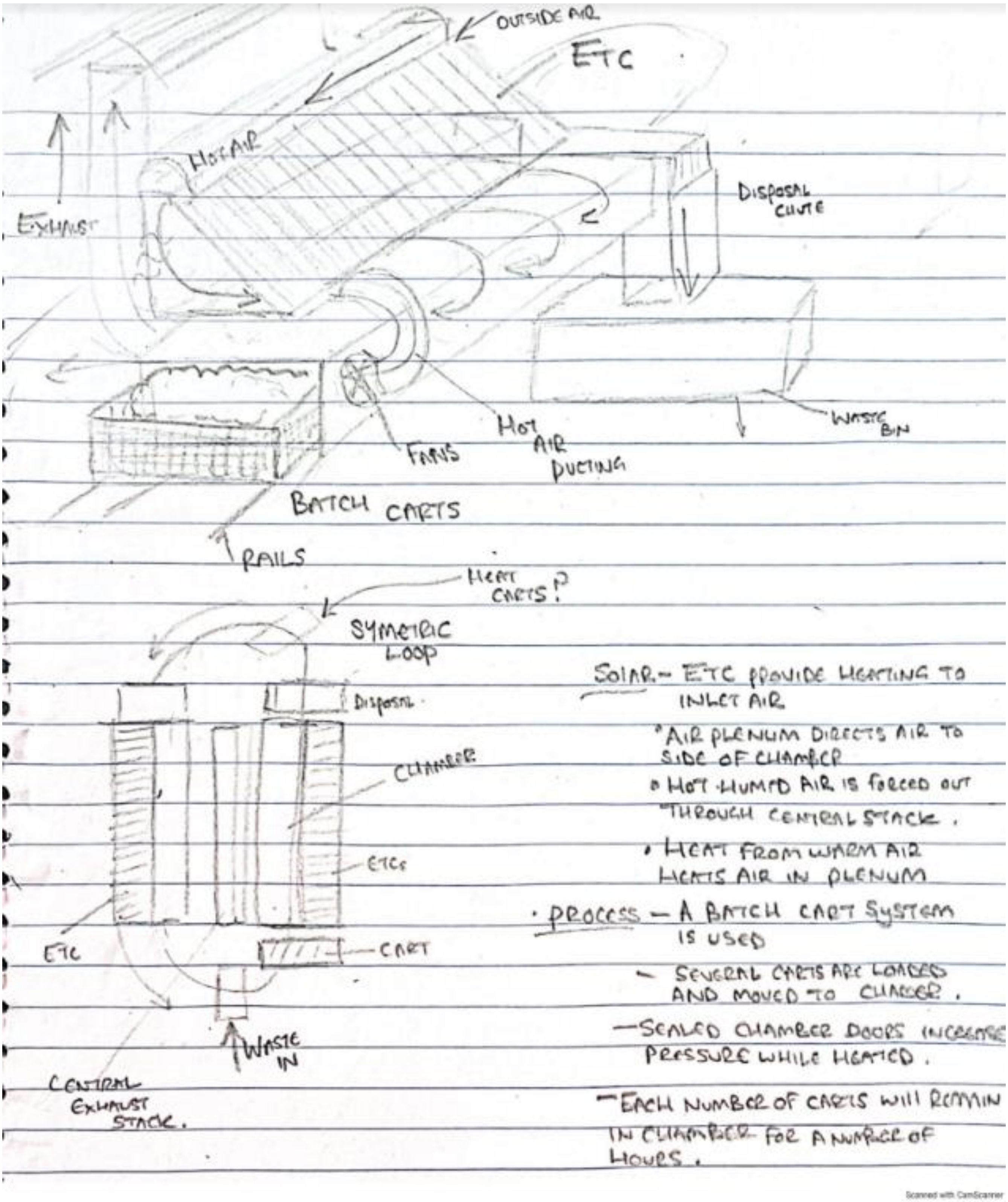


Figure 35– Design 3 (Process and solar) batch dryer design using ETC to heat air with waste carts positioned in the drying chamber for extended period akin to a conventional oven.

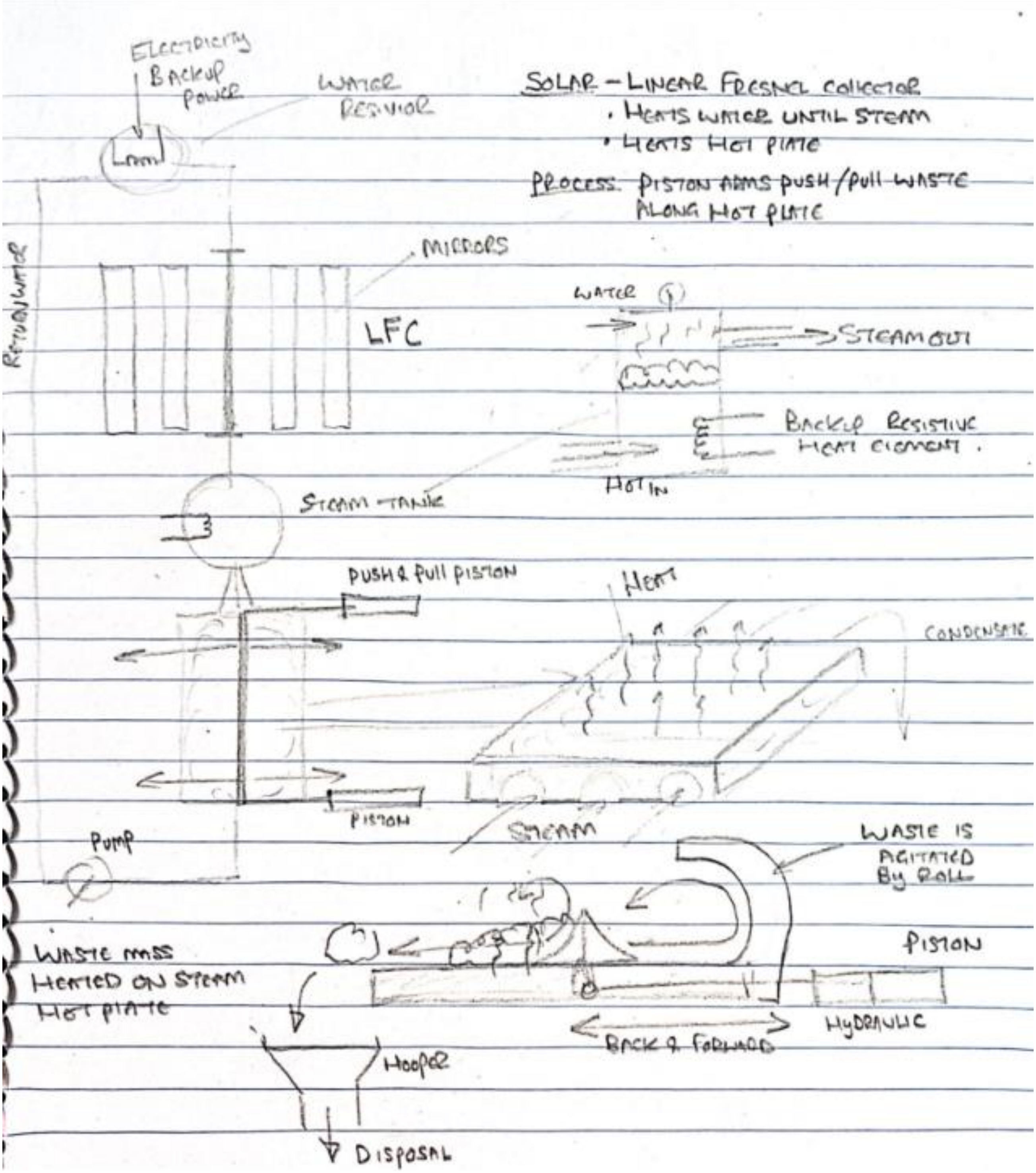


Figure 36- Design 4 (Solar and process) Linear Fresnel collectors heat water to superheated vapour whereby the steam heats a hotplate. Hydraulic pistons move and agitate the waste over the hot plate like dry frying.

4.23 SWOT Analysis – Solar Capture

4.23.1 Thermal

Kalogirou (2023) offer details around solar collector types (see figure X). Based on the literature review findings, the dryer design should maximise thermal heat to the drying chamber to around 100°C. A commonly used solar technology for thermal heating of fluid used in power generation is the Parabolic Trough Collector (PTC). It offers a wide low to medium temperature scale with high solar concentration. Unlike other collectors, the PTC can be used as fixed or with single axis tracking which follows the sun and maximises energy captured on the site. PTCs can be purchased as a pre-manufactured item reducing installation problems with reflector alignment such as in Linear Fresnel Collectors (LFC). Cost is expected to be higher than LFC but will provide the flexibility to obtain high heat energy needed which is essential to the dryer design.

ETC have the advantage of performance without direct solar irradiance which is highly advantageous for coastal areas which can be subjected to cloud coverage. However, some drawbacks are the absorption surface area is limited requiring many collectors to meet demand, the singular concentration ratio limits to a low temperature output and collector tube may become damaged over its service life.

Collector Type	Fluid Type	Temperature Range (°C)	Conc. Ratio	Output	Cost ($)	Tracking	Aux equipment
Flat Plate collector (FPC)	Air or Liquid	40-85	1	Heated Air	Low	Fixed	Fan
PV/T Liquid Collector	Liquid	30-80	1	Heated Liquid and Electricity	Med	Fixed	Pump and Inverter
PV/T Air Collector	Air	30-65	1	Heated Air and Electricity	Med	Fixed	Fan and Inverter
Evacuated Tube Collector (ETC)	Air or Liquid	50-150	1	Heated Liquid/Air	Med	Fixed	Fan or pump
Compound Parabolic Collector (CPC)	Air or Liquid	60-300	5-15	Heated Liquid/Air	Med	Fixed	Fan or pump
Parabolic Trough Collector (PTC)	Liquid	60-300	10-85	Heated Liquid	High	Single Axis or Fixed.	Pump, Tracking control
Linear Fresnel Collector	Liquid	60-250	10-40	Heated Liquid	High	Single Axis	pump and/or tracking control
Parabolic Dish Collector	Liquid	100-500	600-2000	Heated Liquid/Air	High	Dual Axis	Pump, tracking control

Table 14- Solor collector data. Adapted from Kalogirou (2023)

4.23.2 Evacuated Tube Collectors (ETC)

Strengths	Weaknesses
Can still perform without direct solar irradiance i.e. cloud cover. Good thermal efficiencies from the vacuum in the tubes. Modular and scalable to design requirements Can be used directly to heat fluid	Temperature limit for 50 to 120°C (REF) Evacuated tubes are fragile Fixed collector does not track. Limited absorption surface area requiring additional collectors
Opportunities	**Threats**
Increased technology advancement is reducing manufacturing costs. Use of nanofluids has improved efficiencies Used in other applications such as space and water heating Can be used with TES	Maintenance is low and may require specialised parts or expertise to repair. Extreme weather such as hail can damage collectors

Table 15- Evacuated Tube Collector (ETC) SWOT Analysis

4.23.3 Linear Fresnel Collector

Strengths	Weaknesses
Flat mirrors are cheap and readily available Wide temperature range 60°C -250°C Lightweight design and construction Can be scaled up to suit application	High level of mechanical alignment of reflected mirrors is needed Increased spacing for mirrors to prevent shadowing which diminishes performance. Lower solar concentration ratio to that of PTC.
Opportunities	**Threats**
More efficient heat transfer fluids (i.e nonfluids) Used in other industrial applications including desalination, pasteurisation and steam generation Government incentives and business operator's realisation of solar technology usage.	Other solar technologies such as PTC and solar PV fixed panels are also improving performance while reducing in cost. Maintenance of the mirrors is needed to keep up cleanliness, alignment and repair to ensure high performance. Extreme weather conditions such as high winds can damage reflectors.

Table 16 – Linear Fresnel Collector SWOT Analysis

4.23.4 Parabolic Trough Collector (PTC)

Strengths	Weaknesses
Established and mature solar collector technology (Ortiz-Rodríguez et al., 2022). Inexpensive heating method and operational cost compared with other traditional industrial heating processes PTC technology can be scaled into custom array sizes of varying collector area to suit different sites. High efficiency in conversion from solar energy to thermal heat. Provides high temperature heating from renewable solar energy reducing fossil fuel usage (Sakthivadivel et al., 2021)	Requires high amount of direct sunlight which can be intermittent Requires large amount of space for solar arrays (Sakthivadivel et al., 2021) High capital cost to install Increases complexity of system Requires single axis solar tracking (Sakthivadivel et al., 2021)
Opportunities	**Threats**
Reduces reliance on traditional energy Drying of waste allows for alternative to disposal. First stage in waste valorisation (De la Torre-Bayo et al., 2022) Implementation with waste heat from other plant operational process. Improved social and corporate responsibility in waste management Ability to integrate with existing dewatering processes enhancing disposal output Government financial assistance and pathway to meeting UN Sustainable Development Goals (SDGs) (Pordage, 2021)	Initial high capital costs compared with FPC and non-tracking solar technologies (Hamilton, 2020). Disposal of infrastructure/ heat transfer fluid. Intermittent solar energy requires backup power for continuous heating. (Arias et al., 2023).

Table 17- SWOT Analysis for a Parabolic Trough Collector (PTC) as a hybrid thermal heat source.

A SWOT analysis highlights the factors associated with a PTC finding several strengths including technology maturity, high efficiency and scalability. Moreover, there are opportunities for the implementation of waste process heat which offers versatility within this design application.

4.23.5 Solar air flow design

A detailed solar collector system using forced air has been developed. Solar energy heats up thermal fluid to provide temperature differences to heat and cool down air. The system draws in outside air via a fan which then gets cooled by cooling coils achieved by an absorption chiller to reduce the inlet air's moisture content. This dry air is then directed to a crossflow heat exchanger whereby the air is heated and forced over the moist waste in the chamber to dry or diverted to a TES of natural rock which is charged with heat energy during daylight hours. The design uses natural convection airflow to expel the now warm humid air through an air scrubber system. Controlled airflow is achieved by dampers within the ductwork. PV solar provides the electrical supply to the system with backup power provided by a small generator set to power the various plant equipment and control processes in periods of low solar irradiance.

The design features include the return cooled fluid pipes which are directed back through the drying chamber to radiate any remaining heat or to absorb heat back to a reservoir. Electric Duct Heaters (EDH) are electrically resistive elements can be used in support of temperature conditions for the inlet air.

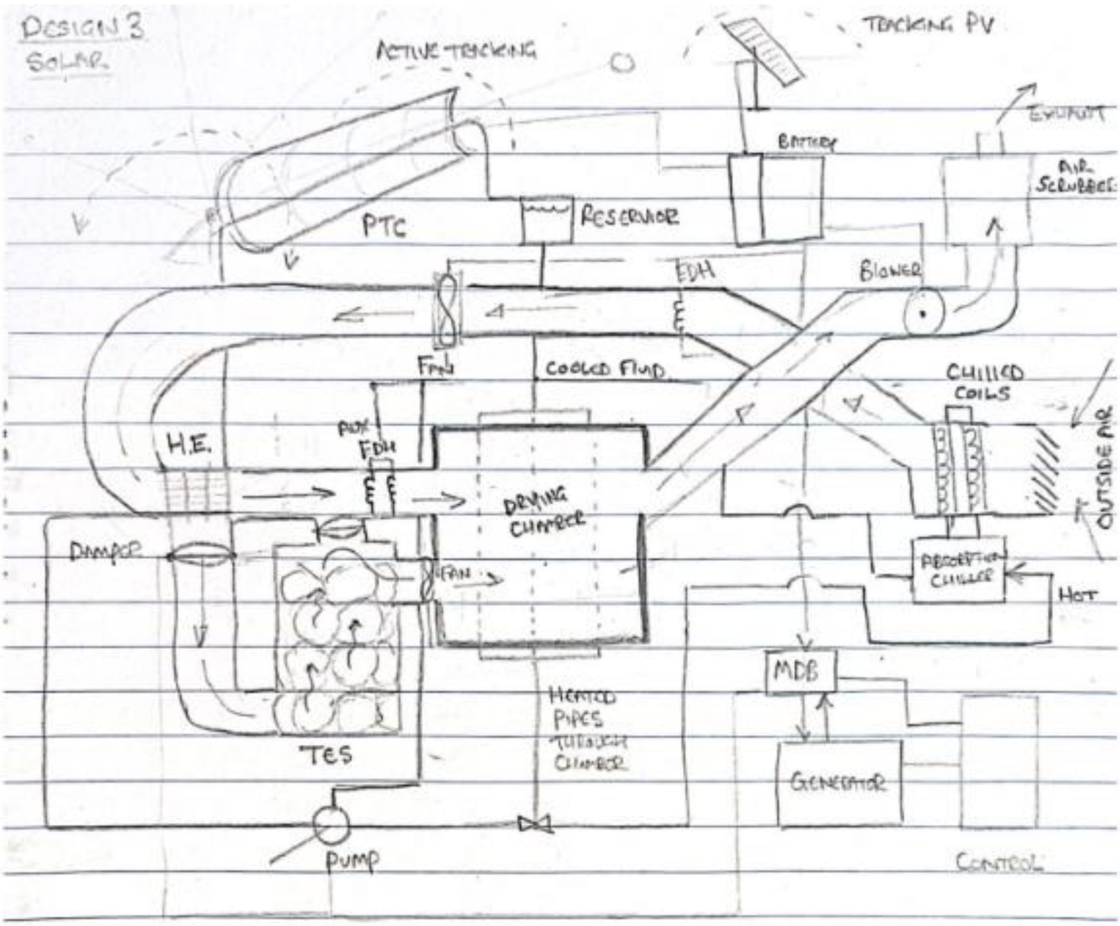


Figure 37-Design forced air flow is cooled and heated by solar thermal heat energy. Solar PV supports the electrical supply of pumps, blowers, tracking and air dampers. Backup power is provided by a generator.

4.24 Quality Function Deployment (QFD)

List of requirements include six key items (listed below) identified from the preceding sections.

The relative importance uses a scale of 1 (least importance) to 5 (highest importance) indicated in brackets after the requirements. The author has taken care in deriving this list from the extensive literature review and conclusions of the preceding sections. The intent is to guide the design to meet the functional solution to the posed problem – the reduction of moisture in screening waste.

- Remove Waste Moisture (5) <30% moisture content.
- Reduce energy consumption (3) – use renewable energy source for thermal or process power.
- Economical (2) – Costs related to a design solution should be low as reasonably practicable.
- Reliable (4) – must operate continuously. Less components and complexity may be assumed to increase reliability.
- Safe (4) – must have considered safety features and design functional safety.
- Waste transportation (3) – Shall move waste through the system to each stage and finally to a disposal point.

It finds that the design solution in requirement terms considers the importance by descending order; removal of waste moisture (23.8%), reliability and safety (both 19%), reduction in energy consumption (14.3%), waste transportation (14.3%) and economical design (9.5%).

These customer requirements are cross reference with nine identified engineering parameters and their corresponding units of measurement. These are, drying time (hours), drying temperature (°C), Power consumption (kW), System cost estimate ($), design lifespan (years), size dimensions (m), Energy capture capacity (kWh), waste storage (m^3) and energy storage (kWh).

The relationship between customer requirements and engineering parameters was assessed using a three-point scale; Strong correlation (9), Medium Correlation (3), Weak correlation (1) and no correlation (0) represented by S, M, W and X symbols respectively. These engineering parameters are scored against the customer design.

It finds that there are strong correlations to increasing energy storage as a means for a design to be economical, reliable, facilitate moisture removal and a means to reduce overall power consumption of the system.

Less importance in this analysis is the size, cost and design lifespan of the design solution.

Through the analysis of the importance weighting, engineering parameter interrelationship can be found. Relationships are listed as strong/weak and positive/negative. For example, if the drying temperature was increased this would also increase the power consumption thus has a strong positive relationship. Figure X shows this analysis and uses the following symbols, strong positive (++), weak positive (+), strong negative (--) and weak negative (-). A blank square represents that there is no relationship to the parameter. Also, the desired direction indicates to whether it is desired to decrease or increase the parameter. For the dryer, it is desirable to decrease the drying time, power consumption, size and cost. Equally, it is desirable to increase the design lifespan, energy capture capacity and energy storage abilities. This data can help designers modify known parameters and aid prediction of interdependence behaviour.

The interrelationships are based on logical reasoning. Fundamentally, it can be assumed that a decrease in drying time will require an increase in drying temperature to remove the same amount of water content. This also assumes that an increase in temperature, increases the systems power consumption. Moreover, there is argument that there will also be an increase system cost since higher temperature may need durable materials, more safety functions and specialised equipment. However, this is a generalisation as small temperature increases may be in the limit of plant materials and not require additional safety measure. Furthermore, this table indicates the desirable direction of the engineering parameter. It is desirable to decrease the drying time so that the waste is quickly dried but caution must be applied. It is not desirable that the speed of drying increases dryer cost or power consumption so that the dryer is too costly to operate. Therefore, this can only serve as a guide not a rule but allows for the consideration of such details in a design solution.

	Drying Time	Drying Temperature	Power Consumption	System Cost Estimate	Design Lifespan	Size Dimensions	Energy Capture Capability	Waste Storage	Energy Storage
	Hours	ºC	kW	$	Years	m	kWh	m^3	kWh
Desired Direction	▽	△	▽	▽	△	▽	△	▽	△
Energy Storage		++	++	-		+	+	+	
Waste Storage				-		+			
Energy Capture Capability		++	++	--		+			++
Size Dimensions				-	-		++	+	++
Design Lifespan				--			+	--	+
System Cost Estimate	-	-			--	+	++	+	++
Power Consumption	-	++		-		+	--	+	--
Drying Temperature	--		--	-			++		+
Drying Time		--	++	+			--	--	-

Figure 38- Interrelationship between customer requirements and engineering parameters determined from the QFD analysis

Interrelationships

	Drying Time	Drying Temperature	Power Consumption	System Cost Estimate	Design Lifespan	Size Dimensions	Energy Capture Capability	Waste Storage	Energy Storage
Energy Storage		++	++	-		+	+	+	
Waste Storage				-		+			
Energy Capture Capability		++	++	--		+			++
Size Dimensions				-	-		++	+	++
Design Lifespan				--			+	--	+
System Cost Estimate	-	-			--	+	++	+	++
Power Consumption	-	++		-		+	--	+	--
Drying Temperature	--		--	-			++		+
Drying Time		--	++	+			--	--	-

Engineering Parameters

	Requirements	Relative Importance	Weight %	Drying Time	Drying Temperature	Power Consumption	System Cost Estimate	Design Lifespan	Size Dimensions	Energy Capture Capability	Waste Storage	Energy Storage	
			Units	Hours	℃	kW	$	Years	m	kWh	m^3	kWh	
			Desired Direction	∇	Δ	∇	∇	Δ	∇	Δ	∇	Δ	
1	Remove Waste Moisture	5	23.8	S	S	S	X	X	X	S	X	S	
2	Reduce Energy Consumption	3	14.3	S	S	S	M	W	W	S	S	S	
3	Economical	2	9.5	M	S	S	S	S	M	S	M	S	
4	Reliable	4	19.0	W	W	W	M	S	M	M	S	S	
5	Safe	4	19.0	X	M	X	W	M	x	M	M	M	
6	Waste Transportation	3	14.3	W	X	W	W	X	W	X	X	X	
	Total	**21**	**100**										**Totals**
			Importance Rating (importance*Rel)	405	505	462	219	329	114	543	386	657	3619
			Importance %	**11**	**14**	**13**	**6**	**9**	**3**	**15**	**11**	**18**	100

Figure 39 – QFD House of Quality (H0Q) for solar assisted waste dryer

4.25 Design Targets

This research has used a mixture of collated data and performance assumptions in the absence of directly comparative designs to briefly outline some of the desired targets of the waste dryer. The literature finds the only know screening waste drying data from De Torre Bayo and collaborators (2022) work which successfully dried out screening waste to 4.5% moisture at 105°C in 48 hours in lab conditions excluding inert fraction (De Torre Bayo et al., 2022).

Previous sections in this report have revealed some essential targets to meet function and some desirable attributes. Benchmarking is a standard method used for product development. However, for this design it is intended to integrate with existing dewatering technologies and not to compete against them. As such, the dryer design should provide equal or greater output performance to that of the Washpactor or Washpress designs currently used.

Table 17 has been devised to guide the targets of this design. It presents the dryer objective to be achieved, the requirement description and whether this is a demand "D" or wish "W" of the design. In this way, the dryer design can be both guided and later evaluated to the degree in which it meets, exceeds or fails to achieve the targets.

Objective	Requirement Description	D or W
Functional	Must dry waste <30% MC	D
Functional	Provide a minimum waste feed rate of >18.5kg per hour	D
High Performance	Dry waste in <24 hours	W
Functional	Must have storage capacity for >2380kg per day	D
Add Value	Provide a disposal compaction of >240kg/m3	W
Reliable	Must maintain an average temperature range of 80°C to 100°C in drying chamber during operation.	D
Reliable	Require minimal maintenance available to operate >95% time.	W

High Performing	Automated - Require <1 hour worker intervention per day	W
Functional	Transport the waste through the system to disposal	D
Reliable	Must have provisions for fire suppression	W
Reliable	Must safely operate – sensor, detectors, interlocks	D
Reliable	Durable materials (Australian Standards)	D
Add Value	Operate an average >2 hours on stored energy	W
Reliable	Must have energy backup	D
Functional	Fully contain odours	D

Table 18 – Design Targets wish and demand table.

4.26 Weighted Decision matrix

The weighted design matrix refers to the customer requirement as identified in the previous sections. The four designs have been evaluated against the listed customer requirements. These requirements are qualitative and are based on the authors judgement at this stage. A simple five-point scale will be used as performance parameters with scale of inadequate, weak, satisfactory, good, and excellent assign to 0-4 respectively in meeting the evaluated requirement. As such, it is prudent to provide a list of justifications applied in how the design alternatives are interpreted to perform listed in chart 1.

Requirement	Relative importance	Scale
Energy Storage	18%	Two-point
Energy Capture Capability	15%	Five-point
Drying Temperature	14%	Five-point
Power Consumption	13%	Five-point
Drying Time	11%	Five-point
Waste Storage	11%	Five-point
Design Lifespan	9%	Two-Point
System Cost Estimate	6%	Five-point
Size Dimensions	3%	Five-point

Table 19 - Dryer System Customer requirements

In addition, some of the objectives are ranked on a two-point scale either meeting the objective (5) or failing to meet the objective (0) where data or judgement is unable to support the anticipated performance of the dryer design.

The total design points accumulated for each customer requirement is then multiplied by the relative importance percentage. This produces an overall total score for each design with the highest total representing the most suitable design solution.

Objective		Design				Scale	Comments
		1	2	3	4		
Energy Storage	18%	5	5	0	5	Two-point	1. Energy storage is via the heated drum and hot oil tank (5) 2. Heated chamber and conveyor belt (5) 3. No Heat Storage (0) 4. Steam Tank (5)
Energy Capture Capability	15%	4	4	4	3	Five-point	1. Use of both Solar thermal and PV flat panels (4) 2. Use of both Solar thermal and PV flat panels (4) 3. Good. ETC do not require direct irradiation (4) 4. Satisfactory. Collector array needed for thermal heat generation (3)
Drying Temperature	14%	4	4	3	3	Five-point	1. PTC collector and oil to air heat exchanger. High Temperatures (4) 2.PTC collector and oil to air heat exchanger (4) 3. Moderate to low temperatures through heated air (3) 4. Moderate temperatures producing steam (3)
Power Consumption	13%	2	3	4	1	Five-point	1. Heat recovery of heated air (2) 2. Maximises heat transfer to chamber (3) 3. Low. Minimal movement (4) 4. Requires Steam to operate. Must have enough heat energy (1)
Drying Time	11%	4	2	3	4	Five-point	1. Rotary agitation promoted waste drying in addition to forced air (4) 2. Drying time can be custom with length of conveyors (2) 3. Increased pressure in chamber can decrease drying time (3) 4. Fry drying envisaged to be quickest of the drying methods (4)
Waste Storage	11%	3	3	1	0	Five-point	1. Front end tank distributes waste. Wate can be re-directed back to holding tanks (3) 2. Drying chamber forms part of the storage of waste. Also features front end tank. (3) 3. limited to waste cart sizes (1) 4. No provision specified (0)

Design Lifespan	9%	5	5	5	0	Two-Point	1. Stainless steel construction. Minimal parts (5) 2. Stainless steel construction. Individual belts may require maintenance. 3. Capacity is limited. Minimal parts (5) 4. Steam may damage materials. Continuous piston and scoop movement will require maintenance (5)
System Cost Estimate	6%	2	1	2	1	Five-point	1. Simple with few different parts (2) 2. Extra complexity with waste compaction (1) 3. Minimal once constructed (2) 4. Water is abundant. Extra durable materials and maintenance likely to increase costs (1)
Size Dimensions	3%	2	3	1	2	Five-point	1. Drum and conveyors can be customed sized to suit specific site (2) 2. Extra driers added in series or increase chamber height with belts vertically (3) 3. Requires a track and carts for large batches (1) 4. Speed of drying does not require long resident time in chamber. Collector field will take up space (2)
Design Points		31	30	23	19		
Total Score		**3.61**	3.60	2.58	2.46		

Chart1 finds that Design 1 is the most suited design to meet the customer requirements from the QFD.

5 Design Evaluation

5.1 Design 1

Design 1 is a multileveled forced air rotary dryer. Partially dewatered screening waste from the initial mechanical dewatering is conveyed to a front-end holding tank. A second screw conveyor transfers waste to the drying chamber whereby a slow turning inclined rotary dryer both transports and agitates the waste. Forced heated air is passed through the drying chamber and rotary drum. This evaporates the waste moisture which is expelled via an air scrubber exhaust.

Synthetic oil is the heat transfer fluid which is heated by a parabolic collector array. The oil is pump through a closed loop pipework. Inlet air is heated passing via a crossflow heat exchanger within the internal ductwork. The cooled fluid is then circulated back to the PTC array.

Airflow is forced by fan which provides high air velocity to both the drying chamber and through the subterrain TES packed rock bed. A control system is intended to make changes to fan speed and air diversion to the TES rock bed. During low solar irradiance or nighttime. The air is passed through the TES which like the heat exchanger provides the heat energy to the air. When the heating falls beyond temperature, backup heater can either directly heat the air or synthetic oil reservoir via a resistive heating element

The following evaluation will investigate the solar collector array location, shadowing, thermal heating temperature generated, solar power, heat exchanger, basic psychometrics on drying air humidity, estimated drying time and moisture removal rates plus additional design considerations uncovered during the theoretical modelling.

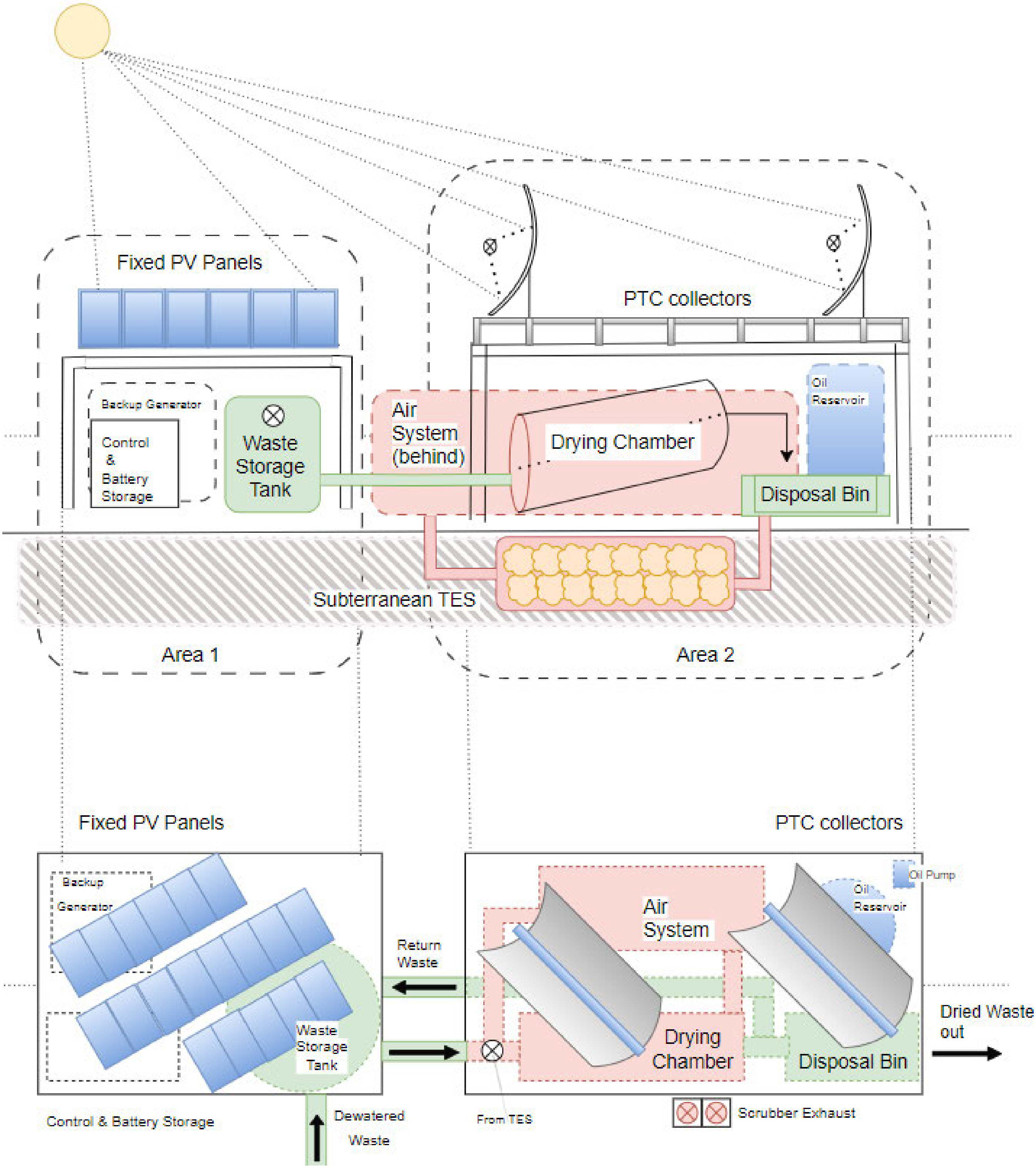


Figure 40 – Proposed Solar Waste Concept Design Diagram

6 Solar Capture

6.1 Parabolic collector

In a two-dimensional analysis a parabola which reflects concentrated solar radiation transferring heat energy to a single focal point. If this is extended into a three-dimensional trough reflected heat energy is absorbed along a focal line through an absorber tube.

There are numerous loses from radiation, conduction and convection during this process. It is desirable to minimises these losses to increase the collector's efficiency. Kalogirou (2023) presents the extensive equations to perform a thermal analysis of a PTC which has been used to model the design.

For this research an indicative PTC has been used to provide the necessary modelling data in this design a SOLITEM PTC was investigated. Solitherm panels have been previously investigated by Lokurlu, Richarts and Kruger (2005) when they presented the SOLITHERM PTC -1800 for steam and chilling applications in a Mediterranean climate (Lokurlu et al., 2005). Moreover, Torres and collaborators (2020) provide the design methodology for creating a PTC (Torres et al., 2020). Whilst this research does not seek to design a PTC, their paper highlights the process of using first principal calculations. The work of these scholars has been used along with Kalogirou (2023).

The analysis of PTC is complex for this research several assumptions have been made to determine the heating capacity and efficiency of the proposed PTC system. Since the design is constrained within physical limits the number of collectors and parabola widths can be modified to determine the most suitable PTC for selection. Parabolic Trough Collectors can only concentrate beam irradiance G_b given in W/m^2. Typically, this is given as an hourly value which changes throughout the day.

The equations (22) to (25) are used to provide an approximation of the potential of this solar technology. Calculations are performed in Microsoft Excel to model the heat transfer from collected solar energy to the heat transfer fluid.

6.1.1 Site Geometry

The practical geometric limitations of the PTC array were approximated. Area 1, the larger of the two selected zones was chosen as the thermal collector site at $400m^2$. The proposed site is N-25 degrees E, initial modelling had the PTC arrays in line with this offset and found a slight decrease (2% less of total power) in solar energy collected.

As such, the collector array has been placed in orientation along the N-S axis with E-W tracking. This orientation maximise the solar irradiance collected and is a close approximation to two axis tracking during summer solstice and equinox but is reduced over winter as suggested by Kalogirou (2023)

To maximise the surface area of solar collection multiple PTC will be arranged in rows or arrays. However, it is known that shadowing reduces the solar energy collected. In a large areas, the effect of shadowing in zenith angle β closer to the horizontal. This effect can be minimised (to a practical point) increasing the distance between collector rows. However, in confined areas such as the design site this becomes much more critical. Masood and collaborators (2016) presented a simplified design procedure for PTC in industrial heat applications including a solar field design. They state that a N-S orientation maximised efficiency of the collectors but is subjected to shadowing by successive collector rows and provide a geometric approximation to determine spacing needed (Masood et al., 2016).

The equation relates panel shadowing H_s to the panel width w, row spacing P less the sun angle β which changes throughout the day. Equation is used to find the minimal row spacing P. Their equation is diagrammatically shown in figure X.

$$H_s = [\,w - p\ cos\beta]$$

(Masood et al., 2016)

$$P = \ H_s + w * [p\ cos\ \beta]^{-1} \tag{28}$$

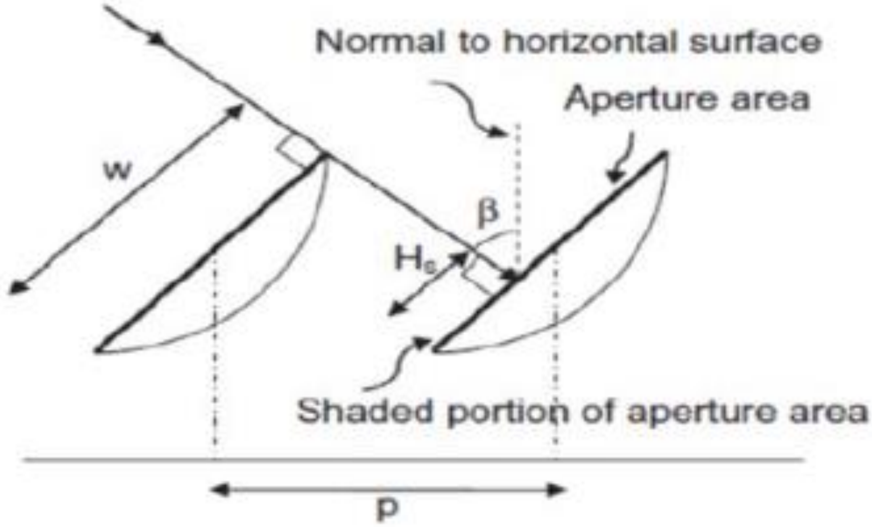


Figure 41-- Diagram of solar shadowing occurring in collector array rows. Image taken from Masood and collaborators (2016).

A minimum clearance P→ 0 has been adopted for angle β, at 60° coinciding with the first few hours of irradiance at sunset and sunrise to minimises shadowing on each row array for the remainer of the day and maximising solar collection at peak hours (Masood et al., 2016).

Figure 31 shows the AutoCAD overlay of the site using different SOLITERM PTC models from appendix B, C, D and the idealised array row spacings.

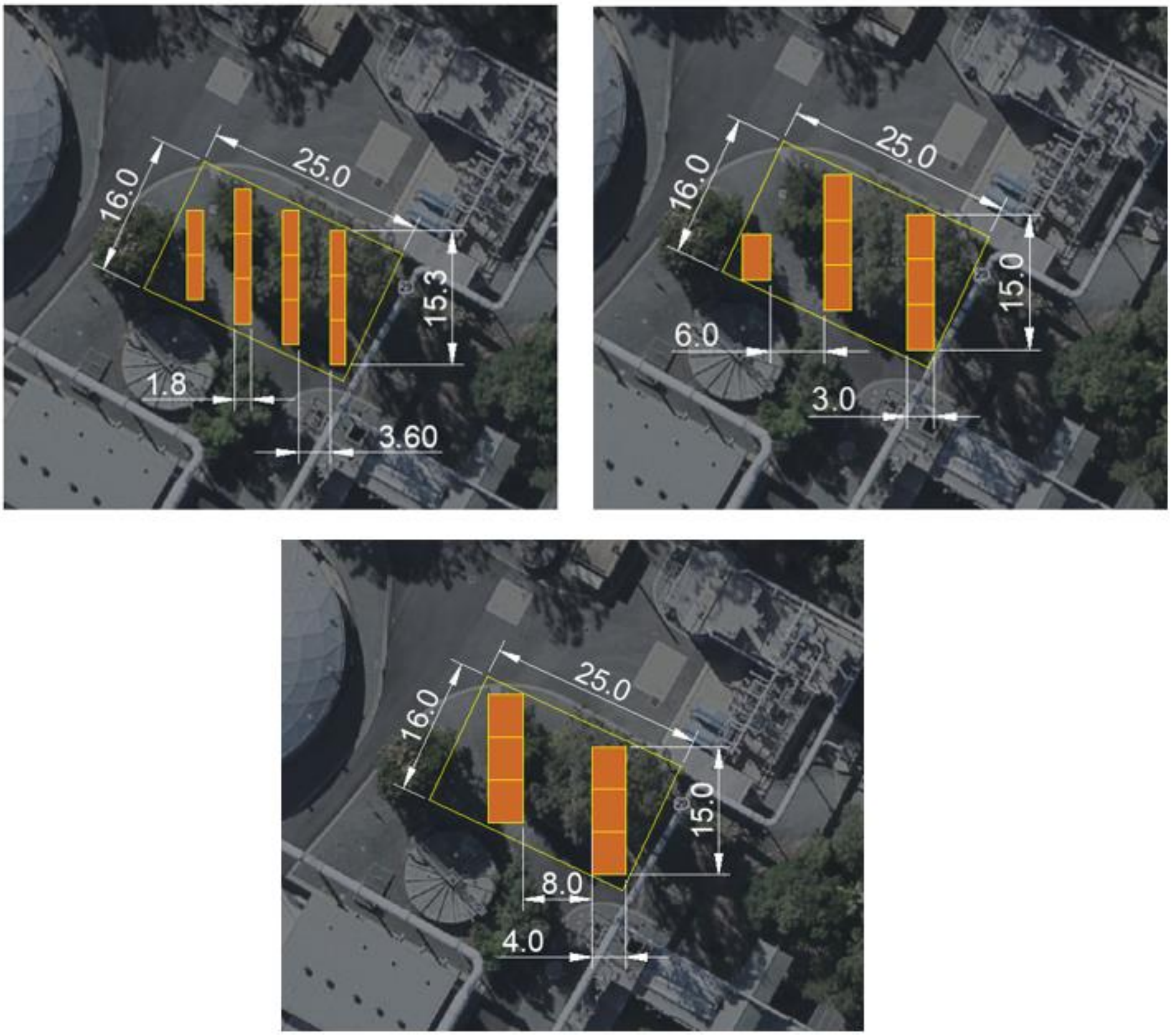


Figure 42- Indicative PTC array using SOLITERM 1800 (top left), 3000 (top right) and 4000 (bottom centre) adjacent to the screening area of Murrumba Downs Sewage Treatment Plant (STP).

SOLITHERM Collector	Length (m)	Width (m)	Aperture Area per collector (m^2)	C	Spacing P @ 60° (m)	Number of Collectors	Total Area (m^2)
1800	5.1	1.8	9	<50	**3.6**	11	99
3000	5.0	3.0	15	<65	**6.0**	7	105
4000	5.0	4.0	20	<80	**8.0**	6	120

Table 20 - Details of PTC collector models including collector area and spacing requirements for the proposed site.

Table 20 collates the calculated data. It finds both Solitherm 1800 and 3000 similar in collector area due to the limitations of collector's numbers that can be installed. The largest collector Solitherm 4000 provides the largest surface area, smallest number of collectors despite large row spacings.

6.1.2 Solar Collector Modelling

It is desired to determine how this collected solar energy can provide heat for the dryer design. The collector is modelled using several equations in which the calculations assume the following: steady operation conditions, average ambient temperature at 20°C, heat transfer fluid properties are constant, a linear heat transfer from the reflector surface to the absorber, no shadows, surfaces are ideal: clean and of uniform emissivity, constant air velocity at 5m/s, and the absorber tube is in a perfect vacuum.

6.1.3 Change of Temperature in Heat Transfer Fluid.

It is necessary to determine the change in temperature ΔT, the collected solar energy transfers to the heat transfer fluid (HTF). The inlet temperature T_{in} will be known, it is required to find outlet temperature T_{out}, which is dependent on many factors including collector materials, physical size, type of HTF, solar energy and heat losses.

$$Q = \dot{m}C_p\,(T_{out} - T_{in})$$

$$T_{out} = T_{in} + \frac{Q}{\dot{m}Cp} \quad (29)$$

Let Q is the absorbed heat of the heat transfer fluid (W), $\dot{m}$ is the mass flow of HTF (kg/s) and specific heat, C_p of the HTF (W/kg. K)

$$\dot{Q} = U\Delta T \quad (30)$$

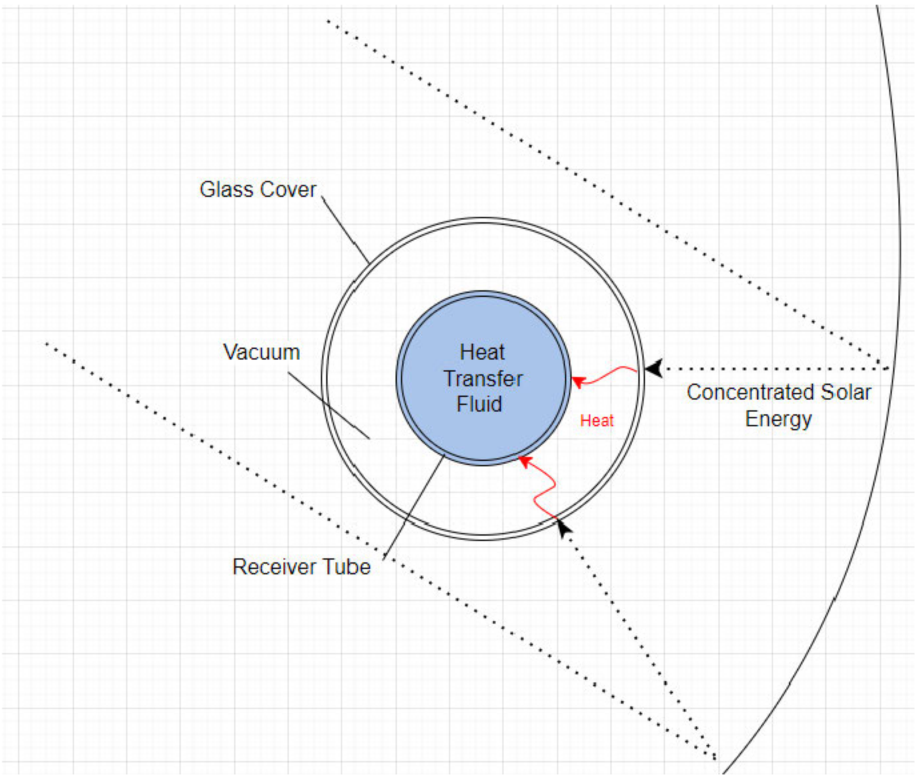


Figure 43 – PTC diagram of reflector and receiver tube

Where $\dot{Q}$ is the heat transfer rate (W/m^2) and U is the 1/ thermal resistance of outer glass surface. It finds that the construction of the SOLITEM collectors have an evacuated tube surrounding the absorber to minimise convection losses to the inner fluid pipe.

$$U_L = \left[\frac{A_r}{A_g(h_w + h_{r,reciever})} + \frac{1}{h_{r,cover}}\right]^{-1} \quad (31)$$

(Kalogirou, 2023)

The areas of the receiver and glass tube are pipes calculated from the diameter and length ($\pi * D * L$). A_r is the reciver area (m^2), A_g is the area of glass tube (m^2).

As solar energy is reflected onto the glass some radiation is absorbed heating the glass. Being in an outside environment, wind will remove this heat by convection as it passes over the glass, h_w is the convective heat transfer coefficient (wind).

For simplicity, linearised radiation coefficient h_r is considered along the length of HTF piping. The temperature difference, T_r is between the glass cover and ambient $h_{r,cover}$.

$$h_{r,cover} = 4\sigma\varepsilon T_r^4 \tag{32}$$

(Kalogirou, 2023)

The radiation heat transfer coefficient between the receiver and the glass cover is more complex and estimated using the following equation.

$$h_{r,reciever} = \sigma\left(T_r^2 + T_g^2\right)\left(T_r + T_g\right) * \left[\frac{1}{\varepsilon_r} + \frac{A_r}{A_g}\left(\frac{1}{\varepsilon_g} - 1\right)\right]^{-1} \tag{33}$$

Where emissivity values of the receiver ε_r and glass cover ε_g, areas A_r and A_g and temperatures T_r and T_g are considered.

Kalogirou (2023) explains that the glass temperature T_g can be found via iteration as needed assuming a temperature close to ambient air T_{amb}.

$$T_g = A_r h_r T_r + A_{glass}\left(h_{r,c-a} + h_w\right)T_{amb} * \left[A_r h_r + A_{glass}\left(h_{r,c-a} + h_w\right)\right]^{-1} \tag{34}$$

Overall heat transfer coefficient, U_o can be calculated factoring in the diameter of the receiver pipe and the convective heat transfer coefficient h_f inside the pipe.

$$U_o = \left[\frac{1}{U_L} + \frac{D_o}{(h_f D_i)} + \left(\frac{D_o}{2k} Ln\left(\frac{D_0}{D_i}\right)\right)\right]^{-1} \tag{35}$$

Convective Heat Transfer coefficient h_f for both the wind and HTF as is found using the following equations. This is based on the Nusselt number, Nu for internal flow of HTF in the pipe assuming turbulent flow Re>2300. Laminar flow can be approximated as Nu = 4.364 (constant).

$$Nu_D = 0.023 * Re^{0.8} * Pr^{0.4} \tag{36}$$

Where k is fluid conductivity (W/mK), μ is the HTF viscosity (kg/ms) and flow velocity V (m/s) gives the variables for the Reynolds number, $Re = \rho VD/\mu$ and Prandtl number $Pr = c_p\mu /k$. These values can be found using material property tables (Cengal & Boles, 2007) and the mean temperature from equation (37).

$$T_{mean} = \frac{(T_a+T_g)}{2} \tag{37}$$

(Kalogirou, 2017 & Torres et al., 2020).

The collector efficiency factor F' is the difference between heat losses and gains.

$$F' = \frac{U_o}{U_L} \tag{38}$$

For low temperature increase in the tube the heat removal factor can be considered equal to 1. For larger temperature increases the following can be used.

$$F_R = \left(\frac{\dot{m}c_p}{A_r U_L}\right)\left[1 - \exp\left(-\frac{U_L F' A_r}{\dot{m}c_p}\right)\right] \tag{39}$$

Following these calculations, it arrives at the useful energy Q_u of absorbed radiation (W).

$$Q_u = F_R[SA_a - A_r U_L(T_i - T_a)] \tag{40}$$

Finally, the HTF temperature T_{out} can be found from the original equation (26).

From the above equations (26 to 27), three parabolic collector sizes PTC- 1800, 3000 and 4000 are modelled. The total collector arrays determined earlier in the site plan are assumed to be connected in series. Table 21 provides the constant assumptions whereas Table Y provides the individualised data from each panel type. Figure 44 shows the comparison between the collector model collection area, useful energy collected and the exit water temperature from ambient. It finds that the larger collector surface area increases the water outlet temperature. The PTC-400 array of 6 collectors has a collection area of $120m^2$ translating to the highest water temperature from 25°C to 84.3°C.

Description	Symbol	Value
Absorbed Solar Radiation (W/m^2)	S	883
Receiver Temperature (K)	Tr	475
Receiver emissivity	εr	0.92
Glass Emissivity	εg	0.87
Specific Heat (HT fluid) $(j/kg.K)$	cp	4180
Entering Fluid temp (K)	Ti	298
Mass Flow Rate (kg/s)	m	0.4
HT coefficient (inside pipe) $(W/m^2\,K)$	h	330
Tube Thermal Conductivity $(W/m\,K)$	k	15
Ambient Temp (K)	Ta	298
Wind Velocity (m/s)	V	5

pipe diameter (outer) (m)	Do	0.038
pipe diameter (inner) (m)	Di	0.0368
glass cover diameter (m)	Dg	0.065
Air Density (kg/m^3)	p	1.146
Kinematic Viscosity $(kg/m\ s)$	u	0.000021
Thermal Conductivity (W/mK)	k	0.0269
Reynolds Number	Re	18,630

Table 21- Provides condition data which will remain the same throughout the modelling. Direct normal insolation has been averaged and assume to be 883 W/m^2 per day

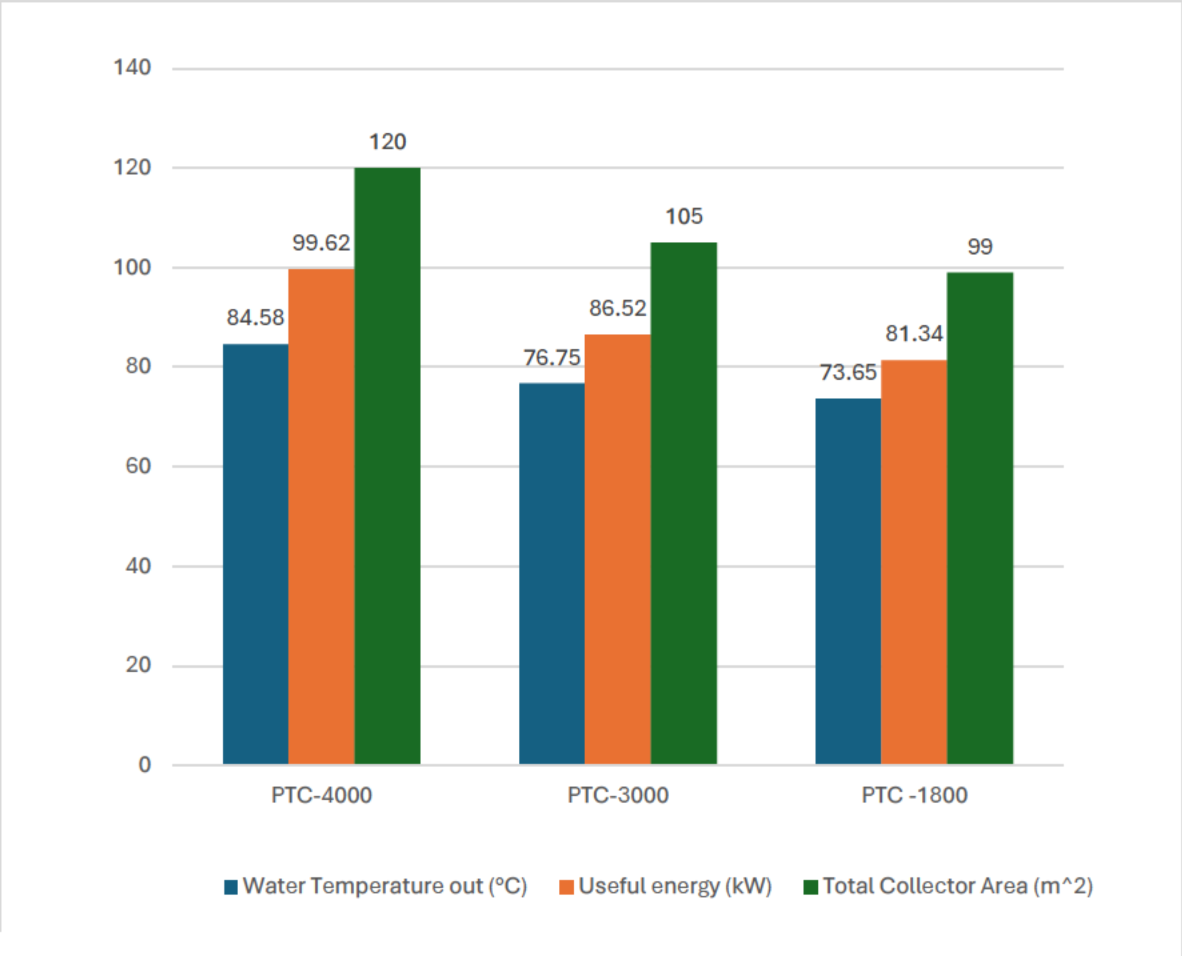


Figure 44- A comparison between SOLITHERM PTC types against Water out temperature, useful energy and Total collector area.

There is small difference between PTC-1800 and PTC-3000 due to the site's physical restrictions. The PTC-4000 present the most suited choice having a large collector area (120m^2) translating to highest fluid temperature difference (ΔT = 59.6 °C) of the three modelled PTC arrays.

6.1.4 Thermal Safety

The PTC modelling has been based on average solar irradiance throughout the year. The system may be subject to higher irradiance thus increasing the heat transfer to the fluid medium. The modelled heat transfer fluid is water. As it is abundant, safe and cost effective. However, one possible scenario is heating water beyond boiling point (>100°C) converting the fluid to steam which would require additional system changes accounting for phase change or limiting temperature through control monitoring. Other heat transfer mediums are used with PTC but require high temperature ranges which goes beyond this design temperature limits with <200°C is classed as low temperature (Wang et al., 2023).

Therefore, it may be prudent to use a synthetic thermal oil as a heat transfer medium which has a higher boiling point than water building in inherent safety in the design in event of control failure. Dowtherm A (Appendix N) is a synthetic oil used within the range of 12 to 400 °C with good heat transfer and low corrosiveness. However, it is more expensive than water, has a relatively low service life (3-5 years) and can pose a fire hazard (Wang et al., 2023). Despite this, the ability to increase the thermal heat gains for the same area is desirable design feature. The SOLITHERM PTC-4000 with synthetic oil is further modelled.

The same calculation procedure was undertaken for Dowtherm HTF. An approximate fluid temperature of the heated oil was found to be 179.1°C at 0.4 kg/s. Using synthetic oil as the HTF present an increase water outlet temperature of 94.5°C (112% increase of heat energy to the fluid).

Figure 45 shows a significant improvement in heating ability using synthetic oil against water. This doubles the increase in the heat transfer to the oil to that of water. Table in Appendix M finds the annual average outlet temperature of 179 °C. However, this increased fluid temperature is still required to be transferred to the waste within the drying chamber.

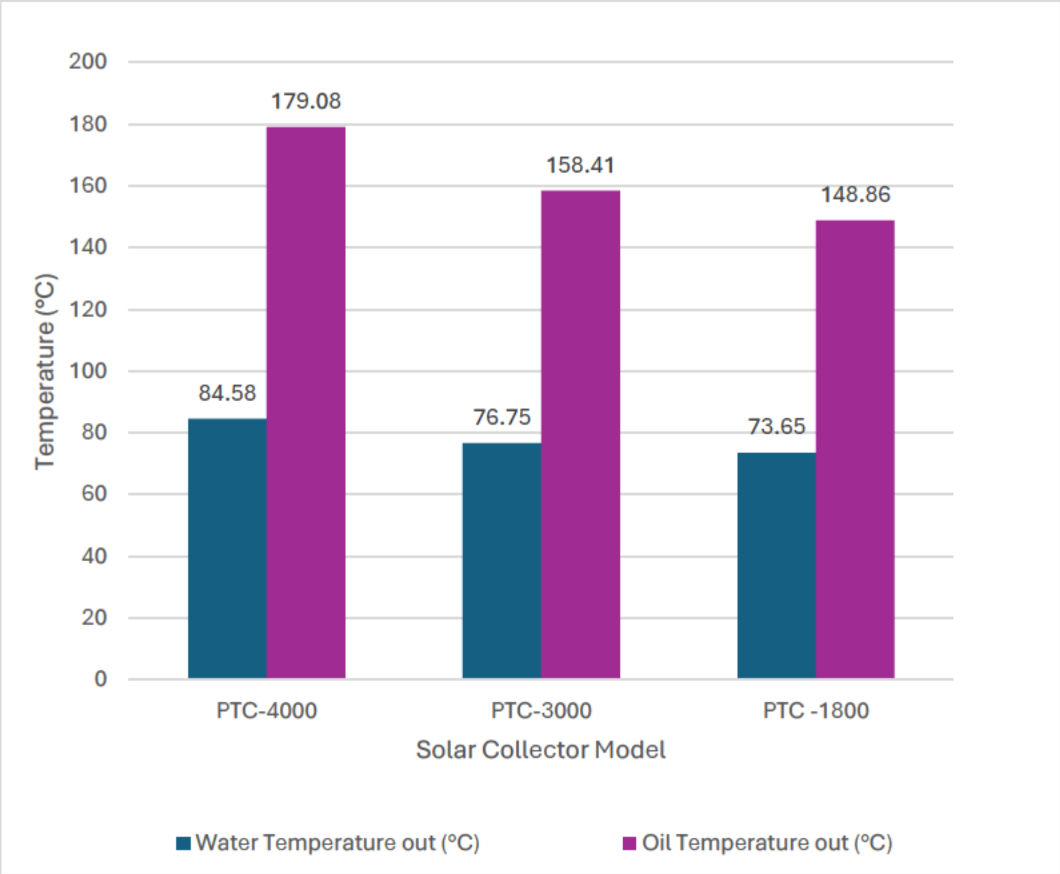


Figure 45- The comparison between SOLITHERM PTC models using water and oil as heat transfer fluid. The graph shows a significant improvement doubling heat transfer when using synthetic DOWTHERM A Oil

Month	Monthly Average Beam Irradiance W/m^2	Oil Temperature out (°C)
Jan	928.24	186.93
Feb	918.66	185.30
Mar	871.71	177.11
Apr	827.67	169.42
May	822.59	168.54
Jun	865.55	176.04
Jul	873.70	177.45
Aug	894.71	181.12
Sep	851.52	173.58
Oct	948.99	190.59
Nov	874.42	177.58
Dec	921.66	185.82
Average	**883.0**	**179.0**

Table 22- Annual monthly solar irradiance and corresponding PTC output temperatures

6.2 Heat Exchanger

Heat exchangers are useful allowing heat transfer between different fluids whilst keeping them separated not allowing them to mix. Heat transfer within a heat exchanger is a mixture of convection and conduction. Depending on the application, such as cooling or heating a fluid, heat exchangers can be designed to maximise heat transfer between fluids which is represented in overall heat transfer coefficient U (W/m^2 K). It is known that forced convection increases the rate of heat transfer through fluid motion (Çengel et al., 2017). This is common in an industrial dryer designs. In this design, circulating fluid will pass and be heated by concentrated solar power and auxiliary power when needed.

A basic analysis has been undertaken to investigate possible heat exchanger design. This assumes steady flow and constant temperature and flow rates using an average temperature (Log Mean Temperature Difference LMTD) with good approximation (Çengel et al., 2017). The design models forced air heating in an unmixed cross flow arrangement from tube flow liquid oil.

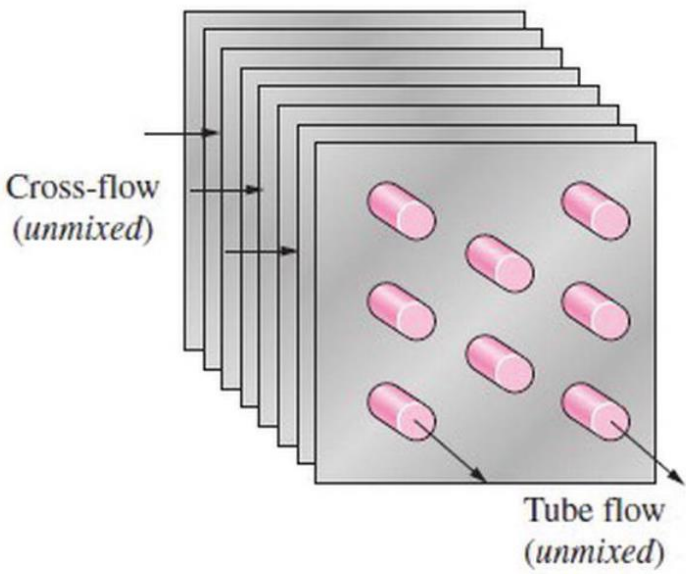


Figure 46- Heat Exchanger in an unmixed cross flow arrangement taken from Cengal et al., 2017). Cold forced air in cross flow is heated from the hot liquid oil in the tube flow.

Appendix M provides the data to the heat exchanger model. Cold ambient air is heated via a crossflow heat exchanger and forced into the drying chamber to remove moisture from the waste. Specific heat, density and volumes have been found in property tables Cengal & Boles (2007) or have been calculated. The area of the square air duct is $1m^2$ for a per area approximation, air velocity is 3 metre per second suggested by Dincer and Zamfirescu (2016) and assumed equal to an ambient temperature 23°C at 1 atm.

6.3 Outside air

The dryer will use outside ambient air and heat it via the heat exchanger**.** It is known that heat exchangers are limited by the difference in temperatures of the fluids. The limiting case is given in the below equation.

$$TC_{out,limit} = T_{c,in} + \left(\frac{Q_{max}}{Cc_{air}}\right) \quad (41)$$

Heating the outside air intake from 20 to 50°C increases the air temperature to the drying chamber but reduces the heat removed (ΔT) from the fluid as shown in Appendix P. The inlet air temperature will be equal to the hot fluid return (Hot out). This is advantageous as excess heat can be stored in TES during low irradiance or nighttime. However, further exploration finds that heating outside air maybe problematic for local Brisbane conditions as the air may possess high humidity. It is desirable to have both high temperature and dry air for dehydrating moist waste. Dincer & Zamfirescu (2016) explain that drying is significantly influence by temperature, humidity, relative air velocity and pressure. At a constant drying rate moisture removal can only occur as fast as the rate of evaporation from the drying item (Dincer and Zamfirescu, 2016).

Using a psychrometric chart for the average Brisbane conditions of 23°C dry bulb and RH 62% the moisture content of air is 11.5g/kg air. Continuously increasing the temperature by heating the incoming air lowers the relative humidity (saturation humidity as a percentage of temperature) but does not change the moisture content of the air. A preconditioning cooling of the inlet air beyond its saturation temperature or dew point reduces the air's moisture through condensation this is then re-heated and can provide the dryer with both hot and dry air. This can be achieved through a series of chilled and heating coil stages in the air ducting.

6.3.1 Dehumidifying humid air intake

Chilled or hydronic coils may seem at odds with thermal heat, but the high temperatures can be used as a temperature difference in absorption chiller model using low boiling point refrigerant. This can provide the chilled water to coils to lower the inlet air's moisture. Like that of vapour-compression systems, the absorption cycle does not use a compressor but instead absorber, generator, regenerator, expansion valve and rectifier. However, Cengal and Boles (2007) explain that are more complex, less efficient and more expensive that vapour-compression systems (Cengal & Boles, 2007). A full analysis of an absorption system is beyond the scope of report. However, a simple calculations for a conventional vapour -compression system has been undertaken. This is envisaged to be powered by PV solar to cool a fluid for the cooling coil.

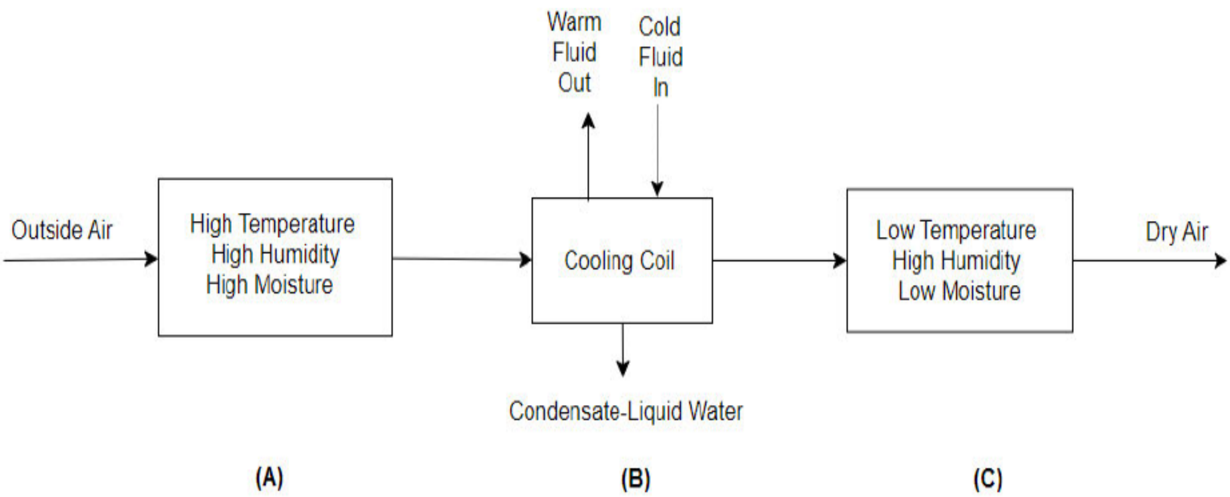


Figure 47- Chilled coil block diagram

A simple analysis has been undertaken to investigate the cooling load needed of a system. The inlet temperature is considering as average Brisbane conditions of 23°C and 63% RH. Volumetric flow rate is calculated as 1.5m^3/s based on the ducting area (0.5m^2) and air velocity (3m/s). Approximations have been made using a psychometric chart and property tables featured in Cengal and Boles

(2016). Appendix Z find that the cooling required is an estimated 50.9 kW (average).

		Inlet Air	Outlet Air	References
Temperature (°C)	T	23	10*	Assume 10°C
Relative Humidity (%)	RH	63	100	Chart approximation - (dew point)
Specific Volume (m^3/kg_{dry})	v	0.852	0.810	Chart approximation
Enthalpy (kJ/kg)	h	51.5	29.0	Chart approximation
Moisture content $\left(\frac{kg_{water}}{kg_{dry\ air}}\right)$	w	0.011	0.0076	Chart approximation
Condensate temperature (°C)	T	10		Same as outlet air
Condensate enthalpy (kJ/kg)	h_w	42.022		Table A-4 (Cengal & Boles, 2016)
Dry air mass flow (kg/s)	$\dot{m}_a$	2.278		$\dot{m}_a = \dot{V} + v_1$
Condensate mass (kg/s)	$\dot{m}_w$	0.0038		$\dot{m}_w = \dot{m}_a(w_1 - w_2)$
Cooling Load (kW)	$\dot{Q}$	50.89		$\dot{Q} = \dot{m}_a(h_{out} - h_{in}) + (\dot{m}_w * h_w)$

Table 23- Chilled coil calculations of cooling load requirements for average Brisbane conditions.

At point A in Appendix Z, ambient inlet air at 23°C and 62% humidity is cooled to saturation (100% RH) at point B approximately 16°C dry bulb temperature. Further cooling beyond the dew point to 10°C reduces moisture content of the air from 11g to 7.6g water vapor per kilogram of dry air shown at point C.

Using the same method to model the site at mean maximum temperature (28.1°C March) and mean 9am Relative Humidity (71%rH March) taken from Bureau of Meteorology historical data observations at Brisbane Airport (Bureau of Meterology, 2023). Appendix X finds that ~100kW of cooling would be required to reduce the air to the same temperature and moisture content as before.

Appendix X shows at point A′, ambient inlet air at 28.1°C and 71% humidity is cooled to saturation (100% RH) at point B′ approximately 23°C dry bulb temperature. Further cooling beyond the dew point to 10°C reduces moisture content of the air from 17.1g to 7.6g water vapor per kilogram of dry air shown at point C estimated ~100kW of cooling load needed.

6.3.2 Air Reheat

From the cooling coil the drier air must now be reheated to through the heat exchanger. Air flow off the coil will now be at 10°C with a density 1.246 kg/m^3 and specific heat of 1.006 kj/kg (Çengel et al., 2017)

The limiting case for the heat exchanger reduces the oil temperature out equal to the air inlet temperature of 10°C. Using the same modelling as before, it finds the heated air temperature of 67°C to the chamber. From the chart, specific enthalpy, relative humidity and specific volume are 85kj/kg, 6%rH and 0.97 m^3/kg respectively. Air properties are taken at 70°C finding density of 1.028kg/m^3 and specific heat of 1.007kJ/kg (Çengel et al., 2017). This is the averaged supply air to the drying chamber.

6.4 Drying

There is an average of 148kg of waste generate per day with 58.6Kg of water to be evaporated in the dryer (Table 24). If it is assumed that 8-hour operation over daylight hours, 18.5kg of waste is to be processed with 7.5kg of water to be removed per hour. Using average Brisbane conditions of 23°C and 63% RH. Volumetric flow rate is calculated as 1.5m^3/s based on the ducting area (0.5m^2) and air velocity (3 m/s).

To estimate the drying time an adiabatic simplification is used. The dry air collects moisture (humidity) as it passes over the wet mixture. The calculations assume that outlet air is 100% saturated thus determining the air moisture content at saturation or wet bulb temperature.

The effect of varying the air velocity and temperature will affect drying time. At a constant temperature and decreased air velocity less drying air volume is passed over the waste increasing drying time. For a constant air velocity and decreased temperature there is a reduction in the final moisture content removed.

A similar process has been applied to two other scenarios using the same air flow conditions. 1) Preconditioning with a cooling coil and 2) high ambient temperature and humidity in the air intake.

Initially an air velocity of 3m/s was used. Calculations found that this required only 6 minutes to evaporate the water content. Further investigations found that a 2m/s and 1m/s air flow would take approximately 10 and 20 minutes respectively. Based on the literature recommendations a minimal air flow velocity of 2m/s was adopted reducing the power requirements of the fan or blower.

For normal average conditions, one kilogram of dry air will remove 13.1 grams of water. To remove 7.5kg of water in an hour 555.34 m^3 /hour is required. The designed air flow delivers 3600 m^3/hour resulting in a drying time of approximately 10 minutes (table 25).

Post Dewatering						
Weight per %	77.0	17.8	8.9	7.4	37.0	148
Average MC %	**41.1**	**41.7**	**31.6**	**22.8**	**40.6**	
Wet basis	0.41	0.42	0.32	0.23	0.41	
Wet mass (Kg)	31.6	7.4	2.8	1.7	15.0	58.6
Dry mass (Kg)	45.3	10.4	6.1	5.7	22.0	89.4

Table 24 – Post Dewatering waste masses and moisture content for Murrumba Downs WWTP.

Moreover, pre-cooled air with cool coil and reheat was found to remove 14.1 grams of water per kilogram of dried air thus reducing drying time to 8 minutes 23 seconds. Whereas, during high ambient conditions 12.9 grams of water per kilogram dry air is removed resulting is a similar drying time as the average modelled conditions at 9 minutes 50 seconds.

The amount of drying required per hour finds the current drying system to dry within 10 minutes thus could adequately dry six times the required mass of ~45kg moisture per hour at the given conditions. However, the effects of pre-cooling the intake air needs to be further explored as based on this simplified analysis it shows no real benefit to drying time. Typically, empirical mathematical modelling and statistical data is used to determine drying and resultant moisture ratios of certain materials. However, there is no such data to perform statistical analysis for Municipal Solid Waste (MSW) (Tun and Juchelková, 2019).

		Inlet Air	Heated Coil	Outlet Air	References
Temperature (°C)	T	23	67	28*	*Wet Bulb
Relative Humidity (%)	RH	63	6	100	Chart approximation - (dew point)
Specific Volume (m^3/kg_{dry})	v	0.852	0.970	0.970	Chart approximation
Moisture content $\left(\frac{kg_{water}}{kg_{dry\ air}}\right)$	w	0.011	0.011	0.0241	Chart approximation
Water removed $\left(\frac{kg_{water}}{kg_{dry\ air}}\right)$		0.0131			$w_2 - w_1$
Dry Air Volume $\left(\frac{m^3}{kg_{dry}} hour\right)$	$v_{dry,hour}$	555.34			$\frac{m_{water}}{\Delta w} * v_{dry\ air}$
Volumetric Air Flow Rate (m^3/h)	$\dot{V}$	3600			Ducting area $0.5m^2$ Air velocity 2m/s
Drying Air Ratio		6.58			$\dot{V}/v_{dry,hour}$
Drying time (mins)	t	**9.15**			$60\ mins\ /\ drying\ air\ ratio$

Table 25 – Drying calculations for average inlet air conditions

6.5 Solar Collector Modelling

Modelling has been performed based on average days per month (Kalogirou, 2009) and the horizontal irradiance (Hh) approximated from figure 26 as a per unit area (square meter). From this, direct irradiance can be calculated and is the key factor in determining electrical energy production, thus allowing for general direct comparison of the usage of fixed and tracked solar collectors at the Murrumba Downs site based on ideal conditions and average assumptions. Yan and collaborators (2013) explain that there are additional limitations including low irradiance, ambient temperature, shadowing, collector efficiency, air flow and reflections which affects energy generation (Yan et al., 2013). These limits have not been factored in and would be governed by individual systems, local conditions and geographical locations. Nevertheless, this provides a general comparison of the collector arrangements for this design.

For the fixed panel, angle of incidence, beta has been set to 26° facing North based on Yan and scholars (2013) recommendations for PV solar. This is typical angle used for PV solar applications in Brisbane and allows for a consistent power output throughout the year of between 1.40 to 1.56 kWh/m^2. This has been averaged as 1.48 kWh/m^2 annually. This energy is intended to be used to electrical power dryer equipment as suggested by Lingayat and others (2021).

As discussed in the literature review for single axis tracking it finds that E-W polar and N-S horizontal are most consistent obtaining similar results as full tracking in figure 6. It finds that N-S horizontal suffers poor performance in winter months. Consistency of solar collection is desirable for the design, E-W tracking is also advantageous due to low shadowing when using in collector rows in large solar farm arrays for power generation. This too could be used in the scale up of this conceptual design where collector rows are used in increase power or solar energy through increased collector area. The tracked system is modelled as a E-W tracking with horizontal N-S axis (figure 7 (d)).

The tracked system requires the value of the beam slope (beta) to be minimized so the panel face is perpendicular to the direct solar irradiation beam (Gb). The model used 180° freedom limits the travel of 90° on both sides, whereby 90° is parallel to due east and -90° is parallel to due west. Collected energy throughout the year of between 1.73 to 2.43 kWh/m^2 . This is averaged as 2.11 kWh/m^2 annually.

Realistically, limits of travel may be less due to practical restrictions on tracking frame, nearby buildings and ground elevation. Nevertheless, it has been modelled as ideal to generally compare the methods of tracking and non-tracking. Table X and graph Y show the comparison of the two methods, finding that a tracked system has the capacity to collect 70% (averaged) more solar energy per square meter than a fixed system under these conditions. These conditions assume perfect irradiance, ideal tracking, theoretical solar position and no losses. Realistically, these values in table 25 will be reduced. Determination of these reductions will be attributed to numerous factors although detailed exploration is limited in this research, instead justified assumptions will be used where possible.

Cost, complexity and panel density are associated with suitability of PV system. The overall benefit of a tracking system is 42% improvement in collected solar energy considering both the high summer and low winter differences to a fixed system. It is expected that cost and complexity would be greater than that of the fixed panels. On the other hand, a fixed system is idealised to produce a steady output with minor fluctuations with minor maintenance. Fixed systems may benefit from being closely installed not needing to consider panel movement only shadowing. Increased quantity of panels and higher efficiency would be envisaged to increase costs in this case albeit while keeping complexity low, reducing the advantages of a tracked system.

A tracking system on average generate 42% more power than that of fixed systems. However, the tracking system power output reduces to ~15% in winter like the fixed system but increases to ~70% during summer.

Area 2 is approximated a 225 square meters, roughly 15 meters wide and 15m in length. Solar PV panels can be added together in arrays to customise collector surface area and thus the electrical output of a given site.

	Power (kWh) per m^2		
Month	Tracked	Fixed	Power increase (%)
Jan	1.44	2.43	68%
Feb	1.49	2.37	59%
Mar	1.44	2.17	51%
Apr	1.46	1.91	31%
May	1.49	1.73	16%
Jun	1.52	1.74	15%
Jul	1.56	1.79	15%
Aug	1.55	2.00	29%
Sep	1.53	2.06	35%
Oct	1.56	2.43	56%
Nov	1.38	2.27	65%
Dec	1.40	2.40	71%
Annual Average	**1.48**	**2.11**	**42%**

Table 25 - Annual Solar modelling of fixed and solar E-W tracking panels.

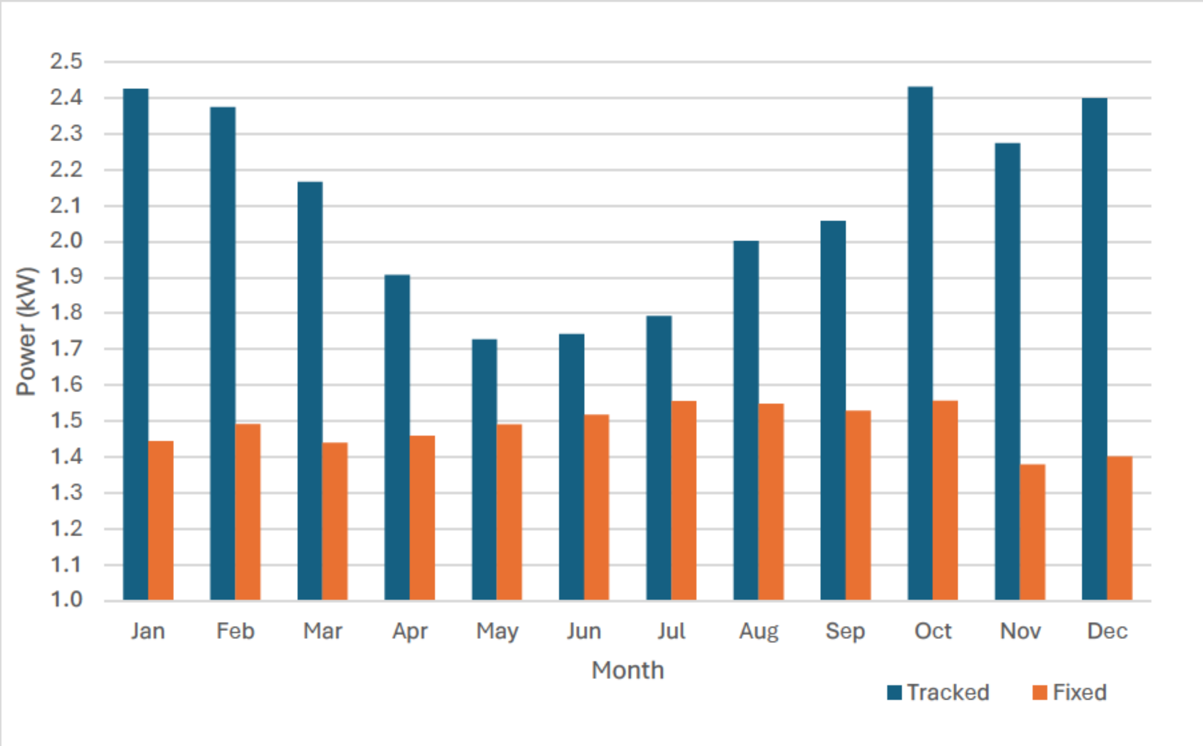


Figure 48 – Comparison between fixed and single axis tracking of PV Solar system

6.6 Solar PV

For this design, a representative single sided solar panel has been chosen. From Appendix A, the *ASTRO 6 Monocrystalline PV Module -CHSM66M-HC Series (210)* is 1.30m wide and 2.38m in length giving a surface area of $3.1m^2$ per panel. Typically, PV solar panels can have efficiencies of up to 20%, the ASTRO 6 has an efficiency η, of 21.7%.

The solar inverter is modelled as the specified 675 Watts (peak) under Standard Testing Conditions (STC).

6.7 Shadowing

Fixed solar will face due north in rows at an incline of 26°. The solar shadowing for the tracked system idealised an angle beta of 60° to minimise shadowing between the rows between peak hours of irradiation. For fixed solar panel, we are most interested in the sun's elevation (ɑ) as it moves from East to West. Shadowing in the early mornings or late evenings will be inevitable.

Through simple trigonometry, the height of the panel from the ground is the panel length L and angle θ is known. Incline is 26° and a length L is 2.28m per panel.

$$H = \sin(\theta) * L \tag{42}$$

$$H = \sin(26°) * 2.284m = 1.045m$$

To calculate row spacing it is prudent to use the lowest angle which will occur at winter solstice.

- Sun's elevation (ɑ)
- Winter solstice declination is δ_0 is -23.45°, the natural tilt of earth
- $Latitude,\ \varphi$ = (−27°)

$$\alpha = 90° - \varphi + (-\delta_0) \tag{43}$$

$$\alpha = 90° - (27°) + (-23.44°) = \mathbf{39.56}°$$

$$\alpha = \ \mathbf{39.56}°$$

Appendix Q is a modified sun chart which shows this pictorially to understand that shadows will be partially cast and the distance between rows to maximise the solar exposure at peak irradiance. For the calculations, it is assumed that this will occur between the hours of 9am and 3pm since increased hours will increase row spacing due to the low solar angles. Appendix Q shows solar elevation angle at different time of day. At 9am to 3pm solar elevation angle is approximately 24° whereas between 8am and 4pm solar elevation angle is approximately 14°. Lower solar elevation angles will increase row spacing. Note, the tilted line between morning and afternoon hours.

The row spacing is calculated using trigonometry.

$$R_{space} = \frac{H}{Tan\ (\alpha)} \tag{44}$$

Between 9am to 3pm, the solar elevation angle is approximately 24° having a row space of 2.35m Whereas, between 8am to 4pm, the solar elevation angle is approximately 14° increasing the row spacing by 1.8m to 4.2m thus reducing the number of panels that can be used in the proposed area.

$$R_{space} = \frac{1.045m}{Tan\ (24°)} = \ 2.35m \qquad \frac{1.045m}{Tan\ (14°)} = \ 4.19m$$

Using the minimum spacing of 2.35m and panel orientation of due north, it is found that 28 PV solar panels can be installed in area 2 shown in figure 47. This provides a surface area of $86.8m^2$

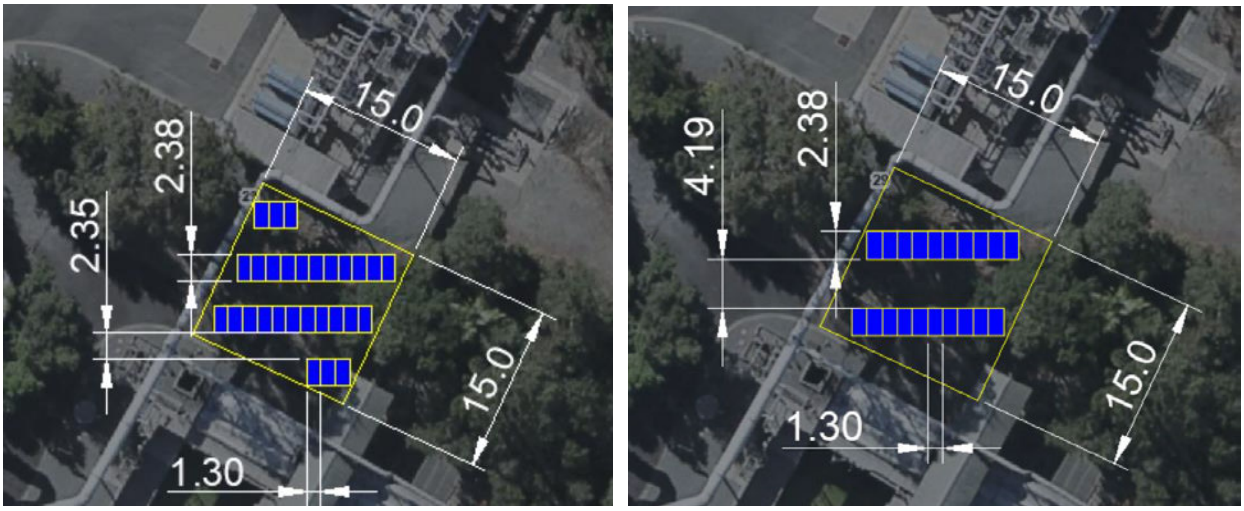


Figure 49- Indicative PV array using ASTRO 6 panels adjacent to the screening area of Murrumba Downs Sewage Treatment Plant (STP).

Figure 47 shows panel spacing of 2.35m (left) with 28 panels at 86.8 m^2 and 4.19m spacing (right) with 20 panels at 62.0 m^2.

It shall be assumed that the effect of shadowing results in no solar irradiation between the specified hours and thus no power generation presenting a worst-case scenario. Partial shadowing would result in some power generation, but this model uses an absolute case of both ideal and no irradiation for design purposes. It is found between 8am to 6pm with spacings of 4.19m power generation is reduced between 8% in January to 15% in July. Additionally, for 9am to 3pm with 2.35m spacings there is a power reduction between 21% in January to 30% in July. Table 25 finds the larger collector area facilitated by the shorter spacings area has the greatest impact on PV electricity supply. As such, the design will use the larger surface area of the two at $86.8m^2$ as its electricity limitations for the dryer design.

The power generated considers a constant panel efficiency η, of 21.7% other variations such as wind and temperature which may affect efficiency has been excluded.

Average					
	Power (kWh) per m^2			Power (kWh)	
Month	Fixed	8am to 4pm	9am to 3pm	8am to 4pm 62.0 m^2	9am to 3pm 89.8 m^2
Jan	1.44	1.33	1.14	82.38	99.03
Feb	1.49	1.35	1.16	84.01	100.35
Mar	1.44	1.29	1.09	80.02	94.96
Apr	1.46	1.29	1.09	80.07	94.37
May	1.49	1.30	1.09	80.69	94.42
Jun	1.52	1.31	1.09	81.07	94.18
Jul	1.56	1.32	1.09	81.99	94.53
Aug	1.55	1.33	1.11	82.71	96.08
Sep	1.53	1.33	1.12	82.76	96.85
Oct	1.56	1.38	1.16	85.40	100.65
Nov	1.38	1.24	1.05	76.65	90.96
Dec	1.40	1.27	1.09	78.89	94.23
Averaged	**1.48**	**1.31**	**1.10**	**81.39**	**95.88**

Table 26- Calculations to determine PV panel array spacing and power in kilowatts per square meter across the idealised year.

Table 25 has attempted to model the expected losses of due to solar angle and array shadows. This chart shows that despite the restrictions of solar irradiance at low solar angles and shadows, an increase in collector area can increase overall power generation. This shows the larger collector area 89.8 m^2 is approximately 18% more than of or 0.52kWh per meter squared to that of the smaller collector area $62.0m^2$.

The electrical storage has not been investigated in this paper. It has been assumed that the system would have sufficient battery capacity to store all generated power and is immediately available for plant process use at any time.

7 Processing

7.1 Rotary Dryer

From the previous sections, it can be assumed that drying could be completed within ~15 minutes within the drying chamber. This can coincide with average rotation of the drum to pass waste from the inlet to the outlet. This is described in Susanto and scholar's (2021) research into a biomass powered sand dryer for Hebel brick manufacture noting that increase dryer rotation, increases the capacity and the motor power but reduces the overall waste travel time (Susanto et al., 2021).

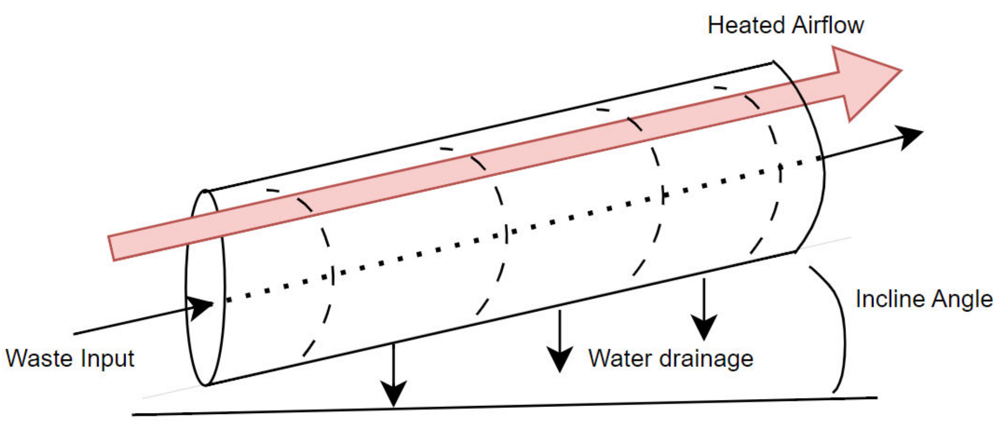


Figure 50 – Rotary dryer diagram

The linear transfer distance L_x of the waste through the dryer is the distance the waste travel for each revolution. Diameter D, in meters and incline angle ɑ in degrees.

$$L_x = 2D * \tan\alpha \quad (42)$$

(Susanto et al., 2021)

The maximum rotations of the drum n_{max} in revolutions for the waste to exit the dryer is given in equation (43). It is the length of the dryer, L_{dryer} in meters over the linear transfer distance L_x.

$$n_{max} = \frac{L,dryer}{L_x} \quad (43)$$

(Susanto et al., 2021)

Dryer time is calculated by ratio of drum rotations in revolutions per minute and the required distance travelled due to the incline angle.

$$t = \frac{n_{max}}{n_{motor}}$$

(Susanto et al., 2021)

$$n_{motor} = \frac{n_{max}}{t} \quad (44)$$

Motor Torque T, is found by waste mass m_w in kilograms, gravity in metres per second squared and diameter in meters,

$$T = \frac{m_w * g * D}{2} \quad (45)$$

This gives us (46) the power needed rotate the waste mass with output rotation of the dryer n_r in revs per minute.

$$P = \frac{2\pi * n_r * T}{60} \quad (46)$$

If we consider the motor to have an efficiency of 85%our motor power needed is as per (47).

$$P_m = \frac{P}{0.85} \quad (47)$$

(Susanto et al., 2021)

If using the above equations (41) to (44), the motor speed can be determined by drying time. At a waste volume of 0.0925 m^3/ hr is 0.00154 m^3/ min. Assume a 4° incline, 1.2m Diameter and a 2.5m length it takes 14.9 revolutions to linearly pass the waste along the drum length. For a 15-minute drying time the motor rotates at a speed of 0.993 revs per minute. Even at an increased waste throughput the motor speed is slow indicating that ~1.5 and ~3.0 revs per minute would transfer waste from inlet to outlet in 10 and 5 minutes respectively.

8 Energy Storage

8.1 Thermal Energy Storage (TES) Design Performance

There are several factors determining energy storage including storage capacity, mass and volume of the storage medium, system efficiency, discharge rate and cycling capacity.

As previously discussed, Sensible Heat Storage (SHS) is the most cost-effective method often utilising natural materials for energy storage. As such, predictability of performance can be problematic. However, in this design critical temperature is not a concern. SHS can use either solid such as rocks or liquids like water or oil.

In design 1, thermal oil is used a will maintain heat energy for a period. Moreover, the heated pipe could be used with the TES to add heat to the media. However, this may also draw heat energy away from the TES to the fluid flow. This is beyond the scope of this report, but a detailed investigation may be worthwhile.

The proposed design has a separate packed bed TES system of granite rocks in which heated air flow is forced from the heat exchanger through the rocks thus transferring thermal energy and charging the TES. On discharge, air is forced through the rocks whereby the heated rocks transfer the thermal energy back to the inlet air as travels through to the drying chamber.

The selected packed bed storage media is idealised as a cylindrical insulated tank with selected an arbitrary dimensions of one metre high to provide a volume of $0.25m^3$. The sensible heat storage medium is granite rocks of ~35mm diameter. Park and collaborators (2014) analysis of heat transfer of rock cavern thermal energy storage has used to guide this current work (Parks et al., 2014). The table 27 has been produced to detail material properties of the granite rocks and heated air properties from the preceding sections of this report.

Numerous studies of SHS TES have been conducted using computational software to mathematically model the complex interactions between the storage medium and airflow during charging and discharging phases (Hassan et al., 2023, Park et al., 2014). In this current work, this modelling is unavailable thus the analysis is limited to several assumptions. The author has attempted to theoretically model the TES behaviour although the accuracy of the data should be verified.

8.1.1 Effect of Air Mass flow Rate on Charge & Discharge

The energy balance equation (11) finds that the heat of air will be transferred to the rock. For simplicity, it shall be assumed that the heat loss Q_{loss} through conductive, radiative and convective means is small and can be neglected. Charging the TES will use heated air to increase the temperature of the rocks using equation (19). Discharging the TES will assume the inlet air is at ambient temperature and is heated as it passes through the rock bed using equation (20). The mass flow rate has been found as 1.95, 3.89 and 5.84 kg/s corresponding to 1, 2 and 3m/s airflow velocity.

The volume of the cylindrical subterranean tank is 4-meter diameter and 2-meter depth. The internal area is $50.3m^2$ and idealised rock surface area of A*(1-ε) accounting for rock porosity at $32.7m^2$ and a rock mass of 67,858 kg (67.86 tonne).

The mass of the rock is constant to directly compare the effect of airflow velocity (thus air mass flow) changes in relation to rock temperature. This is shown in appendix Z. During charging, the increased dry air velocity increases the speed in which the TES rock storage charges. lower mass flow of 1.95kg/s displays a linear relationship between rock temperature in both charging and discharging time. This air flow rate reached only 50°C within the idealised 8-hour period but only decrease by 10°C in three hours. Whereas, at 5.84kg/s a 60°C charge is reached within 5-hour period but quickly dissipates heat to <50°C in one hour.

It finds that is desirable to have a high mass flow rate corresponding to a high airflow velocity to charge the rocks whereas the discharge cycle would be suited to a low airflow velocity when discharging to slowly transfer stored heat. This would have to consider which variable is more important for drying, an increased air temperature or increased airflow velocity. For the former case, internal circulation fans within the dryer chamber may be able to assist.

At longer solar outage periods such as nighttime, a low discharge airflow fan speed would be suitable. This would maximise the duration of elevated temperatures to the drying chamber and could be, if deemed necessary, be supported by electrical heating from backup power. If drying time is not a factor, the waste processing could be suspended until solar availability is restored at sunrise. Moreover, in times where there is solar intermittency due to weather conditions, the TES would be able to stabilise the heat input to the chamber. For air velocities of 2 and 3 m/s (3.89 and 5.84 kg/s respectively) the temperature could stay above >50°C for around one hour.

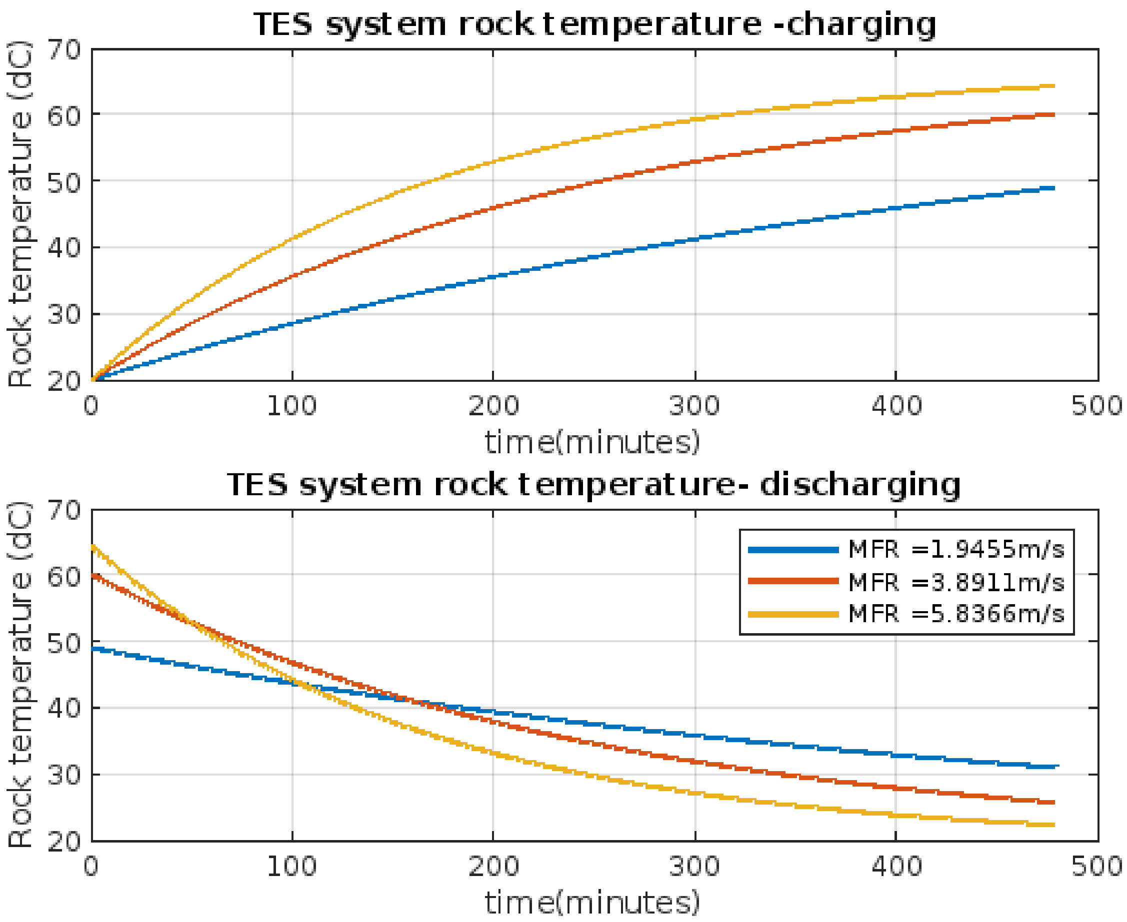


Figure 51 - Effect of temperature charge and discharge over time for a variable air mass flow rate with a constant rock mass (~68 tonnes).

Air control could be achieved through using reverse fan directions for discharge and control air duct dampers. Mechanical actuators, Variable Speed Drivers (VSDs), sensors and control logic can be used to monitor and make system changes to desired programming.

Effect of Rock Mass during Charge & Discharge

The mass of the rocks and the effect of charging and discharging was briefly investigated.

The physical dimensions provide the volume of the cylindrical TES vessel and rock density provides the mass of rock which can be accommodated. The rock surface area to the air flow can be simplified assuming it is equal to internal area of the cylinder vessel less the voids porosity of the rock expressed as $A/(1-\varepsilon)$.

A range of differing dimensions was modelled arriving at the five rock masses from 4 to 100 tonnes of rock shown in table 27. A constant airflow of 3m/s was used to charge and discharge the rocks over an 8-hour period consistent with the average length of solar hours.

Adapting the code in Appendix Z, a generalisation is found showing larger rock masses display a more stable charge and discharge, but the increased mass lowers the overall charge maximum temperature. It is estimated that a mass tonnage <20 tonnes to be sufficient for a 3 m/s air flow rate (or 1.5 kg/s mass flow rate). Further investigations into higher supply temperatures and flow rates are recommended to be pursued.

Cylindrical TES Vessel						
Diameter (m)	1	5	2	3	4	5
Height (m)	2	2	1	2	2	2
Cylinder Volume (m^3)	1.57	70.69	18.85	32.99	50.27	39.27
Rock mass (kg)	4241	10603	16965	38170	67858	106028.75
Area rocks (m^2)	5.11	11.23	12.25	32.67	45.95	70.69

Table 27 -Calculated rock masses for varying cylindrical dimensions of the TES system

8.1.2 Modelled Case

Modelled case has idealised the TES benefit as heat energy stabilisation rather than long duration high temperature output. The charge time is maximised to 6m/s corresponding to 2.98kg/s, charging ~10 tonne of rocks to a temperature of 60°C in 90 minutes. Whereas the discharge air flow velocity is reduced to a 2m/s or to1 kg/s mass flow rate can maintain temperatures above 60°C after full charge for approximately 20 minutes and above 50°C for an hour in the absence of solar heat.

The TES storage tank is 1.8 meters in diameter and 1.5m in depth with surface area of 13.6m^2 and ~8.8m^2 of rock surface. This vessel contains 10,306 kg of granite.

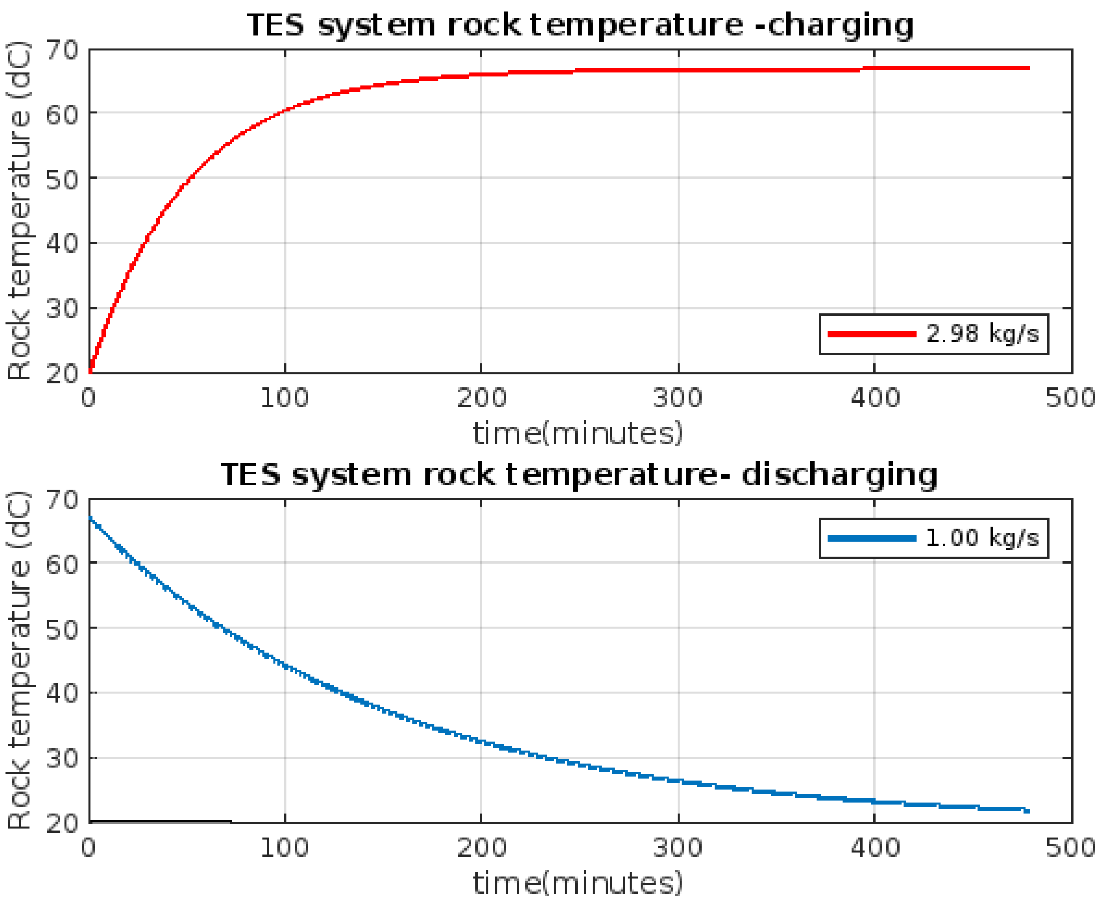


Figure 52 - Effect of charging and discharging temperature over time for a customised TES system for the concept design.

8.2 Discussion

The high energy demands of the TES system for this case means that the dryer operation should only operate during daylight hours to minimise the usage of traditional backup power. Currently the mechanically dewatered waste sent to the disposal bins awaiting transportation to landfill. At this point is where this dryer design can intervene with waste storage instead of a disposal bin.

Backup power can be used for longer solar outages if required which would also charge the TES system else in specific cases the dryer process is bypassed prevent waste becoming unmanageable. Another idea could have the waste reprocessed and sent back to the storage tank to assisting in the absorption of the holding tank moisture.

9 Performance Results

The preceding sections of this report has investigated the features of the proposed design. It has found several anticipated performance values based on theoretical modelling. Where possible calculations have been customised for the Murrumba Downs site. Physical limitations for the PTC and PV array have been observed for the available area by selecting the most appropriate technology and configurations with currently available products.

It finds that for an average and constant solar irradiance of 6 hours, fixed photo voltaic solar power could generate an average ~95.8 kWh using $86.8m^2$ of panels to support plant equipment such as pump, blowers, conveyors and control systems. Investigations into single axis tracked panels was conducted and found higher power yield of ~42%. However, space limitations with panel orientation and shadowing affected the panel quantity thus surface area available. Fixed panels were chosen as a compromise.

PTC arrangement was analysed from three different collector sizes. It was found that the largest Solitherm 4000 the most suited with six single N-S axis collectors (two rows of three) providing $120m^2$. A detailed calculation of the useful heat transferred to HTF from the PTC collector was performed. For the solar thermal energy under the same conditions the proposed PTC array found that fresh water could be heated to ~84°C but given the approximation of the calculation findings the water may heat to boiling point (>100°C) Instead, and to maximise the thermal energy to the dryer, a thermal oil product was selected finding an average temperature of ~ 179°C at a mass flow rate of 0.4kg/s.

A small crossflow heat exchanger can heat ambient air at 23°C and an airflow velocity of 3m/ to ~67°C. This heated air is used within the drying chamber to evaporate residual waste moisture.

Manual approximations using property tables and psychrometric chart was used to model the anticipated air flow through the dryer. For average historical Brisbane conditions inlet air temperature was identified as 23°C dry bulb and RH 62% with the air moisture content of 11.5g/kg air.

Modelling the air flow as 555 m^3 per kilogram per hour at the drying air ratio was ~6 times the required drying airflow per hour or approximately 10 minutes to remove 7.5kg of moisture from the waste mixture assuming 100% water saturation on exhaust. A simple assumption finds that 7.5kg of water could be evaporated within 10 minutes at constant conditions of >60°C at 2 metres per second air flow resulting bone dry waste. This contrasts with De Torre Bayo and collaborators (2022) work with oven drying but is different as the drying chamber exhausts moist air decreasing drying time.

Further investigations into dehumidifying humid ambient air via a pre-cooling system was conducted based on average historical maximum conditions for Brisbane ~70%rH and 28.1°C found a similar drying time. Cooling coil was found to require 50kW for average conditions and up to ~100kW for the maximum expected conditions. It finds that the drier air reduces drying time suited for hygroscopic materials (Dincer and Zamfirescu, 2016). However, given the complexity of the analysis no further results were uncovered to the overall benefit of the precooling stage. Moreover, the use of an absorption cycle supplied with solar energy was identified as being a possible solution, but the analysis of the system is beyond the reports scope.

The TES for the design was idealised a novel subterrain cylindrical tank of ~10 tonnes of granite in a packed bed keeping with the multi-level system concepts. A decision was taken to have the TES primarily used for short term system heat stability (>50°C). This was due to the physical limitations of the TES being no more than 2 meters deep. Moreover, a larger volume of granite rock would also take longer to heat but would extend the heat dissipation discharge. This contrasts with long term overnight heating of the chamber. The system has been designed to dry more than the average rate within ~8 hours of daylight operation when solar energy is available. Overnight suspension of operation is envisaged to be more energy efficient than continuous drying, but the design has provisioned for back-up power for both processing and heating if needed.

TES is influenced by the heated mass flow rate of air which is influence by duct work area and fan speed for airflow velocity. The modelled system uses a higher velocity airflow at 6m/s when charging and a lower airflow velocity at 2m/s when discharging. This is because charging can directly use the solar energy to power the fan which can charge the TES in approximately to 60°C in 90 minutes. At discharge, stored electrical power is limited and it is desired to prolong the high temperatures in the chamber. This allows temperatures of >50°C for a full hour in the absence of solar energy. Future work could investigate a control system including VSDs, dampers and sensors to adjust fan speeds to charge and discharge the TES optimally.

Modelled data is identified as a daily average of 400kg of screening waste with 60kg moisture post mechanical dewatering. If assumed steady conditions, total water removal from the waste (bone dry), and a seven-day continuous operation, the total generated waste mass is 2.8 tonne with a weekly disposal fee, calculated at $240 per kilogram of $812 or $42,224 per annum. On the other hand, the total water removed when drying could reduce the waste weight to 2.38 tonne per week with a weekly disposal fee of ~$690 or $35,890 per annum. This is an approximate saving of $6333 per year and prevents the transportation of 21 tonnes of residual unwanted water. What is not quantified is the reduction in waste transportation cost, transport emissions, water saving and environmental benefits of a waste dryer. Notably and of greater significance is the potential for waste valorisation deriving value in the form of Solid Recovered Fuels (SRF) or generating energy. In the scenario of available Australian markets for SRF, the potential value found by Ngamaket and others (2021) research state up to $30 per tonne which could generate an annual revenue of $3712 for ~124 tonnes of dried screening waste for this site. Moreover, if processed to RDF-4 or RDF-5 as suggested by Chavando and others (2021) the value could be four times greater at $16,492 per year. Unfortunately, energy generation has not been fully defined, but the ability to generate energy to support drying, other WWTP process operations or for export would be a worthwhile investigative endeavour in future works to reduce costs and impacts of screening waste disposal.

10 Conclusion

The aim of this research was to investigate and present a conceptual screening waste drying solution using solar energy assistance. The intent was to reduce the moisture content within the waste which provide both environmental and cost-reduction benefits. This is the first step into waste valorisation for this waste type.

The literature was unable to undercover any structured method to designing a solar dryer. Typically, solar dryer designs are created to serve a specific function at a specific location. As such, this paper, proposed and adopted a design framework to develop a potential solar dryer solution through problem definition, design objectives, limitations and requirements. These systematic steps assisted the author to comprehensively develop and evaluate a design based on a real WWTP location in Brisbane's northern suburbs. Two areas adjacent to the current WWTP inlet screening works was selected of $400m^2$ and $225m^2$ respectively. A novel multi levelled design was theorised to maximise the available space. The ability to use a specific site better defined the problem space and reflected the many integration challenges a dryer design solution may be faced with.

The Functional Analysis Method (FAM) including reverse engineering was found to be useful to identify the system interaction and processes which are at times are obscure. A full appreciation of sub-functions greatly assisted in design boundaries However, weaknesses of the process is attributed to the system complexity, whereby the SWOT analysis presented had little benefit to design selections and the QFD over-elaborated this evaluation process as the author was unable to directly compare each the designs against existing dewatering systems. Moreover, an additional element of the design process explored creative methods and expanding of identified functions to rethink the solution. Further synthesis of the collated data enabled the generation of several design ideas which were evaluated against a developed criteria. Of these ideas, a single design was selected and theoretically modelled.

10.1 Design Proposal

The presented conceptual design is a hybrid solar energy forced air rotary dryer system with a packed rock bed TES backup. Air is heated via a crossflow heat exchanger of a closed loop, high temperature synthetic oil heated via solar thermal energy from the single axis tracking Parabolic Trough Collector (PTC) array. The system also uses and stores electrical power from fixed Photo Voltaic (PV) solar panels and chemical batteries.

The dryer was develop based on four key objectives in mind – High Reliability, High Performance, Functional and Add Value. Firstly, the design response to reliability come in the form of a hybrid design using backup power to continue operations in absence of solar energy. A TES system and batteries can provide heating and electrical power for a short time respectively. Material selection was not investigated in this report, but this would further define the durability of the design proposal.

For the functional criteria, the design has presented as simplistic design with a proven and well-developed method of forced air drying. Waste feed rate is adjustable with provision to re-process the waste back to the front-end storage tank. The design has focused on modular sections including processing, air drying, control & power and solar assistance providing flexibility in its configuration. While unconventional, the multi-level system design could provide a means of utilising space in an efficient way, maximising solar energy collection while minimising system footprint.

The two other objectives of high performance and add value is still undetermined. Costs are linked to material usage and energy consumption which was not investigated. However, some basic equipment sizing and system layout with representative solar collectors has been performed providing a starting point to developed potential costs. Evaluation on the performance requires an in-depth analysis of screening waste drying. Understanding the process will lead to ability to optimise the drying procedure in an efficient manner.

10.2 Dryer selection

A hybrid dryer was selected due the continuous and variable screening waste volumes combined with the unpredictability of solar energy; conventional backup power was required. This report did not explore further but assumes either mains electrical or generator could be suitable to power restive heater elements to heat fluid and power the processing equipment.

Furthermore, the dryer design has incorporated Thermal Energy Storage (TES) system to maintain heat for the periods of solar unavailability including nighttime.

10.3 Drying Design

Forced heated air both evaporates and removes the moisture from the waste mixture. It is extensively used in food drying to reduce drying time and has been used to successfully dry screening waste in laboratory conditions. The waste in this research has been idealised as non-hydroscopic needing high drying temperature at low relative humidity (%RH).

The high drying temperatures are achievable by concentrating solar collectors which can achieve temperature ranges of 60 - 300°C but require single axis tracking to follow the sun. This increases the designs cost and complexity, but this research finds that it increases the solar energy collected by ~40% on average for the same collector area to that of a fixed panel system. A SWOT analysis found that Parabolic Trough Collectors (PTC) to be most suited for this design due to the technology maturity, prefabricated construction, high efficiency and scalability A single N-S tracking, PTC array using six (two rows of three) Solitherm 4000 collectors was selected as the most suitable configuration to provide a large area of 120m^2. These collectors were aligned to E-W tracking offsetting the alignment to the area by 25° increasing solar energy yield by ~8%.

Analytical modelling found that when water (fresh) was the selected heat transfer fluid, temperature could reach to 84°C. This was changed in the design to prevent the potential of steam generation when the water boiled under higher solar irradiance. To address this, a higher boiling point synthetic oil, Solitherm A, was instead modelled and found achievable temperatures of up to 179°C at a mass flow rate of 0.4kg/s. The oil is circulated to heat ambient air in a 1.62m^2 area crossflow heat exchanger located internally of the ductwork. The report found that forced 3 m/s air was heated from an ambient 20°C to 75°C within the drying chamber. Modelling indicates that ~7.5kg of water can be evaporated from the idealised waste mixture in approximately ten minutes under optimal solar conditions.

10.4 Low drying air humidity

To address the need for low relative humidity (RH) air into the drying chamber, a pre-cooling stage was briefly investigated. The pre-cool stage would dehumidify ambient air which can be an average of 63% RH and maximum of 71% RH for local Brisbane conditions. The report finds by using a psychrometric chart that the reduction in moisture content by 3g and 10g dry air per kilogram at a cooling energy of 50.9 and 100kW respectively for average and maximum conditions. Only some small improvements in drying time were found when pre-cooling was used but there is uncertainty in the additional benefits this method may bring. Future research would need to understand the significance of low relative humidity air used to dry the screening waste mixture drying to justify the large energy required to pre-cool the ambient air.

10.5 Design power supply

A fixed panel PV system was chosen in preference to a single axis tracking despite the decrease in energy yield. This was due to limited space and array shadowing in area 2. The fixed panel array of 28 panels provides a 86.8m^2 surface area. The panels align due North at an angle of 26° and could achieve 95.8kWh daily based on six hours of direct solar irradiance (average). This power is envisaged to provide supplementary power to the system equipment such as fans, pumps and conveyors. However, the system equipment energy requirements have not been fully defined in this work.

10.6 Backup power and heat

The TES is an underground cylindrical tank containing ~10 tons of 35mm diameter granite in a packed bed formation. The design was decided to be used for short-term, high-temperature discharge in times of low or unavailable irradiance in bad weather acting as a temperature stabiliser. This is because vast air mass flow or higher forced air temperature is needed to charge this idealised TES for continuous overnight operation providing drying temperatures above

>50°C. This decision resulted in dyer operation being limited to daytime use only unless hybrid backup power is used. Waste generated overnight would remain in a holding tank then would be process when solar energy was available. The TES was charged using 6 m/s air of 2.98 kg/s at 67°C taking 90 minutes to reach the same input temperature. On discharge, lower air mass flow rate of 1kg/s at a velocity of 2m/s was found to prolong TES heat dissipation above >50°C for around an hour.

10.7 Rotary Drum Drying Chamber

Two methods of waste transportation flatbed conveyors and rotary drum was investigated finding that rotary motion is beneficial to the convectional drying as the waste pile is agitated as it transverses through the chamber. The waste volume was calculated at 0.0925m^3 / hr and 10mm in depth. A spiral helix and a shallow 4° incline progress the waste from one end to the other turned by a rotating shaft. The design models a 1.2m diameter drum and a 2.5m drum length. For a 15-minute drying time the motor rotates at a speed of ~1 revs per minute. Even at an increased waste throughput the motor speed is slow indicating that ~1.5 and ~3.0 revs per minute would transfer waste from inlet to outlet in 10 and 5 minutes respectively.

10.8 Dryer Benefits

The report finds that the proposed conceptual system is technically feasible and could means of providing operational cost savings, environmental benefits and pathways to waste to energy markets. Dryer design cost and savings of the system were not fully explored. However, idealised modelling of average Brisbane conditions found that a potential annual saving of ~$6,333 could be achieved for the Murrumba Down WWTP. More significantly, waste valorisation pathways such as Solid Derived Fuel (SDF) and Waste to Energy (WtE) through drying could generate potential earnings of up to $16,000 per year if Australian markets and their demands mimicked the energy demands of European market.

Moreover, energy generation could be used to offset individual WWTP operating costs promoting sustainability in municipal water operators.

10.9 Project Outcomes against Specific Objectives

All but the final research objective was achieved. Given the breadth and limited time of the project, only key system components were investigated to predict the designs potential performance. The suggested Energy and Exergy analysis was unable to be performed and a clear definition of waste volume reduction using numerical modelling was not completed.

Moreover, the author attempted to consider most factors of the system design with the report heavily utilised average values as a base line for many calculations. The reports assumption of ideal conditions to simplify the complex interactions limits this reports performance findings but provides a feasible theoretical system which will require refinement at a detailed design stage. Further investigations could use Computational Fluid Dynamics (CFD) and experimental scale systems to better understand the drying behaviour of screening waste. This would provide theoretical validation of a suitable model and provide the necessary analytical data to refine a drying solution.

Despite this, based on the numerically modelled findings in this report the Murrumba Downs WWTP could benefit from a screening waste dryer system using solar energy as both a heat and power source. The design presented would have both a capital and operation expenditure cost and would be envisaged to be a major barrier to implementation. However, this is but one of many designs that could be a solution. The design framework is intended to guide designs of other WWTPs.

10.10 Lessons learnt

There were many challenges experienced during this project. At first, the authors understanding of wastewater treatment, solar technology and drying phenomenon was limited and required methods to obtain the relevant knowledge to understand the screening waste problem. The initial stages of the design relied heavily on a comprehensive literature review and was further assisted with conversations with local wastewater utilities process engineers. However, conversations with the engineers stalled early as their primary focus is on biosolids management and the literature offered little on screening waste. The literature found that solar technology is well documented for the food industry, but waste dryers are scarce. Also, it found that solar dryer design is not standardised and is usually achieved through trial and error or prior experience which proved to be a further challenge for this projects conceptual design. To address this, the author used adapted prescribed mechanical design methods and included a local WWTP as a model incorporating assumptions about local waste volume, composition and climatic conditions to better define the problem.

Furthermore, the design was an iterative process, undertaking research, performing calculations and theoretical analysis on the multiple sub-systems to enabled component selection and sizing. Calculations proved the conceptual design elements and modelled their dependant interactions with other sub-systems. Often this presented further technical challenges or other considerations not initially identified. These included the effect of inlet air humidity on drying, the temperature of heat transfer fluid for the PTC array and the airflow requirements for packed bed TES. Assistance of the fundamental calculations around solar thermal modelling, psychrometry and drying phenomenon required further reading not originally identified to conduct the required numerical evaluation. The process of finding a solution to such challenges fully utilised the authors logic, engineering judgement and critical thinking skills as intended for an undergraduate research project.

10.11 Future work

This paper has presented a novel conceptual solar waste dryer design including a design framework as a potential solution for reducing the residual moisture content of screening waste. The proposed design indicates that the concept is feasible and could provide unrealised benefits to current practices.

As discussed, numerical modelling and logical assumptions have had to be used limiting the report's findings. Future work requires more input from industry to drive the needs of a solution to focus the designs requirements. Further work needs to adopt the use of CFD and experimental/empirical data to reveal further dryer performance attributes and design considerations.

The system has been designed in stages of solar capture, energy storage, drying chamber and processing which have been briefly addressed. More detailed work should be undertaken including materials, control methods, and costs.

During the project the benefits of low Relative Humidity (RH%) drying air and the effect on water removal was not fully defined. Further work should closely investigate this to determine if pre-cooling of ambient air particularly for humid conditions is a worthwhile feature. Moreover, the significance of waste drying is found to be in the ability to use the dried waste as an energy source. In this work, renewable solar energy has been investigated. However, other process heat sources particularly from biological digestion could be harnessed to assist the drying of screening waste.   This could be utilised overnight when there is no solar available.

10.12 Final Remarks

In conclusion, WWTPs play a key role in promoting waste to energy (WtE) initiatives for the benefit of a sustainable societies. This research provides WWTPs an improvement on current waste management practices reducing operational cost and environmental damage through the reduce of residual waste moisture. This paper has presented a standardised waste dryer design methodology that could be adopted for future work using solar as a sustainable means of both thermal and electrical energy. Screening waste drying can support the aims of the Australian governments environmental sustainability policy based on the broader United Nations (UN) Sustainability Development Goals (SDGs). Significantly, this research can provide a new perspective for local southeast Queensland WWTPs and their screening waste management practices. This paper has taken the initial step of highlighting the many unrealised benefits waste drying and the practical implementation of such a system which can now be further developed.

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12 Appendices

Appendix-A Fixed Solar PV panel datasheet

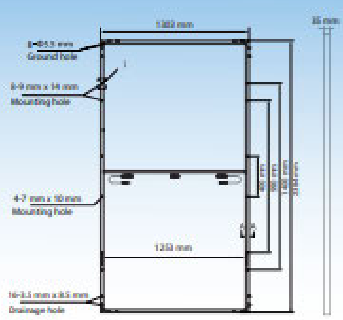
Solar Panel Data 210(660~675)ASTRO 6 Semi_CHSM66M-HC_2384x1303x.pdf (wsimg.com)

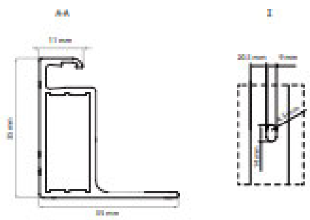
ELECTRICAL SPECIFICATIONS

STC rated output (P_{mpp})	660 Wp	665 Wp	670 Wp	675 Wp
Rated voltage (V_{mpp}) at STC	37.85 V	38.05 V	38.23 V	38.42 V
Rated current (I_{mpp}) at STC	17.45 A	17.50 A	17.54 A	17.58 A
Open circuit voltage (V_{oc}) at STC	45.68 V	45.88 V	46.08 V	46.28 V
Short circuit current (I_{sc}) at STC	18.53 A	18.58 A	18.63 A	18.68 A
Module efficiency	21.2%	21.4%	21.6%	21.7%
Rated output (P_{mpp}) at NMOT	493.2 Wp	497.0 Wp	500.7 Wp	504.4 Wp
Rated voltage (V_{mpp}) at NMOT	35.28 V	35.46 V	35.63 V	35.81 V
Rated current (I_{mpp}) at NMOT	13.99 A	14.03 A	14.06 A	14.10 A
Open circuit voltage (V_{oc}) at NMOT	43.17 V	43.36 V	43.55 V	43.73 V
Short circuit current (I_{sc}) at NMOT	15.03 A	15.07 A	15.11 A	15.15 A
Temperature coefficient (P_{mpp})	- 0.34%/°C			
Temperature coefficient (I_{sc})	+ 0.04%/°C			
Temperature coefficient (V_{oc})	- 0.25%/°C			
Nominal module operating temperature (NMOT)	43±2°C			
Maximum system voltage (IEC/UL)	1500V_{DC}			
Number of diodes	3			
Junction box IP rating	IP 68			
Maximum series fuse rating	30 A			

Power Sorting: 0~+5W
* Measurement tolerance +/- 3%
STC: Irradiance 1000W/m², Cell Temperature 25°C, AM=1.5
NMOT: Irradiance 800W/m², Ambient Temperature 20°C, AM=1.5, Wind Speed 1m/s

MODULE DIMENSION DETAILS



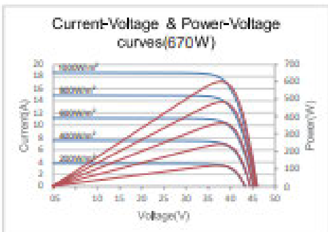


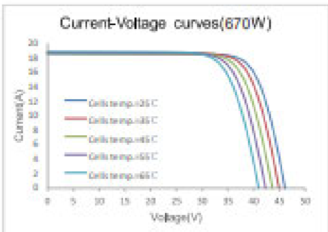
MECHANICAL SPECIFICATIONS

Outer dimensions (L x W x H)	2384 x 1303 x 35 mm
Frame technology	Aluminum, silver anodized
Front glass thickness	3.2 mm
Cable length (IEC/UL)	Portrait: 350 mm Landscape: 1400 mm
Cable diameter (IEC/UL)	4 mm² / 12 AWG
[*] Maximum mechanical test load	5400 Pa (front) / 2400 Pa (back)
Fire performance (IEC/UL)	Class C (IEC) or Type 4 (UL)
Connector type (IEC/UL)	HCB40 or PV-KST4-EVO2/XY-UR, PVKBT4-EVO2/XY-UR(optional)

[*] Refer to Astronergy crystalline installation manual or contact technical department.
Maximum Mechanical Test Load=1.5×Maximum Mechanical Design Load.

CURVE





PACKING SPECIFICATIONS

[*] Module Weight	34.8 kg
[*] Packing unit	31 pcs / box
Weight of packing unit (for 40'HQ container)	1119 kg
Number of modules per 40'HQ container	527 pcs

[*] Tolerance +/- 1.0kg
[*] Subject to sales contract

Made in Zhejiang, Jiangsu and Anhui of China, Made in Sincan/ Ankara of Turkey

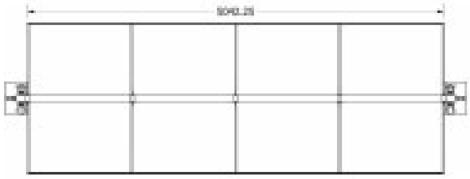
http://www.astronergy.com.au

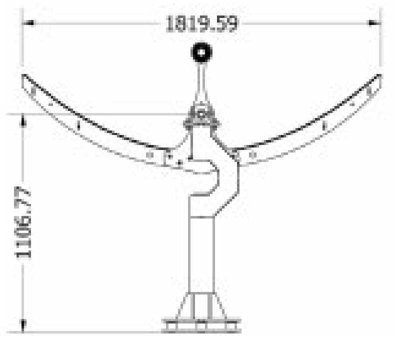
Astronergy 07-2021

Appendix-B - PTC Specification Sheet – Solitherm 1800 model

SOLITERM Group
Rutherford 108 D-52072 Aachen
TEL + 49 (0)241 980 906-0
info@solitermgroup.com
www.solitermgroup.com

PTC - 1800





COLLECTOR

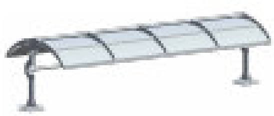
PARAMETER	VALUES
Length	5100 mm
Width	1800 mm
Aperture Area	9 m²
Material	Aluminum
Mirror Surface Material	Polished Aluminum

PERFORMANCE

PARAMETER	VALUES
Concentration	Up to 50
Temperature Range	100°C–250°C

ABSORBER

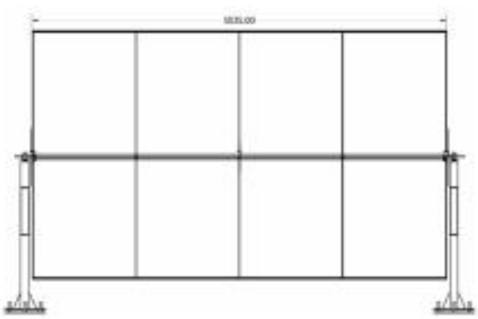
PARAMETER	VALUES
Material	Steel
Hull Material	Glass

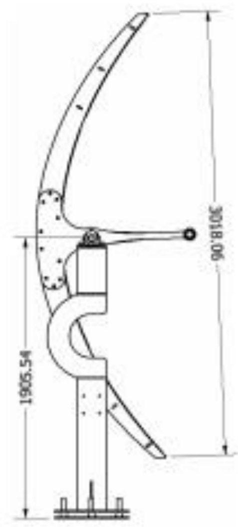


Appendix-C -PTC Specification Sheet – Solitherm 3000 model.

SOLITERM Group
Rutherford 108 D-52072 Aachen
TEL. + 49 (0)241 980 906-0
info@solitermgroup.com
www.solitermgroup.com

PTC - 3000





COLLECTOR

PARAMETER	VALUES
Length	5000 mm
Width	3000 mm
Aperture Area	15 m²
Material	Aluminum
Mirror Surface Material	Polished Aluminum

ABSORBER

PARAMETER	VALUES
Material	Steel
Hull Material	Glass

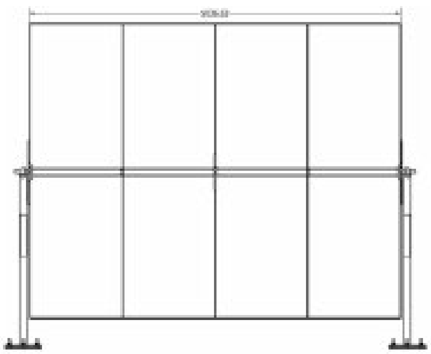
PERFORMANCE

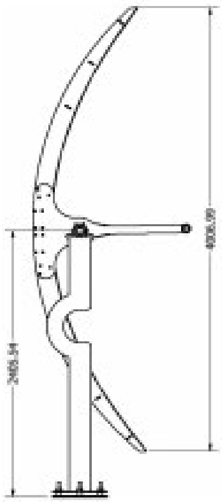
PARAMETER	VALUES
Concentration	Up to 65
Temperature Range	100°C–250°C

Appendix-D -PTC Specification Sheet – Solitherm 4000 model

SOLITERM Group
Rutherford 108 D-52072 Aachen
TEL. + 49 (0)241 980 906-0
info@solitermgroup.com
www.solitermgroup.com

PTC - 4000





COLLECTOR

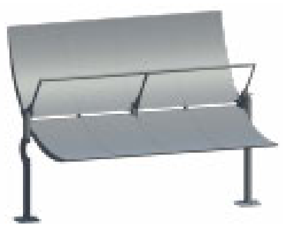
PARAMETER	VALUES
Length	5000 mm
Width	4000 mm
Aperture Area	20 m²
Material	Aluminum
Mirror Surface Material	Polished Aluminum

PERFORMANCE

PARAMETER	VALUES
Concentration	Up to 80
Temperature Range	100°C–250°C

ABSORBER

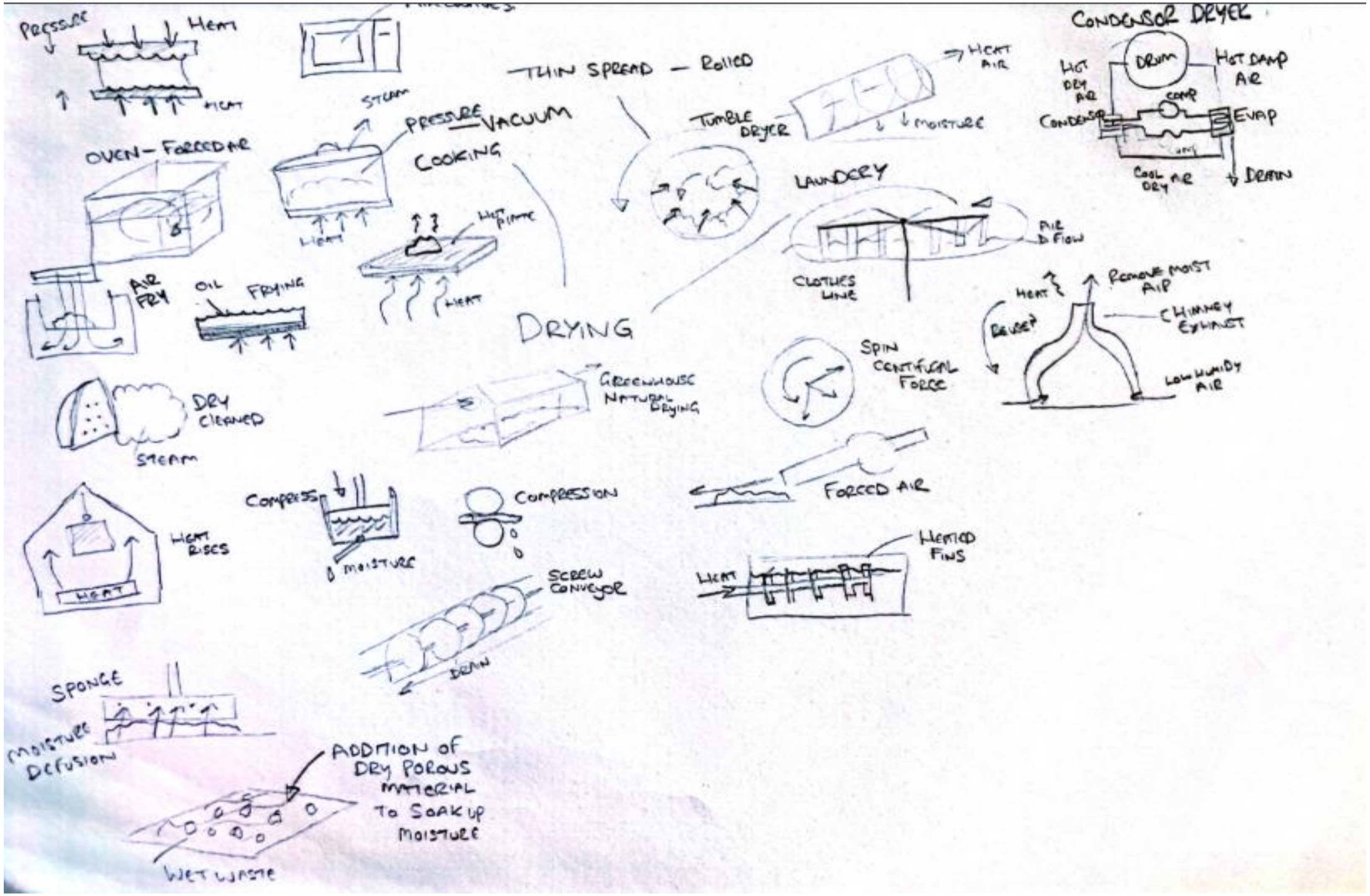
PARAMETER	VALUES
Material	Steel
Hull Material	Glass



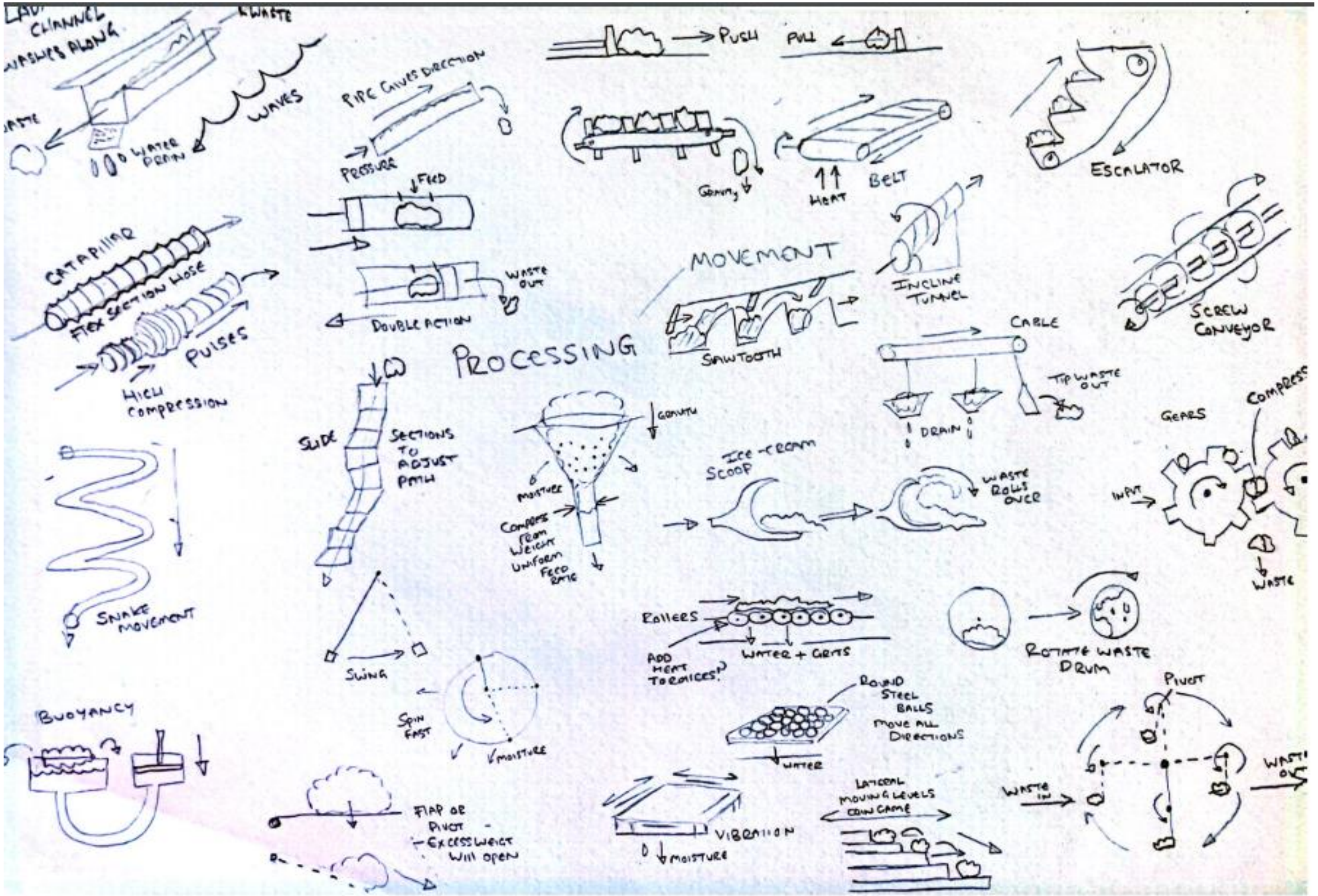
Appendix-E Objective Weightings Matrix

	Objective	1	2	3	4	5	6	7	8	9	10	11	12	13	14	**Total**
1	Reduce Moisture	-	1	1	1	0	1	1	1	1	1	1	1	1	1	**12**
2	Reduce Volume	0	-	0	1	0	1	0	1	1	1	1	0	1	1	**8**
3	Must be reliable	0	1	-	1	0	1	1	1	1	1	1	1	1	1	**11**
4	Must be durable	0	1	0	-	0	1	0	1	1	1	1	0	1	1	**8**
5	Odour Control	1	1	1	1	-	1	1	1	1	1	1	1	1	1	**13**
6	Transport Waste	0	1	0	1	0	-	0	1	1	1	1	0	1	1	**8**
7	Efficiency	0	1	0	0	0	1	-	1	1	1	1	0	0	1	**7**
8	Dryer Capacity	0	0	0	0	0	0	0	-	0	1	0	0	0	1	**2**
9	Flexibility	0	0	0	0	0	0	0	1	-	1	0	0	0	1	**3**
10	Modular	0	0	0	0	0	0	0	0	0	-	0	0	0	1	**1**
11	Ease of maintenance	0	0	0	0	0	1	1	1	1	1	-	0	1	1	**7**
12	Backup Power	0	1	0	0	0	0	1	1	1	1	1	-	1	1	**8**
13	Integration with existing systems	0	0	0	0	0	0	0	0	1	1	0	0	-	1	**3**
14	Feed rate	0	0	0	0	0	0	0	0	0	0	0	0	0	-	**0**

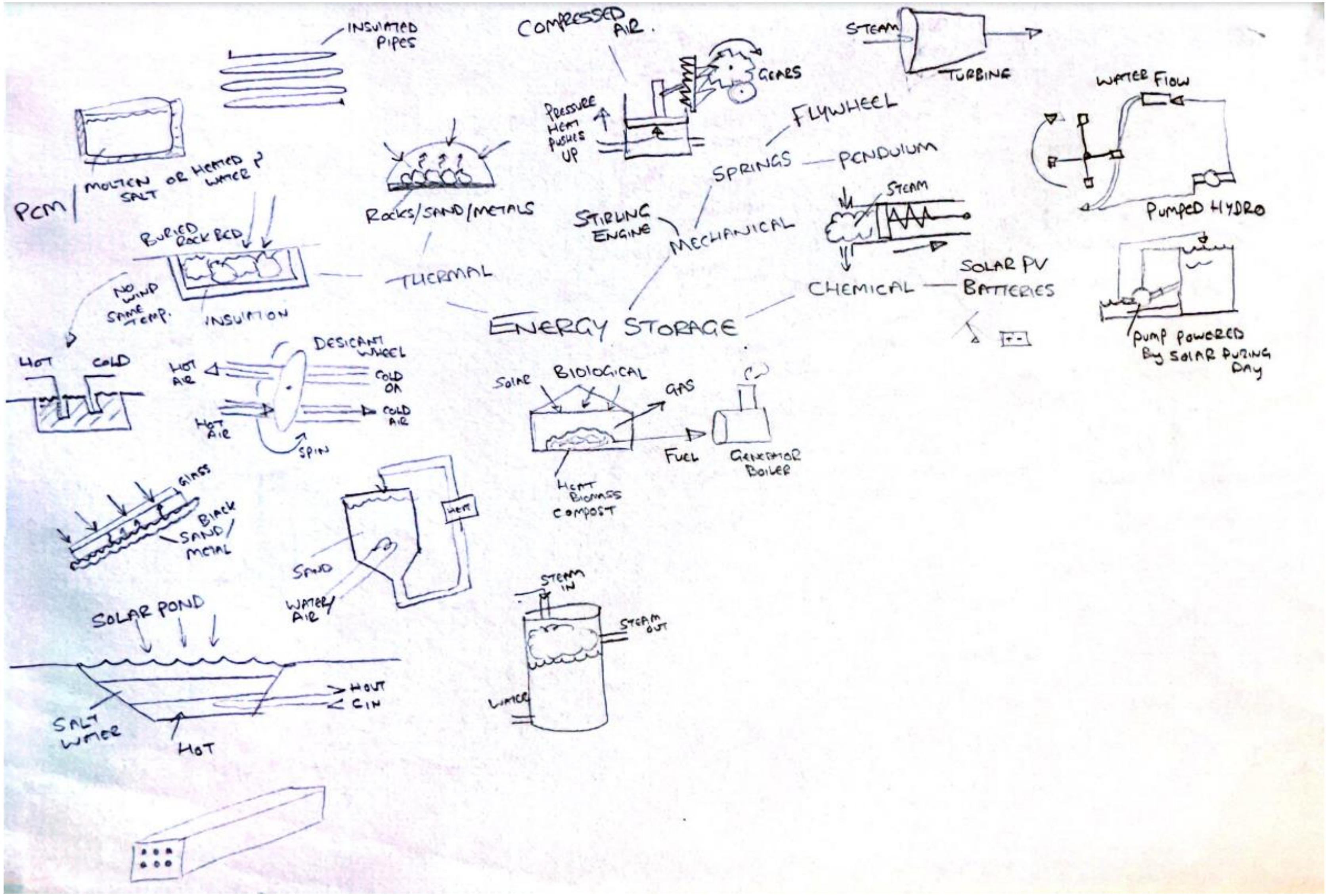
Appendix-F Brainstorm Sketches – Drying



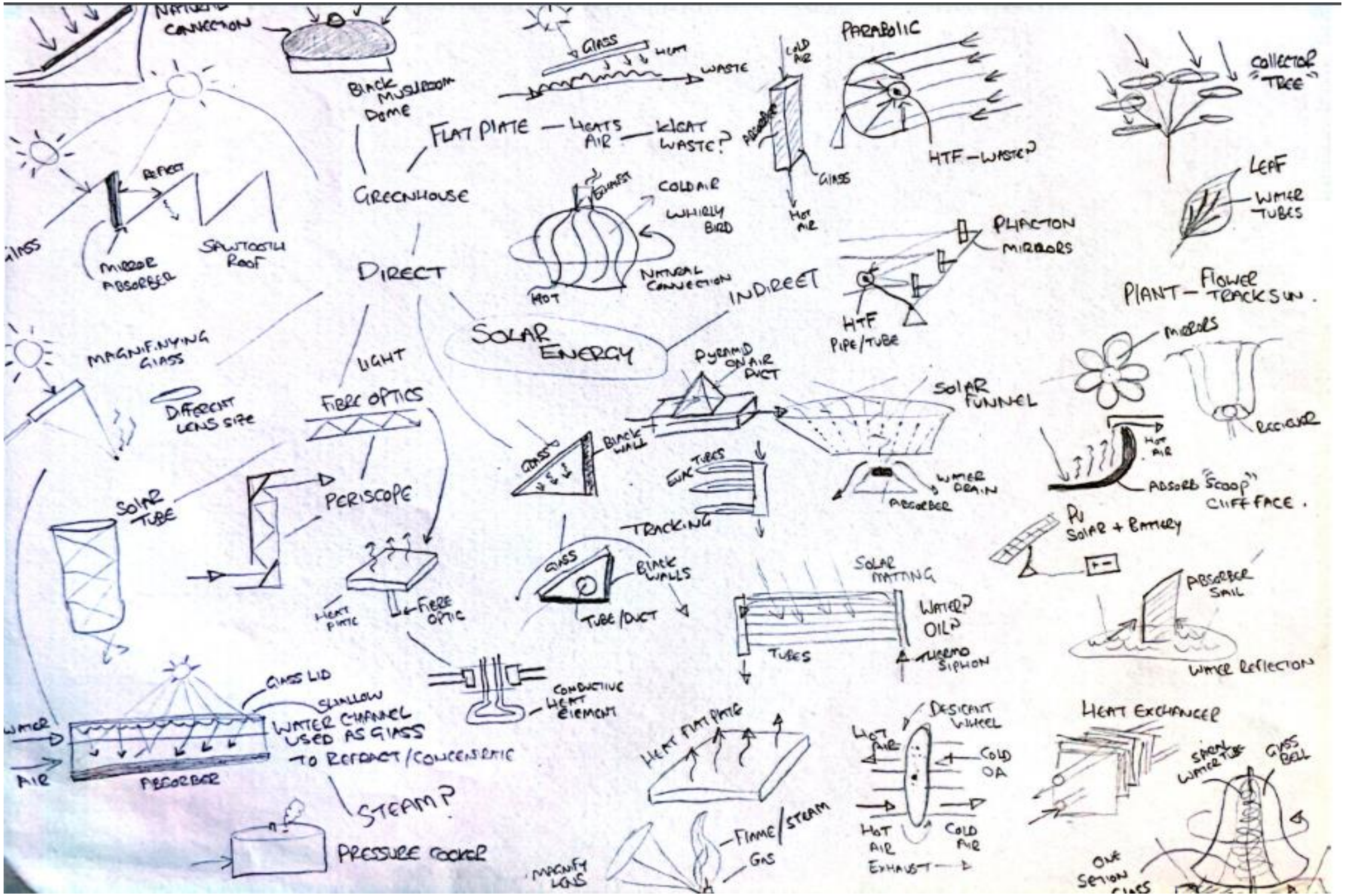
Appendix-G Brainstorm Sketches – Processing



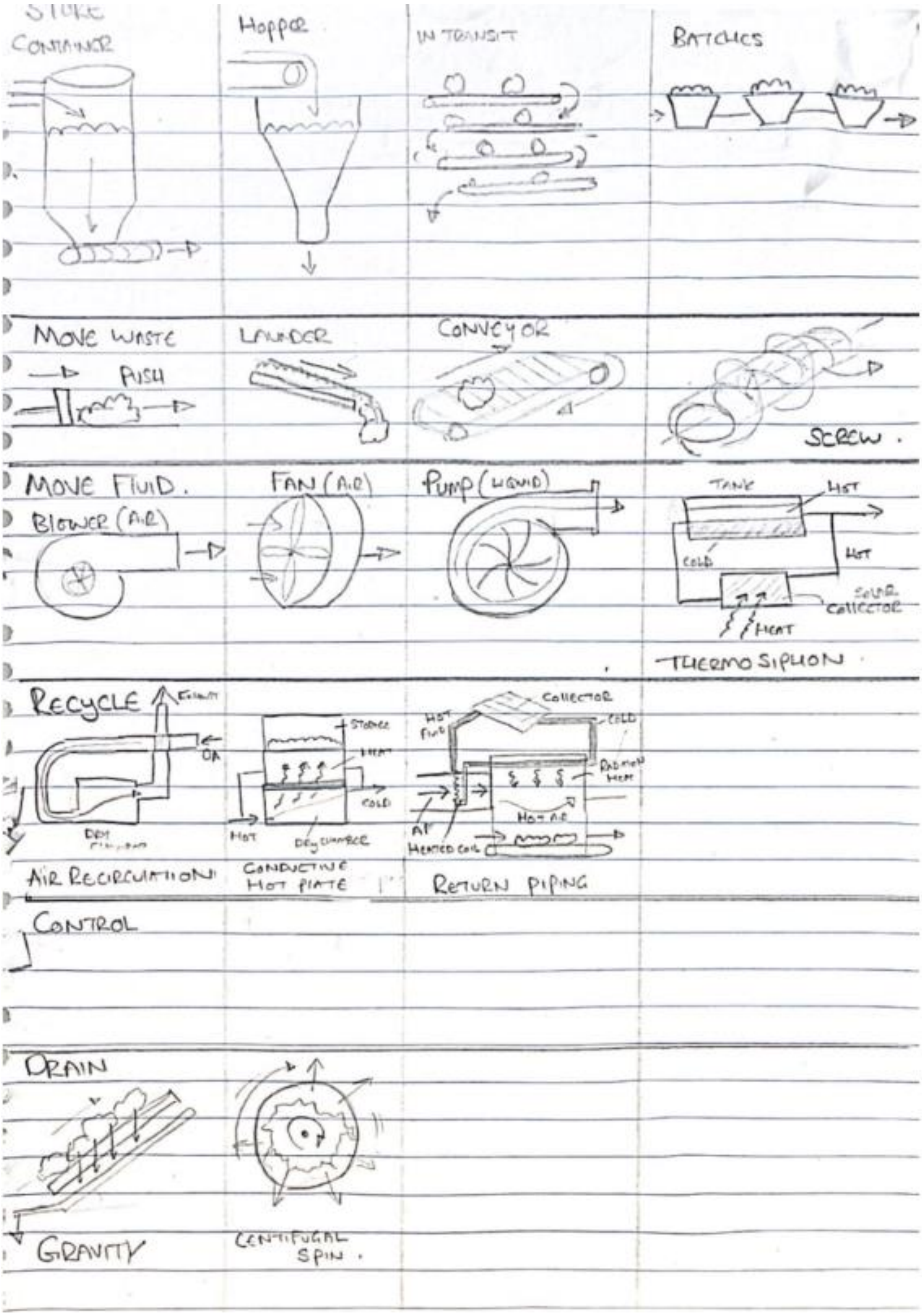
Appendix-H Brainstorm Sketches – Energy Storage



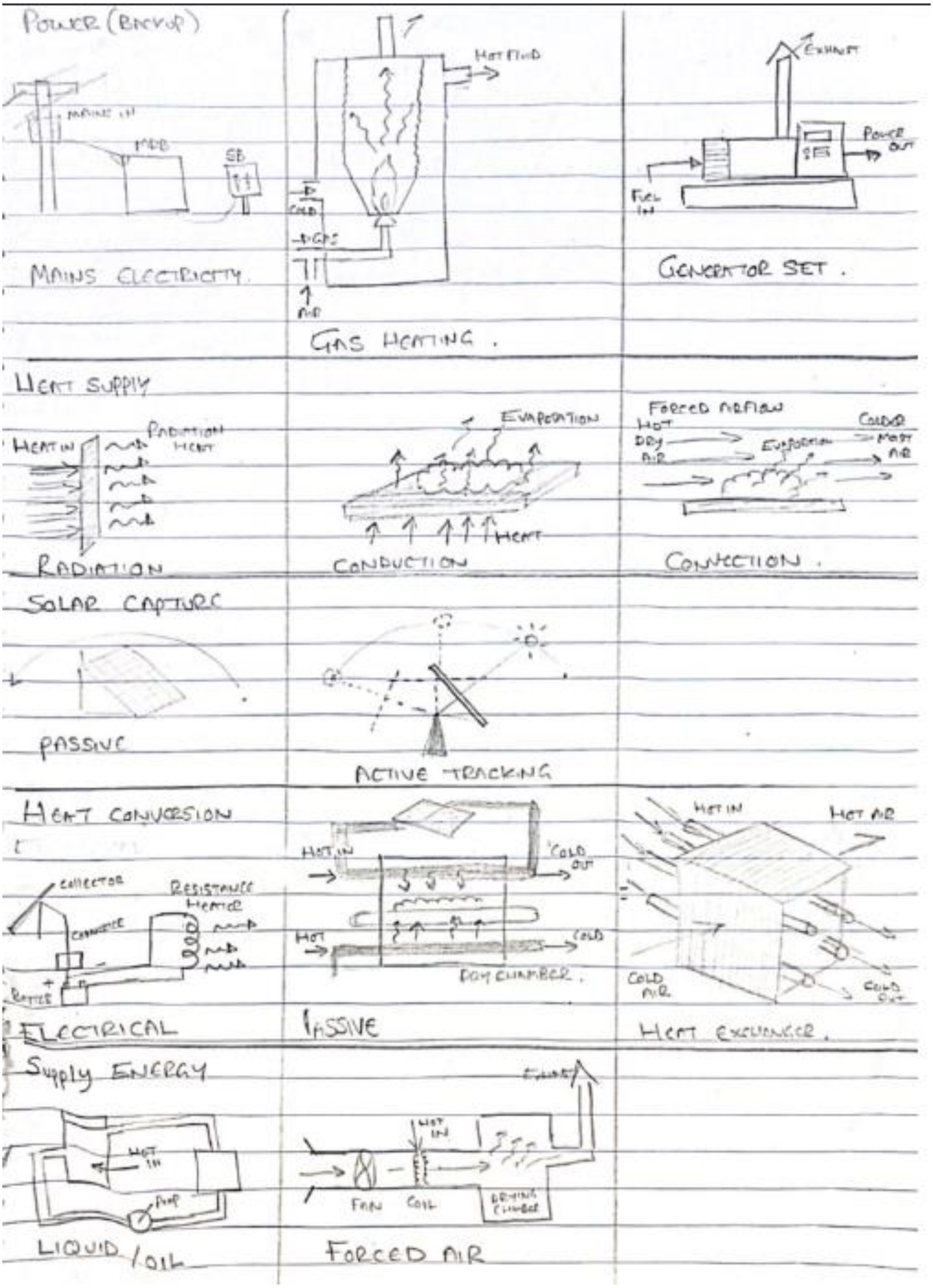
Appendix-I Brainstorm Sketches – Solar Energy Capture



Appendix-J Morphological Matrix -Part 1



Appendix-K Morphological Matrix – Part 2



Appendix-L PTC thermal analysis – Table of values for collector models

Description	Symbol	Units	PTC-4000	PTC-3000	PTC -1800
Collectors	C		6	7	11
Collector length (each)	L	m^2	5	5	5.1
Collector Area (each)	A_c	m^2	20	15	9
Total Collector Area	A_c	m^2	120	105	99
Total Length	L	m	30	35	56.1
Aperture Width	w	m	4	3	1.8
glass cover temp	T_g	K	319.50	319.8	320.6
Receiver Area	A_r	m^2	3.58	4.18	6.70
Glass Cover Area	D_g	m^2	6.13	7.15	11.46
Unshaded aperture Area	A_a	m^2	118.05	102.73	97.33
Average temperature	T_{avg}	K	308.75	308.90	309.3
Wind convective coefficient	hw	W/m^2K	43.43	45.4	43.43
Radiation coefficient	hr	W/m^2K	5.81	5.82	5.85
Radiation, receiver to glass	hr_{r-g}	W/m^2K	12.47	12.48	12.51
Loss Coefficient	U_L	W/m^2K	10.86	10.92	10.86
Collector Efficiency Factor	F'		0.967	0.966	0.966
Heat removal Factor	FR		0.9528	0.9415	0.9269
Useful energy	Qu	kW	99.62	86.52	81.34
Fluid Temperature out	To	$°C$	**84.58**	**76.75**	**73.65**
Inlet Temperature	Ti	$°C$	25	25	25
Temperature Difference	ΔT	$°C$	59.58	51.75	48.65

Appendix-M Heat Exchanger Calculations

Equations from *Fundamentals of thermal-fluid sciences - Heat Exchangers* (Cengal et al., 2016). Equations modelled in Microsoft Excel.

Cold forced air in cross flow is heated from the hot liquid oil in the tube flow				
Cold in	Tc,in	20.0	$°C$	Ambient Air, 1 atm, 20°C (DRY)
Cold Out	Tc,out	**75.0**	$°C$	$Tc,out = Tc,i + Q/Cc$
Hot in	Th,in	179.1	$°C$	Heated oil from PTC
Hot Out	Th,out	22	$°C$	
Maximum Temperature	$Tmax$	159.1	$°C$	$T_h,in - T_c,in$
Limiting Case		75.7	$°C$	$Tc,in + \left(\frac{Qmax}{Cc,air}\right)$
Duct Width	w	0.707	m	
Duct height	h	0.707	m	
Area of duct	A_{duct}	0.5	m^2	
Density, Air	ρ	1.204	kg/m^3	1 atm, 20°C (DRY)
Air velocity	v	3.0	m/s	Ideal range 2-6 m/s
Volume, Air	V	0.67	m^3	
Cold mass	m,c	1.806	kg/s	$\dot{m} = \rho * A_{duct} * v$
Hot mass	$m.h$	0.40	kg/s	
HOT Specific heat, Oil	cp,oil	1.587	kj/kgK	Dowtherm @ 105°C
COLD Specific heat, Air	cp,Air	1.005	kj/kgK	table A-2 (Cengal et al,.2007)
HOT Heat capacity rates	Ch,oil	0.63	kW/K	$ch = mh * cp,h$
COLD Heat capacity rates	Cc,Air	1.81	kW/K	$Cc = mc * cp,c$
Min heat capacity rate	$Cmin$	0.63	kW/K	
actual heat transfer rate	$Q,cold$	99.80	kW	$Cc(Tc,out - Tc,in)$
actual heat transfer rate	Q,hot	99.8	kW	$Ch(Th,in - Th,out)$
Max heat transfer rate	$Qmax$	101.0	kW	$c_{min} * (th,in - tc,in)$
heat transfer effectiveness	ε	0.988		$e = Q/Qmax$
NTU relation	c	0.350	dimensionless	$cmin/cmax$
Log Mean Temp diff	$\Delta T1$	104.078	°C	$th,in - tc,out$
	$\Delta T2$	1.868	°C	$th,out - tc,in$
	$\Delta T,lm$	25.42	°C	
P Value	P	0.53	dimensionless	$P = t_2 - t_1/T_1 - t_2$
R Value	R	2.86	dimensionless	$R = T_1 - T_2/t_2 - t_1$
Correction factor	F	1.00	dimensionless	Correct Factor chart
Cross Flow Pipe Length	L	0.7	m	Limited by Duct length and width
Cross Flow Pipe Diameter	D	0.0368	m	
Number of pipes	n	20	tubes	
Heat Exchanger Area	A_{HE}	1.62	m^2	$n * \pi * D * L$
Overall Heat Transfer coefficient	U	3250.75	W/m^2K	$Qmax /(\Delta T,lm * F * A_{HE})$

Appendix-N Dowtherm Synthetic Oil Properties

Saturated Liquid Properties of DOWTHERM™ A Fluid (SI Units)

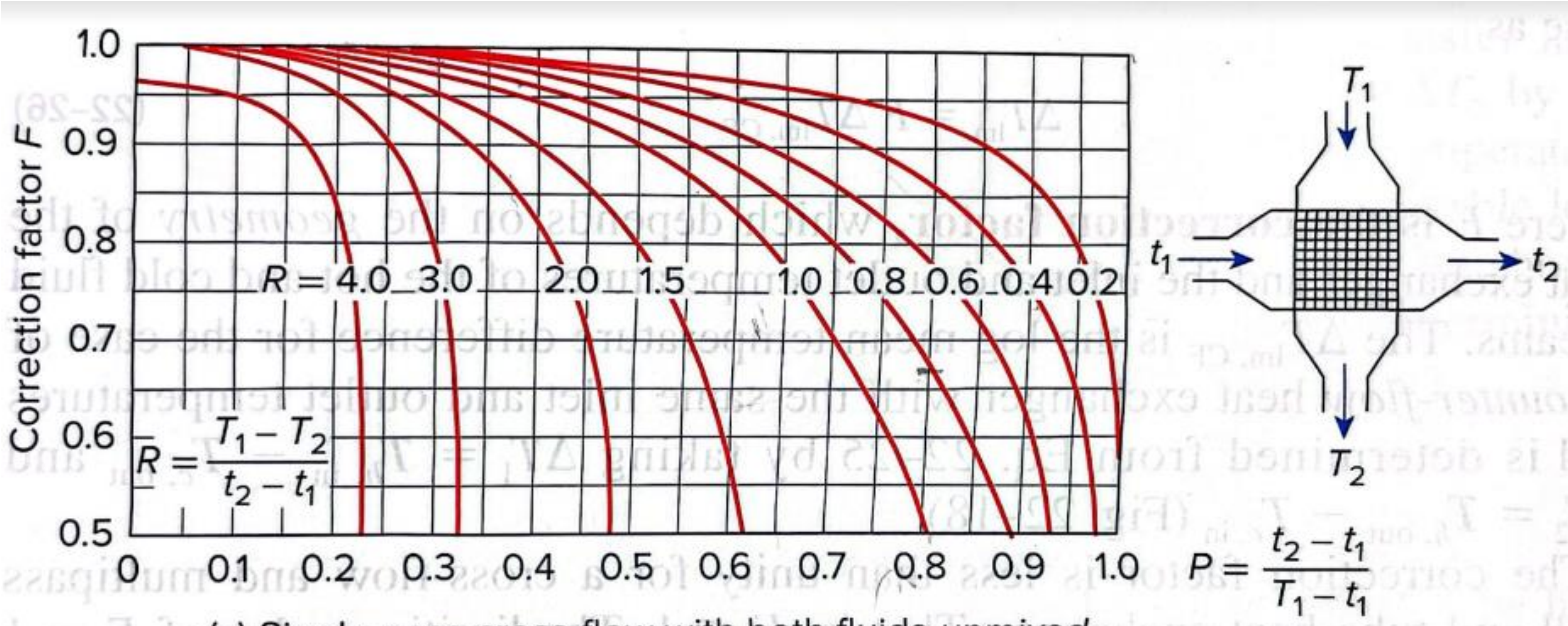
Temperature °C	Specific Heat kJ/kg K	Density kg/m³	Thermal Conductivity W/mK	Viscosity mPa sec	Vapor Pressure (bar)
15	1.558	1063.5	0.1395	5.00	0.00
65	1.701	1023.7	0.1315	1.58	0.00
105	1.814	990.7	0.1251	0.91	0.01
155	1.954	947.8	0.1171	0.56	0.06
205	2.093	902.5	0.1091	0.38	0.28
255	2.231	854.0	0.1011	0.27	0.97
305	2.373	801.3	0.0931	0.20	2.60
355	2.527	742.3	0.0851	0.16	5.80
405	2.725	672.5	0.0771	0.12	11.32

Dowtherm A synthetic oil properties table

Dowtherm A specific heat as 1.587 kj/kg K at 25°C using interpolation viewed at https://www.glycolsales.com.au/wp-content/uploads/2022/10/176-01463-01-dowtherm-a-tds.pdf

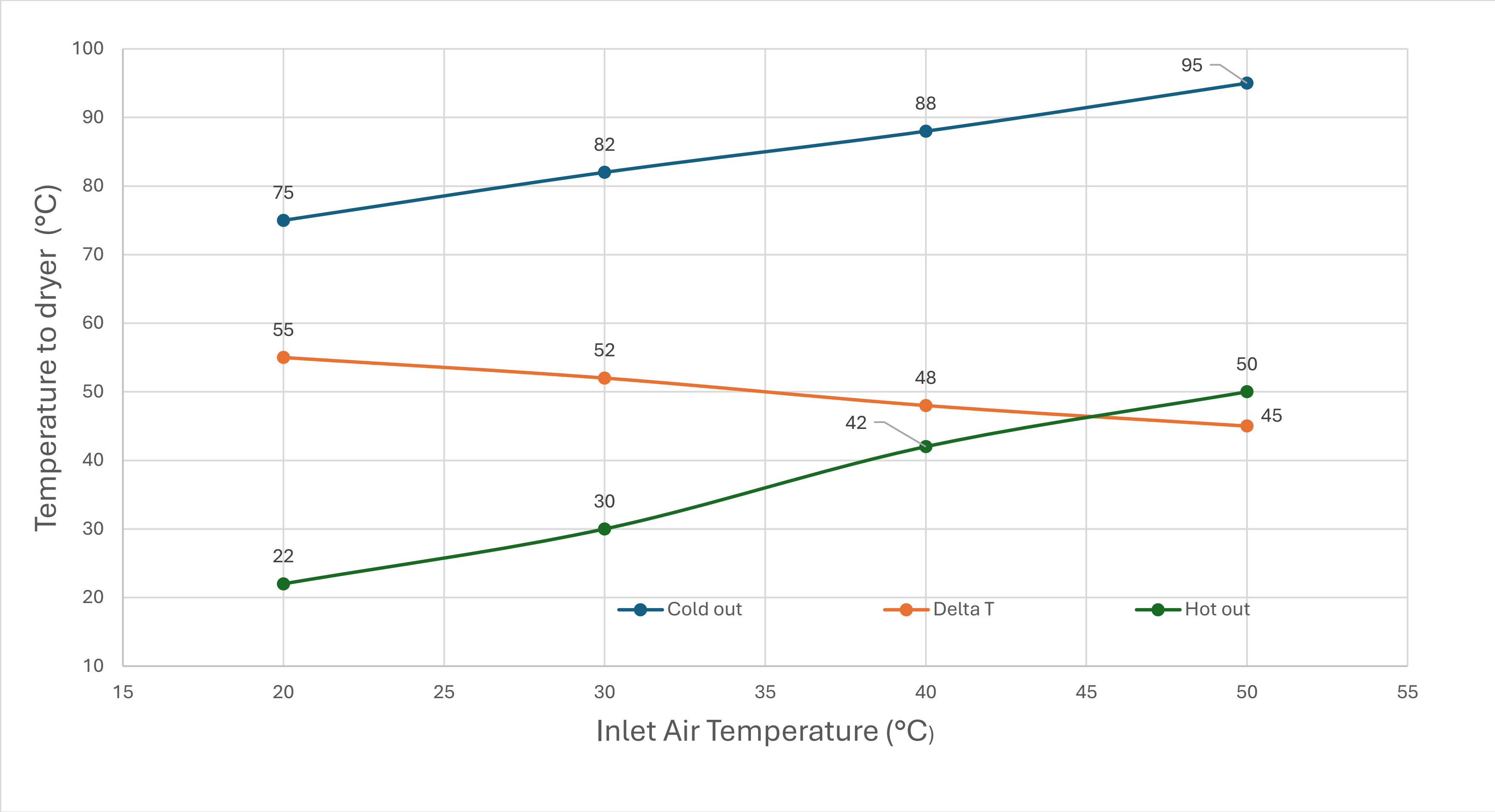
Appendix-O Single Pass cross flow heat exchanger correction factor chart

Heat Exchanger single-pass cross flow (unmixed) arrangement taken from *Fundamentals of thermal-fluid sciences - Heat Exchangers* (Cengal et al., 2016). The correction factor F is approximated from the chart to be ~0.95.

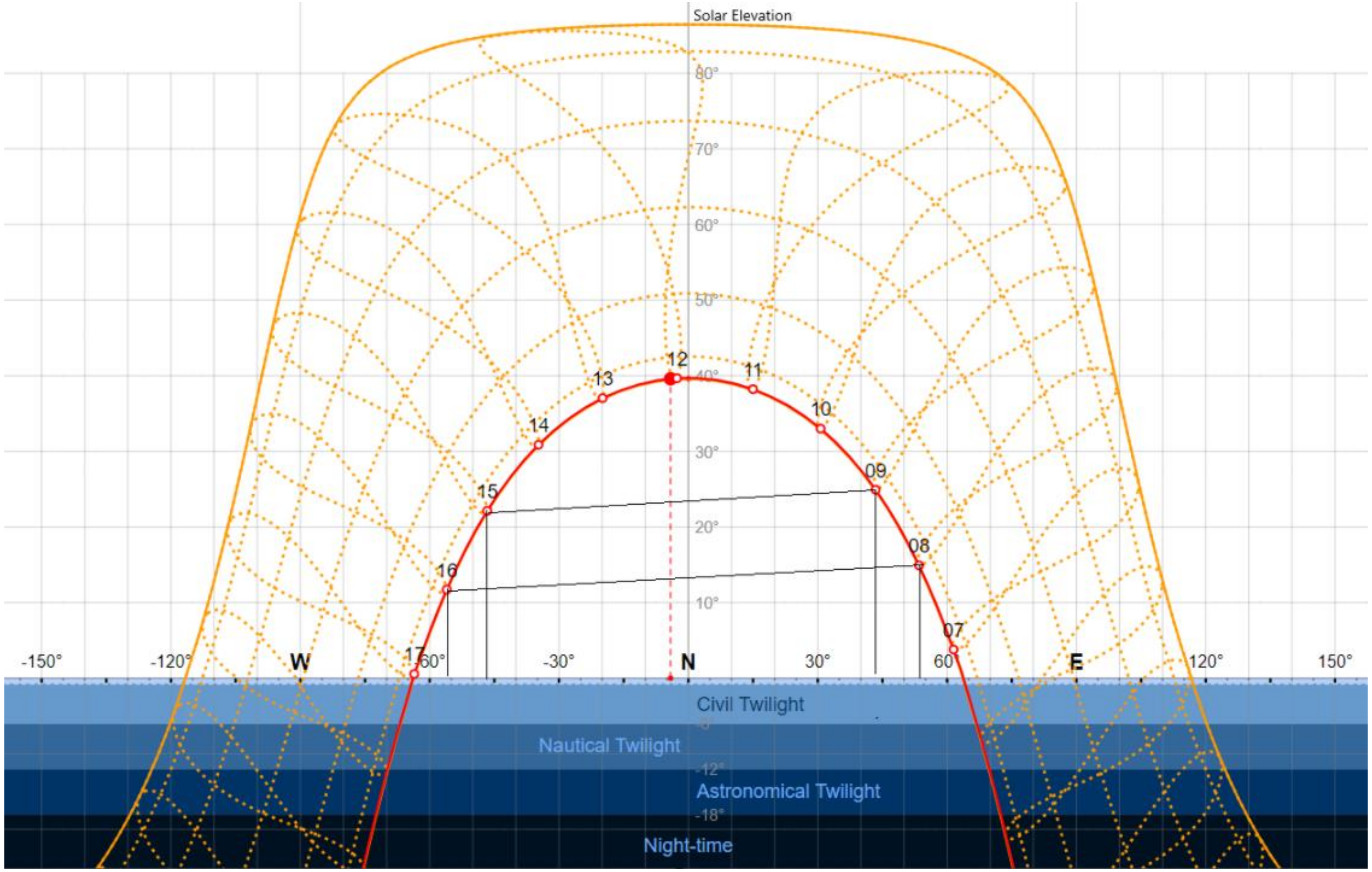


(c) Single-pass cross-flow with both fluids *unmixed*

Appendix-P Effect of increasing the temperature of the inlet air to the dryer



Appendix-Q Two-Dimensional Sun Path Diagram for Murrumba Downs–Winter Solstice



Modified Sun path diagram for Murrumba Downs WWTP generated using 2D Sun-Path Diagram. Viewed and modified at https://andrewmarsh.com/apps/releases/sunpath2d.html.

Appendix-R TES packed rock bed parameters

Parameters	Symbol	Value	Units	Comments
Ambient Temperature	T_{amb}	20	$°C$	293K
Rock Temperature (initial)	T_{rock}	20	$°C$	293K Equal to ambient temperature
Air Temperature	T_{air}	67	$°C$	
Ambient Temperature	T_{amb}	20	$°C$	
Air Density	ρ	0.9938	kg/m^3	table A-2 (Cengal et al,.2007)
Air velocity	v	3	m/s	
Air mass	m_{air}	1.49	kg/s	
Air volume	Vol	1.50	m^3/s	Half flow rate-50% diversion
Specific heat (air)	cp_{air}	1.008		
Height TES vessel	H	1	m	Vessel dimensions
Width TES vessel	W	0.5	m	Vessel dimensions
Depth TES vessel	D	0.5	m	Vessel dimensions
Volume TES vessel	V	0.25	m^3	
Specific heat (Rock)	cp	0.862	kJ/kgK	(Park et al., 2014)
Density (Rock)	p	2700	kg/m^3	(Park et al., 2014)
Mass (Rock)	M	675	kg	
Porosity (Rock)	ε	0.35		(Park et al., 2014)
Volumetric HTC	h_{vol}	1029.7	$W/m^3\ K$	
Thermal Conductivity (Rock)	k	3.0	w/mk	(Park et al., 2014)
Heat Capacity (Rock)	cp_{rock}	581.85	kJ/K	
Storage density (TES)		51202.8	$kJ/kg\ K$	

Appendix-S PTC modelling – Thermal Energy

Description	Symbol	Value
Absorbed Solar Radiation (W/m^2)	S	883
Receiver Temperature (K)	Tr	475
Receiver emissivity	εr	0.92
Glass Emissivity	εg	0.87
Specific Heat (HT fluid) $(j/kg.K)$	cp	4180
Entering Fluid temp (K)	Ti	298
Mass Flow Rate (kg/s)	m	0.4
HT coefficient (inside pipe) $(W/m^2\ K)$	h	330
Tube Thermal Conductivity $(W/m\ K)$	k	15
Ambient Temp (K)	Ta	298
Wind Velocity (m/s)	V	5
pipe diameter (outer) (m)	Do	0.038
pipe diameter (inner) (m)	Di	0.0368
glass cover diameter (m)	Dg	0.065
Air Density (kg/m^3)	p	1.146
Kinematic Viscosity $(kg/m\ s)$	u	0.000021
Thermal Conductivity (W/mK)	k	0.0269
Reynolds Number	Re	18,630

The above table provides local condition data which will remain the same throughout the modelling.

Direct normal insolation has been averaged and assume to be 883 W/m^2 per day

Appendix-T Design Criteria list with referencing

Major Criteria	Sub-criteria	References
Reduce moisture	drying time	Oritz-Rodriguez et al., 2022
	energy source	
	efficiency	Oritz-Rodriguez et al., 2022
	moisture removed	
	complexity of drying	
	heat source	Tun and Juchelkova, 2019
	material to be dried	Bazregari et al., 2021
Operation	complexity operation	
	feed rate ability	Tun and Juchelkova, 2019
	flexibility	
	maintenance	
	ease of integration to existing systems	
	odour reduction	Pawale, 2015
	usefulness/suitability	
Dryer	Capacity /scale up	Oritz-Rodriguez et al., 2022
	space required/ size	Tun and Juchelkova, 2019
	constructability	
	material availability	
	Durability	Oritz-Rodriguez et al., 2022
	upgrades	
Value	operational cost	Tun and Juchelkova, 2019
	construction cost	Tun and Juchelkova, 2019
	energy saving	Oritz-Rodriguez et al., 2022
	benefits	Arachchiege et al. 2019
	indirect expenses	
	Potential for material recovery	Arachchiege et al. 2019, Tun and Juchelkova, 2019

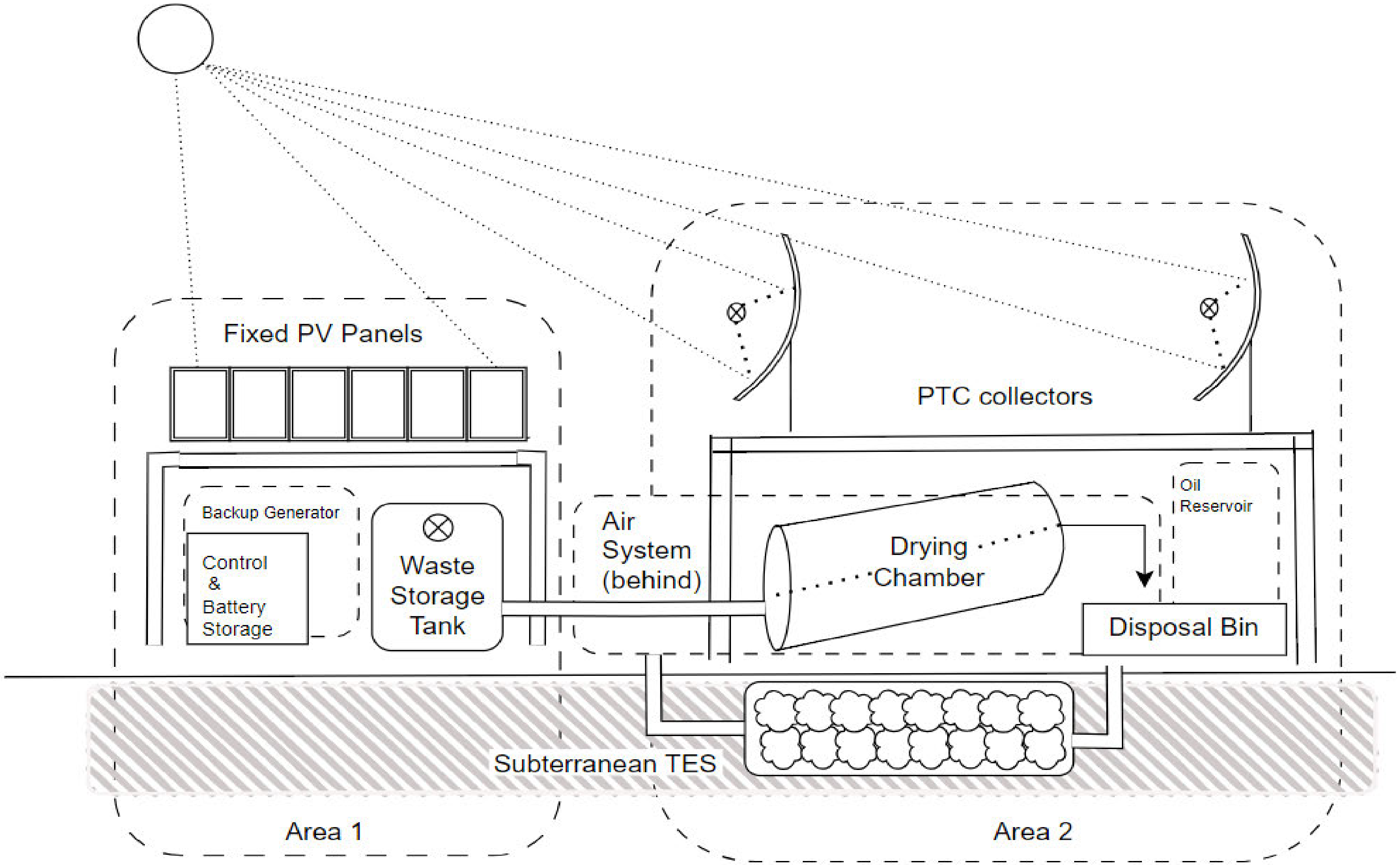
Appendix-U Quality Functional Deployment (QFD) Table

Key:		
S	9	Strong
M	3	Medium
W	1	Weak
X	0	None

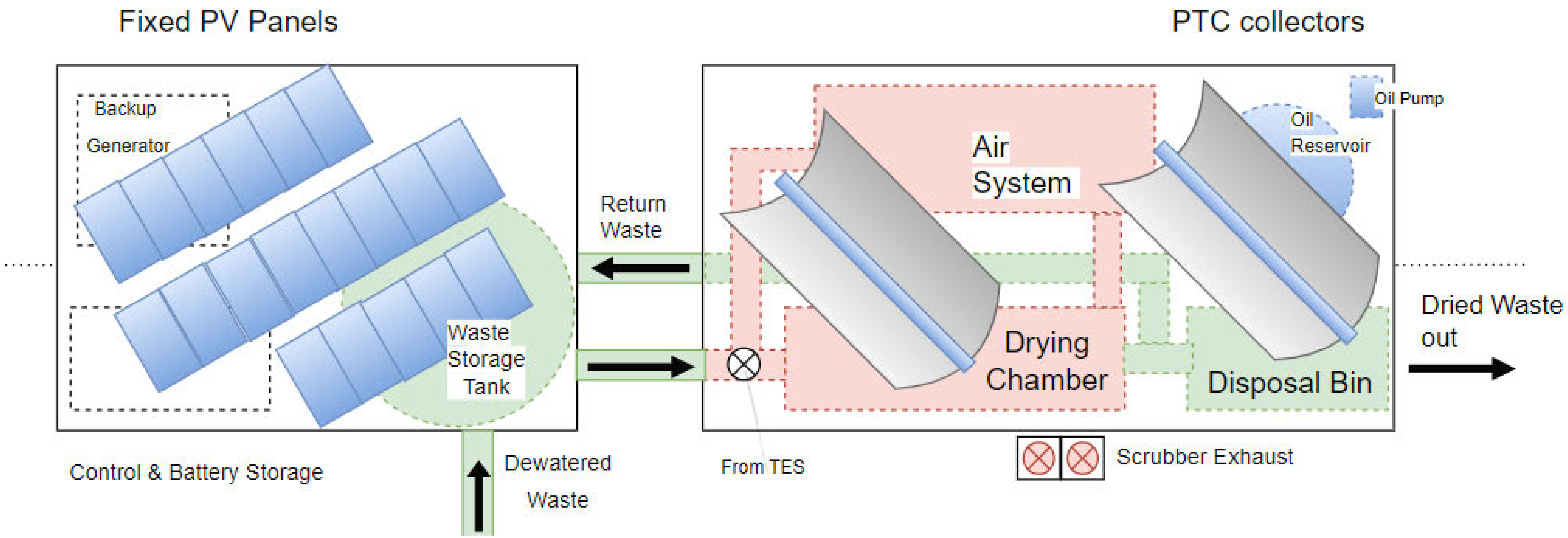
Interrelationships	Drying Time	Drying Temperature	Power Consumption	System Cost Estimate	Design Lifespan	Size Dimensions	Energy Capture Capability	Waste Storage	Energy Storage	
Energy Storage		++	++	-		+	+	+		
Waste Storage				-		+				
Energy Capture Capability		++	++	--		+			++	
Size Dimensions				-	-		++	+	++	
Design Lifespan				--			+	--	+	
System Cost Estimate	-	-			--	+	++	+	++	
Power Consumption	-	++		-		+	--	+	--	
Drying Temperature	--		--	-			++		+	
Drying Time		--	++	+			--	--	-	

			Engineering Parameters	Drying Time	Drying Temperature	Power Consumption	System Cost Estimate	Design Lifespan	Size Dimensions	Energy Capture Capability	Waste Storage	Energy Storage		Design 1	J&A Washpactor	Kuhn Washpress (KWP)	Stronga Flowdry
			Units	Hours	°C	kW	$	Years	m	kWh	m^3	kWh					
			Desired Direction	∇	Δ	∇	∇	Δ	∇	Δ	∇	Δ					
	Requirements	**Relative Importance**	**Weight %**														
1	Remove Waste Moisture	5	23.8	S	S	S	X	X	X	S	X	S		S	M	M	M
2	Reduce Energy Consumption	3	14.3	S	S	S	M	W	W	S	S	S		S	M	M	W
3	Economical	2	9.5	M	S	S	S	S	M	S	M	S		M	M	M	W
4	Reliable	4	19.0	W	W	W	M	S	M	M	S	S		M	M	S	M
5	Safe	4	19.0	X	M	X	W	M	x	M	M	M		M	S	S	S
6	Waste Transportation	3	14.3	W	X	W	W	X	W	X	X	X		S	S	S	S
	Total	**21**	**100**										**Totals**	36	30	36	26
			Importance Rating (importance*Rel)	405	505	462	219	329	114	543	386	657	3619	**614**	**500**	**614**	**452**
			Importance %	**11**	**14**	**13**	**6**	**9**	**3**	**15**	**11**	**18**	100				

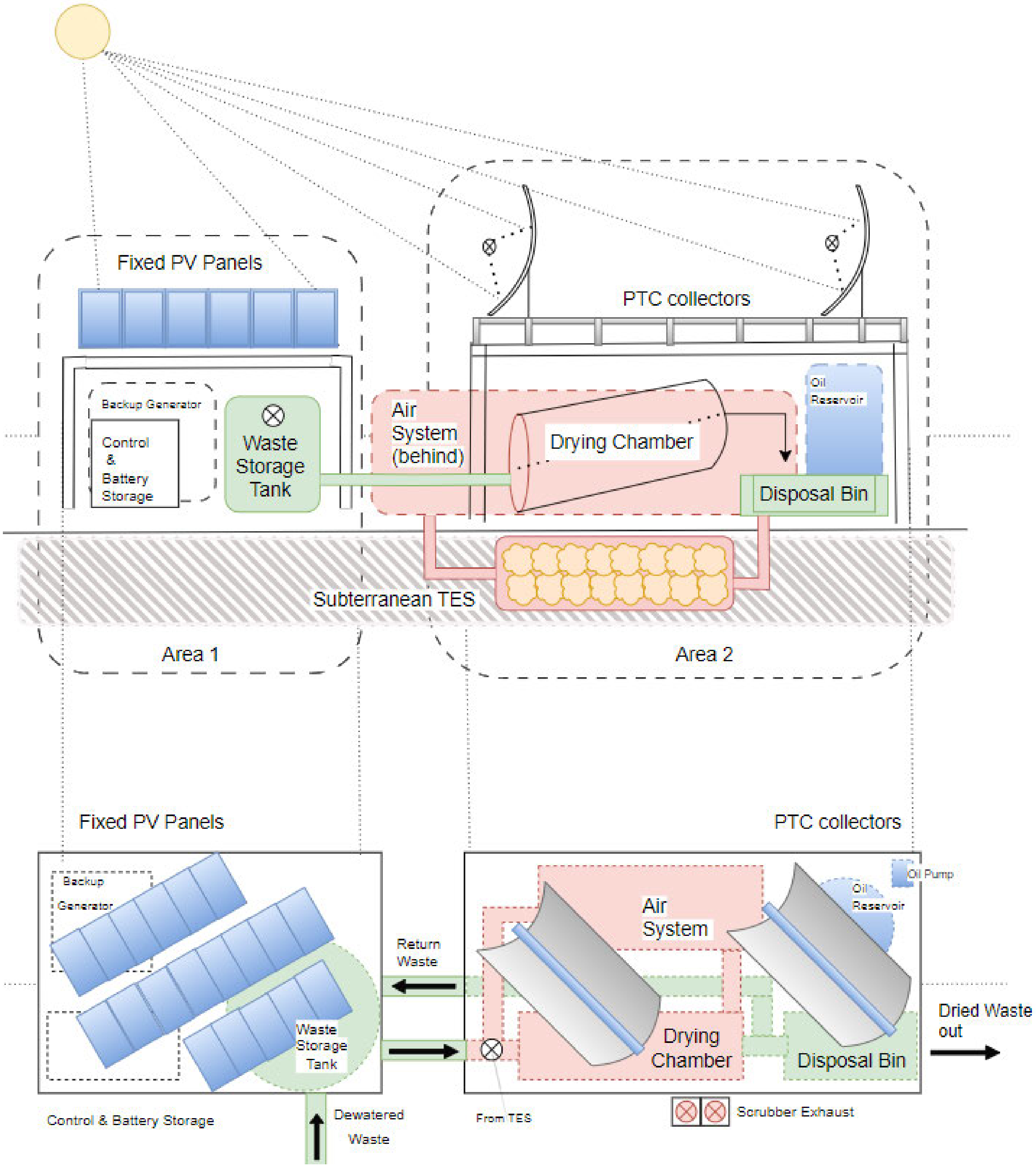
Appendix-V Design 1 system diagram



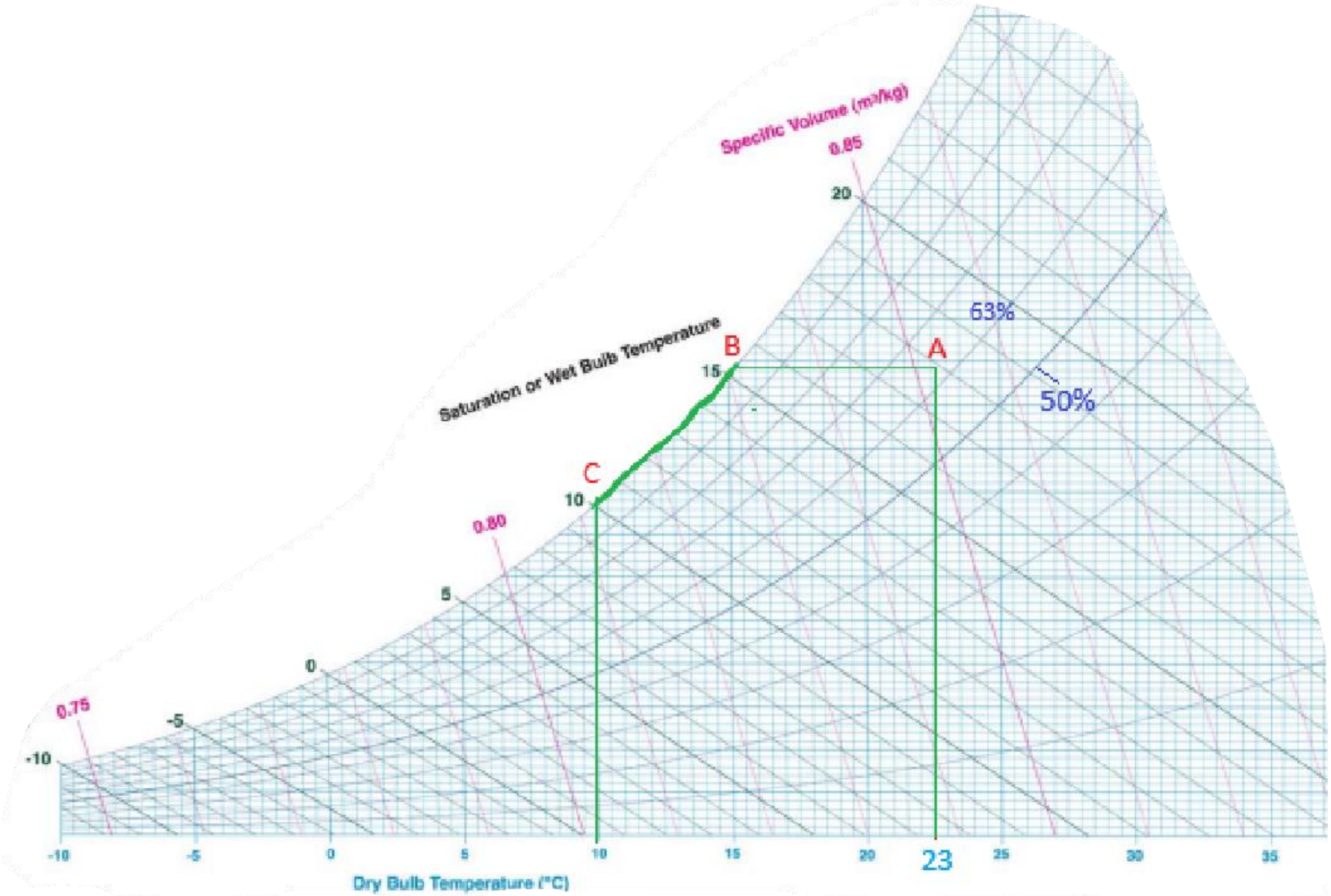
Plan View


Fixed PV Panels
PTC collectors
Backup
Generator
Oil Pump
Oil
Reservoir
Air
System
Return
Waste
Waste
Storage
Tank
Drying
Chamber
Disposal Bin
Dried Waste
out
Control & Battery Storage
Dewatered
Waste
From TES
Scrubber Exhaust

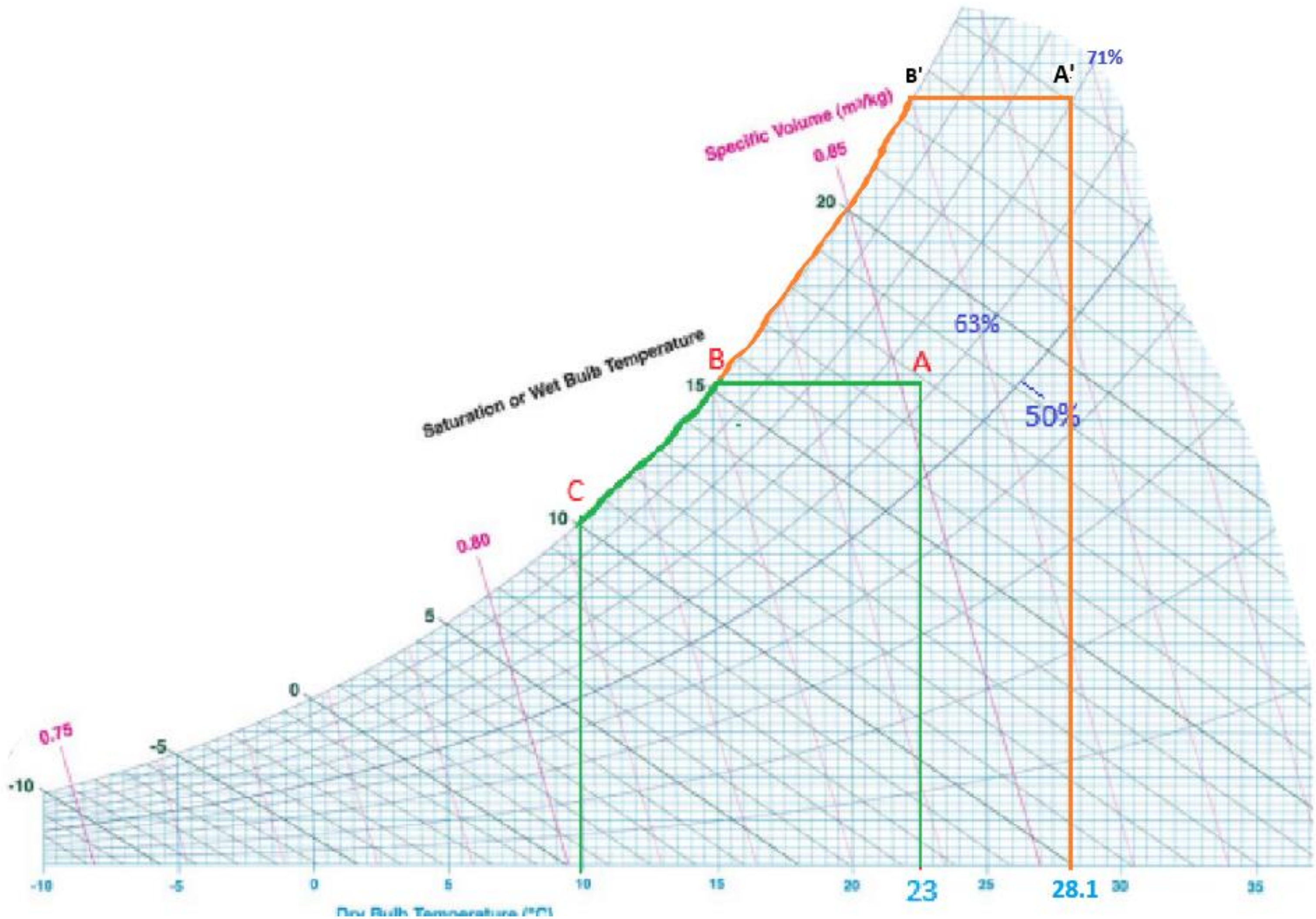
Design 1 system diagram



Appendix-W – Pre-cooling of humid intake air psychrometric chart



Appendix-X - Pre-cooling of humid intake air psychrometric chart



Appendix-Y MATLAB CODE for TES modelling

```
% TES code Charging and Discharging a Cylindrical TES Vessel over 8 hours.
% Solar dryer design project
% airflow is a 3m/s for both charge and discharge
% constant rock mass
% *******************   Setup
clear;
clc;

% parameters
density_rock =  2700 ;                   % Rock density kg per m^3
cp_rock = 860;                             % Specific heat, cp k/kg*K
mass_rock = 67858;             % Rmass of rock (kg)
k_rock = 3 ;                          % thermal conductivity of the rock W/m^2K
T_int_charge = 20 + 273;             % Int temperature  20dC to K +273
T_air =67 + 273 ;                      % heated inlet air
cp_air = 1008;                                  % Specific heat of air, cp_air k/kg*K

% airflow is a 3m/s for both charge and discharge
MFR_air= 3;                        %% MFR air m/s>>> 3 m/s

t_total_charge = 8*3600;                %Charge time total ~8hours - same as
length of solar day?
T_ambient = 20+273;             % ambinet outside air  = 20dC

% cylinder tank
A_tank = 32.67;                    % interal surface area of the tank

%******************** Charge
% time
dt = 1;                                 % 1 sec intervals

t_charge = 0:dt:t_total_charge;         % charge time in seconds at 8 hours

%  array
T_rock_charge = zeros(size(t_charge));
T_rock_charge(1) = T_int_charge;

% FOR loop based on formula
for i = 2:length(t_charge)
    T_rock_charge(i)= T_air-(T_air-T_int_charge) *exp(-MFR_air
*cp_air/(mass_rock*cp_rock)*t_charge(i));  % t_charge(i) ++
end

% Charge -  store the temperatures in array
T_final_charge = T_rock_charge(end);

%****************   Discharge
t_total_discharge =8*3600 ;                               %% discharge at 8
hours in seconds
t_discharge = 0:dt:t_total_discharge ;

% array
 T_rock_discharge = zeros(size(t_discharge));
T_rock_discharge(1) = T_final_charge;              % start at the final temp,
then discharge
```

```
 % FOR loop Discharge
for i = 2:length(t_discharge)
    T_rock_discharge(i) = T_ambient +(T_final_charge -T_ambient) * exp(-
MFR_air*cp_air /(mass_rock * cp_rock) * t_discharge(i)) ; % t_discharge(i)
end

%Temmperature array is in K, we wil need to bring back to dC
 T_rock_charge_dC =T_rock_charge - 273;  % lees 273k
T_rock_discharge_dC = T_rock_discharge - 273;

% same page_ sub plot
figure('Name', 'TES System') ;
subplot(2,1,1); % top to bottom
plot( t_charge /60,T_rock_charge_dC,'LineWidth' ,2 ) ; % have it cover 8 hours

xlabel ('time(minutes)');
ylabel('Rock temperature(dC)')  ;
title('TES system rock temperature -charging');
grid on;                                            % lines for clarity

% second graph - discharge
subplot(2,1,2);  % 2,1,2
plot( t_discharge /60,T_rock_discharge_dC,'LineWidth',2);

xlabel('time(minutes)');
ylabel('Rock temperature(dC)');
title('TES system rock temperature-discharging');
grid on;                                             % lines for clarity

%******************** End*********************
```

Appendix-Z MATLAB CODE -TES variable airflow for constant rock mass

```
% TES code Charging and Discharging a Cylindrical TES Vessel over 8 hours.
% Solar dryer design project
% airflow is Variable from 1m/s to 3m/s for both charge and discharge
% constant rock mass  - shown as MFR  (kg/s)
% *******************   Setup
clear;
clc;
% Parameters
density_rock =2700;                    %  Rock density kg per m^3 - Not used
cp_rock =860;                   %    Specific heat, cp k/kg*K
mass_rock = 67858 ;            % Rmass of rock (kg)]
k_rock = 3;                       % Thermal conductivity W/m^2
T_ambient = 20+273;           %  Add 273 to change into Kelvin
T_heated_air = 67+273;                     % Int temperature  20dC to K +273

cp_air =1008 ;                              % % heated inlet air
density_air =1.028;                    % Air at ~70dC - Property table A-22
t_total_charge =8*3600 ;  % %Charge time total ~8hours - same as length of solar
day?
t_total_discharge =8*3600 ;      % discharge time total ~8hours - same for direct
comparison

% cylinder tank
A_tank = 32.67 ;                    %  % interal surface area of the tank
duct_area = 0.5 ;                  % 0.5m^2
% mass flow rates
MFR_air_one =(1/(duct_area*density_air)); % 1m/s
MFR_air_two =(2/(duct_area*density_air)); % 2m/s
MFR_air_three =(3/(duct_area*density_air));  %3m/s

% An Array of MFR
MFR_air =[MFR_air_one, MFR_air_two,MFR_air_three] ;    % kg/s
% Velocity_air = [,MFR_air_two, MFR_air_three] ;    % m/s  Display m/s rather than
mass flow.

%time
dt = 1;                                               % 1 second time step dt =1
 time_charge =0:dt:t_total_charge  ;           % Charge time
   time_discharge =0:dt:t_total_discharge; % Dicharge

   % figure name
figure('Name','TES system varying mass flow rates');

% *************************   FOR Loop

for MFR_air= MFR_air  % array of 3 values 1, 2, 3 m/s AF
    T_rock_charge =zeros(size(time_charge)) ; % intilaise the array
      T_rock_charge(1) = T_ambient;     % inital temperature is the
    % nested  LOOP charge time
```

```
  % charge
    for i = 2:length(time_charge)
         T_rock_charge(i) = T_heated_air - (T_heated_air - T_ambient) *exp(-
MFR_air *cp_air/ (mass_rock * cp_rock) * time_charge(i));
    end

   % final charge temp
     T_final_charge = T_rock_charge(end) ;
    % discharge
     T_rock_discharge= zeros(size(time_discharge)) ;
    T_rock_discharge(1) = T_final_charge;     % Start at final charge temp

    % Discharge process
   for i = 2:length(time_discharge)
        T_rock_discharge(i)= T_ambient + (T_final_charge - T_ambient) *exp(-
MFR_air * cp_air/ (mass_rock * cp_rock) * time_discharge(i));
    end

    % Convert temp from K to dC
    T_rock_charge_dC =T_rock_charge - 273;
     T_rock_discharge_dC =T_rock_discharge - 273;
    % Plot charging phase

subplot(2,1,1) ;
  %plot(t_charge/60, T_rock_charge_dC, 'LineWidth', 2, 'DisplayName', ['MFR =
'num2str(MFR_air) ' m/s']);
  plot(time_charge/60 ,T_rock_charge_dC , 'LineWidth', 2, 'DisplayName',['MFR ='
num2str(MFR_air) 'm/s']);
  hold on;
% discharge plot
 subplot(2,1,2) ;
   %plot(t_discharge/60, T_rock_discharge_dC, 'LineWidth', 2, 'DisplayName', ['MFR
= 'num2str(MFR_air) 'm/s']) ;
   plot(time_discharge/60, T_rock_discharge_dC ,'LineWidth',2, 'DisplayName',
['MFR =' num2str(MFR_air) 'm/s']);
  hold on;
end
% Label, titles etc
subplot(2,1,1);
xlabel('time(minutes)') ;

 ylabel('Rock temperature (dC)');
  title('TES system rock temperature -charging') ;
%legend('Location','northwest');
  grid on;                                       % lines for clarity

subplot(2,1,2);
xlabel('time(minutes)');

  ylabel('Rock temperature (dC)');
  title('TES system rock temperature- discharging');
    legend show;

grid on;                                          %lines for clarity
%******************** End********************
```

Appendix-AA MATLAB CODE -TES Design variable airflow for charge and discharge

```
% TES code Charging and Discharging a Cylindrical TES Vessel over 8 hours.
% Solar dryer design project
%Design TES

% airflow is Variable from at 6m/s when charging and 1m/s for discharge
% constant rock mass  - shown as MFR  (kg/s)

% ******************   Setup
clear;
clc;
% Parameters
density_rock =2700;                    %  Rock density kg per m^3 - Not used
cp_rock =860;                    %    Specific heat, cp k/kg*K
mass_rock =10628.75 ;             % Rmass of rock (kg)]
k_rock = 3;                        % Thermal conductivity W/m^2
T_ambient = 20+273;           %  Add 273 to change into Kelvin
T_heated_air = 67+273;                     % Int temperature  20dC to K +273

cp_air =1008 ;                               % % heated inlet air
density_air =1.028;                    % Air at ~70dC - Property table A-22
t_total_charge =8*3600 ;  % %Charge time total ~8hours - same as length of solar
day?
t_total_discharge =8*3600 ;      % discharge time total ~8hours - same for direct
comparison

% cylinder tank
A_tank = 32.67 ;                 %  % interal surface area of the tank
duct_area = 0.5 ;              % 0.5m^2
% mass flow rates

%air_velocity_charge = 6;                  %6m/s ==2.98kg/s
MFR_air_charge =2.98 ;
%air_velocity_discharge = 2;                  % 2m/s ==1kg/s
MFR_air_discharge =1 ;


%time
dt = 1;                                            % 1 second time step dt =1
 time_charge =0:dt:t_total_charge  ;          % Charge time
   time_discharge =0:dt:t_total_discharge; % Dicharge

        % figure name
figure('Name','TES system model');


T_rock_charge =zeros(size(time_charge));
T_rock_charge(1) = T_ambient;

% discharge
```

```
T_rock_discharge =zeros(size(time_discharge));
T_rock_discharge(1) = T_heated_air ;

  % charge FOR loop
    for i = 2:length(time_charge)
         T_rock_charge(i) = T_heated_air - (T_heated_air - T_ambient) *exp(-
MFR_air_charge *cp_air/ (mass_rock * cp_rock) * time_charge(i));
    end

   % final charge temp
     T_final_charge = T_rock_charge(end) ;

   %discharge FOR loop - Use the final charge temperature as starting point

     for i = 2:length(time_discharge)
         T_rock_discharge(i)= T_ambient + (T_final_charge - T_ambient) *exp(-
MFR_air_discharge *cp_air/ (mass_rock * cp_rock) * time_discharge(i));
    end

    % final charge temp
     T_final_discharge = T_rock_discharge(end) ;

%Temmperature array is in K, we wil need to bring back to dC
 T_rock_charge_dC =T_rock_charge - 273;  % less 273k
 T_rock_discharge_dC =T_rock_discharge - 273;  % less 273k


subplot(2,1,1) ;

  plot(time_charge/60,T_rock_charge_dC, 'LineWidth', 2,
'DisplayName',sprintf('%.2f kg/s', MFR_air_charge),'Color','r');
  hold on;

  % discharge plot
 subplot(2,1,2) ;

  plot(time_discharge/60, T_rock_discharge_dC ,'LineWidth',2,
'DisplayName',sprintf('%.2f kg/s', MFR_air_discharge));
  hold on;


% Label, titles etc
subplot(2,1,1);
xlabel('time(minutes)') ;

 ylabel('Rock temperature (dC)');
  title('TES system rock temperature -charging') ;
legend('Location','southeast');

  grid on;

subplot(2,1,2);
xlabel('time(minutes)');

  ylabel('Rock temperature (dC)');
  title('TES system rock temperature- discharging');

    legend show;
grid on;                                         %lines for clarity
```