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This is the Published version of the following publication

Hamilton, James, Seyedmahmoudian, Mehdi, Jamei, Elmira, Horan, Ben and Stojcevski, Alex (2020) A systematic review of solar driven waste to fuel pyrolysis technology for the Australian state of Victoria. Energy Reports, 6. pp. 3212-3229. ISSN 2352-4847

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Energy Reports 6 (2020) 3212–3229

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Review article

A systematic review of solar driven waste to fuel pyrolysis technology for the Australian state of Victoria☆

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ARTICLE INFO

Article history:
Received 12 July 2020
Received in revised form 16 October 2020
Accepted 7 November 2020
Available online 4 December 2020

Keywords:
Renewable energy system (RES)
Solar-driven pyrolysis
Concentrated solar power (CSP)
Municipal solid waste (MSW)
Direct normal irradiance (DNI)

ABSTRACT

Australia's waste management is heavily dependent on landfill. The Australian Bureau of Statistics predicts that as Australia's population and economy grow, there will be a significant increase in the magnitude of waste output. Concentrated solar driven pyrolysis has been identified as a promising means in creating renewable liquid fuel and improving waste management. This technology is based on the upgrading of waste into a valuable commodity. This is of interest to city councils, communities and stakeholders, as both Australia's annual waste generation and energy demands are growing rapidly. This paper provides a case for the implementation of solar-driven pyrolysis for biofuel production in the Australian state of Victoria as well as a comparative analysis of different Renewable Energy Sources and biomass reactions to justify the combination of Concentrated Solar Power with pyrolysis. This study is the first to assess the solar-driven pyrolysis under a Victorian setting. Victoria was chosen due to the comprehensive and readily available waste data kept by its government. The review concluded that a combination of Fresnel Reflector CSP and pyrolysis are best suited for regional Victorian environment. Fresnel reflector technology was found to complement slow pyrolysis well due to its 250–500C operating temperature, while regional Victoria was found to be a good trade-off between feedstock distance and DNI exposure. These requirements were important because feedstock transportation was found to cost \$AUD 96 per 500km, and it was observed that there could be up to 1200 kWh/m^2 solar exposure difference between Victorian rural and metropolitan locations. This study provides a comprehensive framework of technical requirements pertaining to a Victorian solar-driven pyrolysis system, which will then act as a guidance for future designers.

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☆ This document is a collaborative effort.

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https://doi.org/10.1016/j.egyr.2020.11.039
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List of abbreviations

ANN	Artificial neural network
CSP	Concentrated solar power
C&I	Commercial and industrial
C&D	Construction and Demolition
DNI	Direct normal irradiance
HHV	Highest heating value
HTF	Heat transfer fluids
MSW	Municipal solid waste
O&M	Operation and maintenance
PDC	Parabolic dish collector
PTC	Parabolic trough collector
PV	Photovoltaic
STC	Solar tower collector
RES	Renewable energy system

1. Introduction

Australia's population is estimated to reach 35.9 million by 2050 (Buckmaster and Simon-Davies, 2010). It is known that an in increase in population will lead to increased energy demand (Pérez-Lombard et al., 2008; Holdren, 1991). Despite their declining use, coal, oil, and gas are still expected to make up 25% of the world's energy needs by 2040 (Cronshaw, 2015). Additionally, Australia is highly dependent on non-reusable energy sources, with fossil fuels accounting for 85.2% of all electricity produced from 2015 to 2016 (Department of the Environment and Energy, 2017). This is of concern, as it has been estimated that fossil fuel-based oils will be depleted within the next 162 years (Shafiee and Topal, 2009). The energy from this period came from the burning of coal. Coal is a fossil fuel that produces carbon dioxide (CO_2) when burnt and CO_2 is the major greenhouse gas responsible for much of the climate change that is currently being witnessed around the world. Biomass technology is a promising alternative energy source to fossil fuels and enable the users to mitigate the adverse impacts of climate change while fulfilling a large portion of the world's energy demand (Weldekidan et al., 2018). A biomass process can produce energy by either burning the biomass, or converting the biomass to solid, liquid or gaseous fuels (Fan et al., 2011). The five common methods for waste to energy conversion are torrefaction, combustion, pyrolysis, gasification, and digestion (Weldekidan et al., 2018). The types of biomass that can be used include food waste, papers, textiles, leathers, municipal solid waste (MSW), agricultural crop waste (Qureshi et al., 2018), as well as construction and demolition waste (Fan et al., 2011). Pyrolysis is the direct thermal decomposition of an organic material under an inert environment (Jahirul et al., 2012) and the focus of this paper. This process produces useable chemical energy as bio-oil, bio-char, and syngas (Abnisa et al., 2013). In addition to upgrading waste material to a useful resource, pyrolysis has the added benefit of reducing the risk of secondary pollution to the environment when compared to processes such as combustion. The current drawback to this process is that the chemical reaction is highly endothermic, requiring a large amount of heat input supplied from non-renewable sources (Morales et al., 2014). To remedy this problem solar concentrating technology can be used to supply the required input heat (Weldekidan et al., 2018). This is particularly promising in an Australian context, as the country is well endowed with solar resources (Geoscience Australia, 2017). The aim of this study is to explore the feasibility of solar assisted biomass technology, focussing on the state of Victoria. The importance of location and context is highlighted, as both the concentrated solar power (CSP) and pyrolysis components of this technology depend greatly on environmental parameters. This paper will first provide a literature review of pyrolysis, solar concentrating technologies, and their integration. A comparison between renewable energy sources (RES) and biomass technologies is then provided to justify the combination of CSP/pyrolysis. Such a justification has not been made before in literature. Finally, the implementation and future works of this technology in Victoria will be provided at the end of the paper. This final section will focus on the technical aspects of a solar-driven pyrolysis system, and provide details on the optimization of such a system. Table 1 lists the different CSP, RES, and waste to energy types that will be assessed against solar-driven pyrolysis. These technologies were chosen for comparison as they often appeared in solar concentration and pyrolysis literatures.

2. Literature review

2.1. Current methods in biomass pyrolysis

Biomass can be converted into useable energy under a wide range of conditions and temperatures (600–2000 °C) (Chintala, 2018). Fig. 1 from Chintala (2018) details the different routes for biomass to energy. This review specifically focusses on waste to fuel solar-driven pyrolysis. The reasoning for focussing of pyrolysis is due to the advantages that pyrolytic fuel, which is produced as a solid, liquid, and gas, has over the other types of thermochemical fuels. The waste to fuel and solar aspects are to do with the environmental impact that can be achieved by applying these concepts to pyrolysis fuel production. These points will be justified and critiqued against other technologies in chapters 4 and 5 of this paper. There are three predominant types of pyrolysis: slow, fast and flash (Kan et al., 2016). Slow pyrolysis produces char, gas, and 35%–50% liquid fuel (Jahirul et al., 2012) and is characterized by lower heating rates of 5–20 °C/min with temperatures up to 500 °C (Dijan et al., 2016). Fast pyrolysis consists of high heating rates and short vapour residence times (Sharma et al., 2015), while flash pyrolysis has significantly higher heating rates of >1000 °C/s and temperatures of up to 1000 °C (Jahirul et al., 2012). Of these processes, Qureshi et al (2018) considers the liquid bio-oil produced to be the main product, with any char and flash being produced as a by-product (Qureshi et al., 2018). The yield of bio-oil obtained is usually 60–70 wt% (Smolders et al., 2006). The moisture content of the feedstock is kept low to limit the water content in the bio-oil (Van de Velden et al., 2010). Velden et al. (2010) stipulates that the heart of a biomass pyrolysis system is its reactor. Most of the current research into pyrolysis revolves around the reactor, as the peripheral physical and chemical processes (such as product separation or feedstock ball-milling) are already well-known (Bridgwater, 2003). Velden et al. states that fluidized beds are the most common reactor design as they can achieve high oil yields (Van de Velden et al., 2010). Recent publications make use of quartz or borosilicate reactors (Weldekidan et al., 2018) like that used in the lab-scale apparatus featured in Rony et al. (2018). From Velden et al. (2010), biomass mainly consists of three components: 30%–60% cellulose, 20%–35% hemicellulose

Table 1
RES, CSP, and Waste to energy types that will be studied in this paper.

Type		Description
CSP	Parabolic Reflector Trough (PTC)	A series of parabolic concentrators are placed on a rigid solar tracking mechanism. The absorber is fixed permanently at the focus of the parabolic concentrator.
	Fresnel reflector	Similar to PTCs except with flat, rather than parabolic mirrors. The use of flat mirrors drives down the cost.
	Parabolic Dish Collector (PDC)	An array of parabolic shaped mirrors that focus solar energy to a point on a receiver containing heat transfer fluid.
	Solar Tower Collectors (STC)	An array of flat, movable mirrors focuses sunlight to a collector tower containing a heat transfer or storage medium.
RES	Concentrated Solar Power (CSP)	Solar energy typically concentrated to either a point or along an axis via mirrors. The heat is either transferred or stored by the receiver.
	On-shore wind	A series of turbines powered by the force exerted by air currents on the turbine blades.
	Photovoltaic (PV) solar	Arrays of panels harness sunlight to drive a photovoltaic effect to produce electricity
	Geothermal	Heat from shallow hot ground water or hot rock is transferred to the surface.
	Hydroelectric	The same principle as wind turbines, except the force comes from the potential energy of dammed water.
Waste to energy	Anaerobic digestion	A complex fermentation process where organic matter is broken down to produce methane and carbon dioxide.
	Combustion	The direct combustion of carbonaceuous compounds to produce heat.
	Pyrolysis	Carbonaceous compounds are heated under a lack of oxygen to upgrade to useable fuels.
	Gasification	Similar to pyrolysis. Produces gaseous products under the presence of a medium such as oxygen or supercritical fluids.
	Torrefaction	A mild form of pyrolysis at temperatures typically between 200 and 320 °C. Torrefaction changes biomass properties to provide a better fuel quality for combustion and gasification applications.

(polysaccharides) and 15%–30% lignin (a polymer of methoxy substituted cyclic organics), together with some resins and minerals. It is important to consider the thermochemical reactions these components undergo to maximize yield and avoid side reactions (Van de Velden et al., 2010).

Cellulose, $(C_6H_{12}O_5)$n, is the main component of plant cell walls (Van de Velden et al., 2010). It is a linear polymer with a degree of polymerization of up to 10,000 size-carbon anhydroglucose sugar units. The cellulose fibres are held together in a matrix of lignin and hemicellulose (Lede, 1999). Three competitive primary reactions with cellulose occur under pyrolysis: (i) fragmentation to hydroxyacetaldehyde and other carbonyls, acids and alcohols; (ii) depolymerization to levoglucosan and other primary anhydrosugars; (iii) dehydration to char, gases and water (Van de Velden et al., 2010). Lignin is the strengthening component of the cell wall (Van de Velden et al., 2010), and is present in relatively high yields in forest-derived biomass (Lede, 1999). Lignin is a constituent of the cell walls of almost all dry land plant cell walls. It is the second most abundant natural polymer in the world, surpassed only by cellulose (What is Lignin?, 2016). The structure of lignin depends on plant species and as a result, pyrolysis with it produces various products (Van de Velden et al., 2010). Lignin is more thermally stable than cellulose and hemicellulose and yields more char and aromatic compounds (Shafizadeh, 1982; Demirbas, 2000). Hemicellulose binds the cellulose microfibrils of the cell wall. It consist of various different sugar units, arranged in different proportions and with different substituents. For example, wheat straw contains various branches such as arabinose, xylose, and uronic acid (Viikari et al., 2009). It varies in structure and composition and has a low thermal stability (Demirbas, 2000; Alén et al., 1996; Demirbas, 2004). It decomposes similarly to cellulose: by dehydration at low temperatures (<553K) and depolymerization at higher temperatures (Boukis, 1997). So it is apparent that the chemical process behind pyrolysis is well established. Now the focus must shift to the driving force behind the reaction. Achieving sustained temperatures of 600–2000 °C requires a lot of energy, which is why CSP technology has been proposed as a solution to this energy requirement. The next section of this paper will delve into CSP technology and provide insight into the possible technical solutions to generating conditions appropriate for pyrolysis to occur.

2.2. Solar concentration technology

Solar concentrating technology is a promising means of providing the required energy to drive an endothermic pyrolysis reaction. The first successful use of concentrated solar energy was attributed in the 19th Century to Augustin Mouchot, who used a parabolic trough to power a steam engine (Butti and Perlin, 1980; Meinel and Meinel, 1976). The first commercial CSP plant was developed by Francia in Italy during 1968 (Butti and Perlin, 1980). This was a steam plant capable of generating 1 MW of power. A major improvement to large scale concentrated solar power came about in 1995 with the 10 MW Solar Two project, which used molten salt as a thermal storage medium, so that power could be produced during periods of bad weather or night time. The use of molten salt as a thermal storage medium represented a solid technological improvement, as previously water-based solar engines were not able to operate without a shining sun (Needham, 2009). Modern commercial solar thermal plants typically produce in the range of 30–80 MW of power (Kalogirou, 2004), with proposals from Hoshi et al (2005) that a 240 MW molten salt plant is feasible (Hoshi et al., 2005). Modern concentrator temperature outputs range from 400 to 2000 °C depending on concentrator type (Weldekidan et al., 2018). There are four common types of concentrator shown in Fig. 2. These concentrator technologies can be broken down into two categories: linear and point concentration systems. The following sections will briefly summarize and review the current literature both kinds of systems.

2.2.1. Linear concentration systems

Parabolic trough collectors (PTC) consists of the main reflective plate, an absorber, and a concentric transparent cover (Jebasingh and Joselin Herbert, 2016). The absorber is fixed permanently at the focus of the parabolic concentrator (Jebasingh and

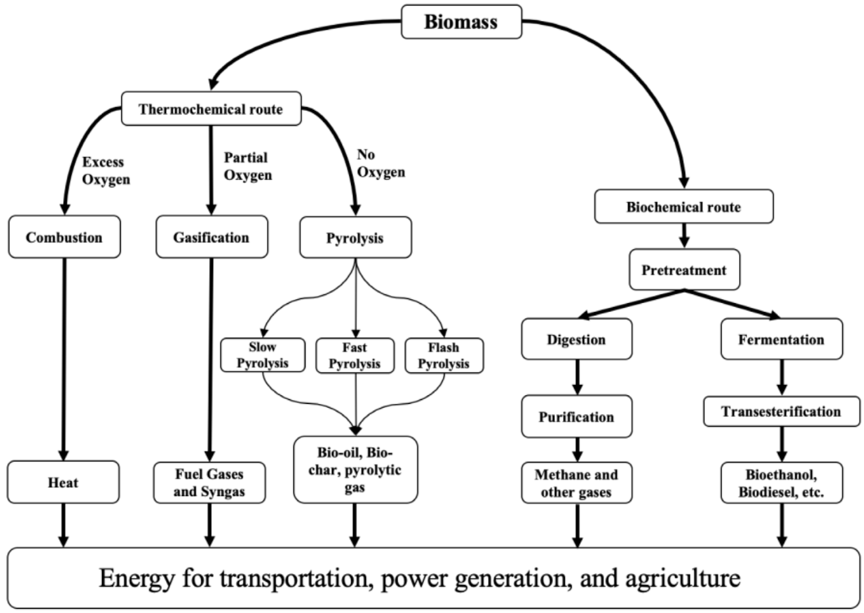


Fig. 1. Thermochemical and biochemical routes for biomass to energy.

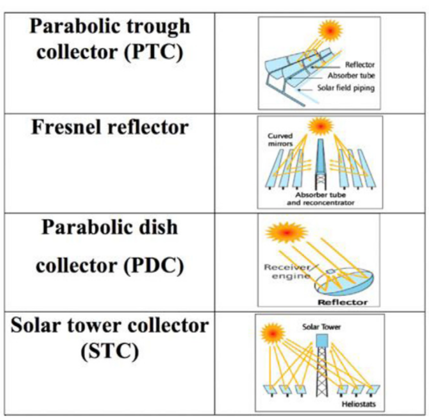


Fig. 2. The four types of CSP technology.

Joselin Herbert, 2016). The concentric transparent cover is used to protect the absorber tube from the heat losses and hence a vacuum pressure is maintained. The parabolic concentrator is placed on a rigid structure and the solar tracking mechanism is placed on the rigid structure to track the solar radiation by the parabolic concentrator (Jebasingh and Joselin Herbert, 2016). Commercially, these types of concentrators are constructed as a series of long parabolic mirrors which concentrate and reflect sunlight onto the horizontal absorber tube (Needham, 2009). Fluid running through the absorber picks up heat and is used to heat steam in a standard turbine generator (Needham, 2009). The typical working temperatures of these concentrators is over 400 °C with concentration ratios of 30-100 (Duffie and Beckham, 2013). High solar ratios (also known as solar flux ratios) are important in CSP, as it implies less heat loss and therefore greater solar-to-heat efficiency (Chueh et al., 2010). This high temperature and concentration ratio make PTCs especially popular for energy generation. Importantly, a large amount of high pressure steam is required for power generation, so the technology has been optimized to cope with large in and out-flows; Douani et al (2013) cites coping up to 18 bars of pressure (Douani et al., 2013). This high flow rate is of interest as it is feasible that an inert gas could be used in place of steam to run a pyrolysis reaction. The higher the pressure, the greater the reaction volume can take place, which could lead to greater volumes of biofuel being produced. Linear Fresnel reflectors are similar to PTCs in that they consist of a series of long, narrow, shallow-curvature or flat mirrors focus light onto one or more linear receivers positioned above the mirrors (Needham, 2009). Like PTCs, this technology utilizes linear concentration, where sunlight in focussed along a line. This is opposed to focussing to a single point. The advantage of this is that concentration optimization can be achieved by adjusting a single spatial coordinate (Gharbi et al., 2011). The concentration ratio of Fresnel reflectors varies from 25–100, and possess an operating temperature of 250–500 °C (Gharbi et al., 2011). This, like PTCs, also makes Fresnel reflector technology a viable means of running a slow-pyrolysis reaction. The cost of Fresnel reflectors systems is cited as being lower than PTC and dish technology because a single receiver is shared between several mirrors; there is just one axis for tracking; and as the receiver is stationary, fluid couplings are not required (Needham, 2009). Weldekidan et al. (2018) also states that the mirrors themselves are cheap, as they are flat, rather than curved. This low cost comes with a trade-off, as Cau et al (2014) lists single-axis tracking as a disadvantage. This is because single-axis tracking cannot maintain constant Direct Normal Irradiation (DNI) of the collector surface with the sun; only double-axis tracking can do this (Cau and Cocco, 2014). Interestingly, Gharbi et al (2011) alludes to Fresnel reflectors and PTCs being very similar technologies, as it was shown that the characteristics of a PTC can be approximated by arranging the mirrors of a Fresnel system in a parabolic manner (Quoilin, 2007).

2.2.2. Point concentration systems

From the literature, it appears that linear reflector systems would only be suited to drive slow pyrolysis reactions. Reflectors that concentrate sunlight to a point can achieve much higher temperatures. An example of this type of reflector is the parabolic dish collector (PDC), which can reach temperatures up to 3000 °C (Needham, 2009). Modern PDCs consist of an array of parabolic shaped mirrors that focus solar energy to a point on a receiver containing heat transfer fluid (Tian and Zhao, 2013). Given this technology's high temperature range, PDCs should therefore be able to drive any type of pyrolysis reaction. Dish systems possess a solar flux concentration ratio of 10,000 which is 10 times greater than the next best technology (solar tower collectors) (Chueh et al., 2010), and much higher than any linear system. However, Cau et al (2014) writes that dish systems do not play a relevant role in new CSP construction due to limited reference plants and massive land use requirements (Cau and Cocco, 2014). The only dish technology currently operational use are small research-scale facilities, such as those at the Australian National University in Canberra, Australia, and a planned 40 MW project for South Australia. Furthermore, Zhang et al (2013) provides a comparison of various CSP technologies, which cite that dish systems are expensive and incompatible with thermal storage and hybridization Zhang et al. (2013). Another popular form of point concentration reflector technology is the solar tower collector (STC). An array of flat, movable mirrors (heliostats) focuses sunlight upon a collector tower, in which a substance is heated (Needham, 2009). Water was originally used for immediate power generation via a steam turbine, which did not allow for power generation when the sun was not shining (Needham, 2009). Other media can be used to store heat from which steam can be generated to run turbines at any time of day: purified graphite is being used in the 10 MW power plant in Cloncurry; liquid sodium (sodium is a metal with a high heat capacity) has also been successfully demonstrated as a heat storage medium (Needham, 2009). In terms of installed capacity in Australia, the only notable CSP projects are a solar tower currently planned for South Australia with a capacity of 150 MW and energy generation of 1100 GWh/year, the biggest of its kind in the world (Solar reserve, 2017). Solar tower technology has the typically highest storage capacity as well as the highest site gradient potential (a measure of a CSP system's locational flexibility) (Peterseim et al., 2013). This is due to the utilization of heat transfer fluids (HTF), which serve as both a medium for transferring heat from the tower for energy generation, as well as a means of storing captured heat. This allows STCs and any technology that utilizes HTFs to operate during the night and times of low solar intensity. STCs however suffer from an extremely high capital cost (Elliston et al., 2016) compared to other forms of solar concentration. Additionally, both STC and PDC systems require more complex control schemes than linear systems. This is because focussing sunlight to a point requires tracking over multiple axis, rather than a single axis in the case of linear systems.

3. Solar-driven pyrolysis

Two common types of pyrolysis reactor operating processes appear in literature: batch and continuous. A batch process is defined by Qureshi et al. as being a closed system where the reactants and products are held in the reactor for a period of time while the reaction occurs (Qureshi et al., 2018). This means a single batch of biomass is reacted for each reactor heat cycle. Batch processes are problematic due to their extended reaction time, inconsistency between batches of biomass, high labour cost, constant heat cycling, and difficulty when applied to a large scale (Anuar Sharuddin et al., 2016). Because of these issues, continuous processes have garnered interest as a viable form of pyrolysis (Qureshi et al., 2018). A continuous pyrolysis process is one that adds feed into the reactor as the reaction proceeds (Qureshi et al., 2018). By controlling the rate of addition of feedstock and removal of product in the reactor, a continuous process can achieve steady-state, therefore making it more efficient for bio-oil production (Green and Perry, 2008). The first step in a semi-continuous and continuous process is to change or destroy the lignocellulosic cell structures of the biomass feedstock to enhance pyrolysis efficiency (Kan et al., 2016). From Kan et al (2016), the two types of biomass pretreatment are physical treatment (such as milling and grinding), and thermal treatment (such as ultrasonic and microwave irradiation) (Kan et al., 2016). Physical treatment typically reduces particle size to 1–2 mm for bio-oil production (Kan et al., 2016; Isahak et al., 2012; M et al., 2006). This bolsters the reactivity of the feedstock through increasing surface area (Ngoh and Lim, 2016). Thermal treatment also includes a drying process to regulate feedstock moisture, which can affect liquid product stability (Bridgwater, 2003). Once feedstock pretreatment has been accounted for, the next item to consider is the feed equipment. Qureshi et al. (2018) provides a comprehensive review of feed equipment for continuous pyrolysis applications. It is specified in this review that the type of feed equipment used will depend on the specific pyrolysis configuration and parameters. The four popular types of feed equipment covered were hopper, screw, conveyor belt, and pinch valve. Fig. 3 shows a summary table from Qureshi et al. (2018) that details the positives and negatives of each feed system.

Deepak et al. (2016) shows that screw/auger feeders in particular are best suited for a wide range of solids and feeding rates. Feeding equipment selection should account for material, particle size, particle shape, bulk density, good feed control and energy required to drive the feeding system (Couper et al., 2010). Even after the appropriate feed equipment has been selected, it should be noted that intermittancy of solar radiation throughout the day presents a control problem that is yet to be overcome (Lede, 1999). Chintala (2018) states that there is a large difference between the reactor temperature and reaction temperature due to the surface area effects of the biomass. This means that the product quality and quantity can vary wildly depending on the input reactor temperature. Chuayboon et al. (2019) therefore advises that dynamic control should be implemented by adjusting the biomass feed-rate into the reactor in response to variable solar input. Doing so will optimize the product output.

3.1. Modelling

The most common method in the literature for modelling pyrolysis of plastic, paper, and wood material is with the solid-state Arrhenius equation (Chrissafis, 2009; Encinar and González, 2008; Gao et al., 2003b; Zhou et al., 2006; Kple et al., 2017):

$$\frac{d\alpha}{dt} = A\exp(-\frac{E_a}{RT})(1-\alpha) \tag{1}$$

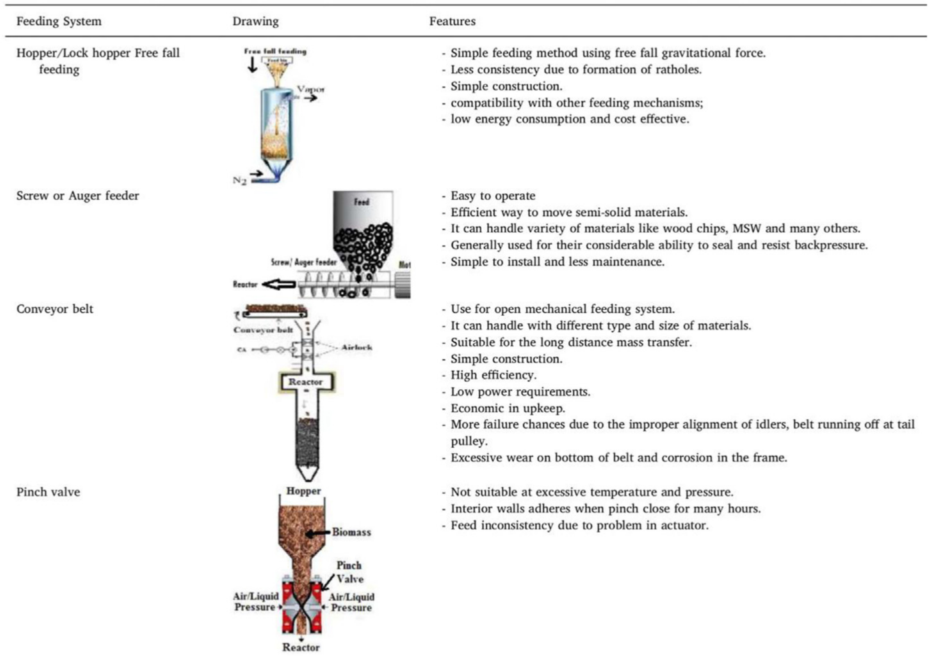
where A and Ea are the Pre-exponential factor and Activation energy of the feedstock material respectively, R is the gas constant, and α is the conversion factor:

$$\alpha = \frac{1-m}{1-m_{char}} \tag{2}$$

where m is the sample mass, and mchar is the product yield. This model is isothermal, where the temperature does not change. Introducing the heating rate expression β = dT/dt gives the non-isothermal model:

$$\frac{d\alpha}{dT} = \frac{A}{\beta}\exp(-\frac{E_a}{RT})(1-\alpha) \tag{3}$$

In literature, this model is typically used to find the kinematic parameters for different materials under pyrolysis. A and Ea values of the feedstock are found by experimental Thermogravimetric Analysis (TGA) at different heating rates (Kayacan and Doğan, 2008; Kumar and Singh, 2014; Sùrøm et al., 2001; Jomaa et al., 2015; Agrawal, 1992). TGA works by weighing a sample of feedstock while undergoing a thermal process in order to gauge the mass-loss from product conversion. The kinetic parameters are then calculated from by linear regression. These parameters can be used in Eq. (3) to predict the product output as a percentage



Feeding System	Drawing	Features
Hopper/Lock hopper Free fall feeding		- Simple feeding method using free fall gravitational force. - Less consistency due to formation of ratholes. - Simple construction. - compatibility with other feeding mechanisms; - low energy consumption and cost effective.
Screw or Auger feeder		- Easy to operate - Efficient way to move semi-solid materials. - It can handle variety of materials like wood chips, MSW and many others. - Generally used for their considerable ability to seal and resist backpressure. - Simple to install and less maintenance.
Conveyor belt		- Use for open mechanical feeding system. - It can handle with different type and size of materials. - Suitable for the long distance mass transfer. - Simple construction. - High efficiency. - Low power requirements. - Economic in upkeep. - More failure chances due to the improper alignment of idlers, belt running off at tail pulley. - Excessive wear on bottom of belt and corrosion in the frame.
Pinch valve		- Not suitable at excessive temperature and pressure. - Interior walls adheres when pinch close for many hours. - Feed inconsistency due to problem in actuator.

Fig. 3. Types of feed equipment and their features (Qureshi et al., 2018).

of the initial feedstock mass under non-isothermal conditions. A gap identified in this model however is that solar-driven pyrolysis will not be isothermal, as β will vary due solar intermittancy and other environmental factors. Sobek and Werle (2019) specify a range of model-free methods that can potentially overcome this problem. This method is dubbed "iso-conversion" and works by taking the TGA data from various literatures over a range of heat rates to generate a set of equations that can generate the A and Ea values for an unestablished process. Iso-conversion is covered in great detail by Vyazovkin et al. (2014), and includes the its use for both biomass and polymer/plastic degradation. This provides a convenient way of evaluating thermal processes such as pyrolysis, as the exact mechanism is not known (Sobek and Werle, 2019). In terms of solar-driven pyrolysis, there is currently no governing model in literature. Recent researches have modelled solar-pyrolysis of specific materials under specific conditions, such as Zeng et al (2016) who modelled the solar-pyrolysis of beech wood using the kinematic expression given in Eq. (3) and TGA methods previously discussed (Zeng et al., 2017). A sample of beech wood was pyrolysed with a parabolic reflector. A target heat rate was reached with a PID controlled shutter. Rony et al. (2019) used model-free methods and a solar simulator to model the solar-pyrolysis of corn stover. Both of these approaches show promise in their respective research gaps, however they do not provide a general model for solar-pyrolysis and there is a lack of focus on the intermittancy problem associated with the CSP aspect of the technology. Potentially, the concentrated solar component of the system may be modelled separately. This would involve translating the solar irradiance from the concentrator into the input temperature change induced on the pyrolysis reactor. The formula for DNI to heat according to Pitz-Paal (2007) is as follows:

$$Q = A_{A_p} \cdot [F(\alpha \cdot C \cdot E^S - \epsilon \cdot T_F^4 - U_L \cdot (T_A - T_a))] \tag{4}$$

with Q being heat produced by the reflector, A_{A_p} being the aperture area, α being the average absorptivity of the absorber with respect to the solar spectrum, F being the heat removal factor, C the concentration factor, E^S the radiation density of the direct solar radiation and ϵ the average emissivity of the absorber with respect to the black body radiation at the absorber temperature T_A, T_F being the average temperature of the heat transfer fluid, θ being the Stefan–Boltzmann constant, U_L is the heat loss coefficient due to convection and conduction. Thermal radiation input from the ambient (with the ambient temperature T_a) to the receiver is neglected. Converting heat to reactor temperature change will simply be:

$$\Delta T = Q/mc \tag{5}$$

where m is the mass of the reactor material in kg, and c is the specific heat of the reactor material. As can be seen from both formulae, the temperature of the reactor will be proportional to DNI at any given time. From this the heat rate can be deduced. This, combined with the kinematic methods described above provide a model for predicting solar-pyrolysis product output.

3.2. Reactor design

Sobek and Merle categorize solar-driven pyrolysis design into two categories: natural and artificial light source (Sobek and Werle, 2019). Natural light source reactors operate purely through sunlight, while artificial light reactors typically operate off of solar simulators (Sobek and Werle, 2019). A notable example of a natural light system was the one built by Zeng et al (2017) which mounted a heliostat-reflector/parabolic dish concentrator hybrid to the side of a building (dubbed a "vertical solar furnace") to concentrate sunlight from the sun into a 6L pyrex balloon reactor to produce bio-char, bio-oil, and gas (Zeng et al., 2017). A novel natural light system can be found in the smaller-scale example by Rony et al (2018) who created a room-scale 5 kW solar-pyrolysis simulator using a modified cinema projector to simulate concentrated solar energy on a quartz pyrolysis reactor (Rony et al., 2018). This set up displayed very high simulated solar flux stability over time at temperatures below 300 °C and reasonably high stability above 400 °C. Variance in stability from the results above 400 °C were cited as originating from the input power supply (Rony et al., 2018). These flux characteristics were then successfully modelled with a Monte Carlo raytracing program, Soltrace, which validated the performance of the simulator. This

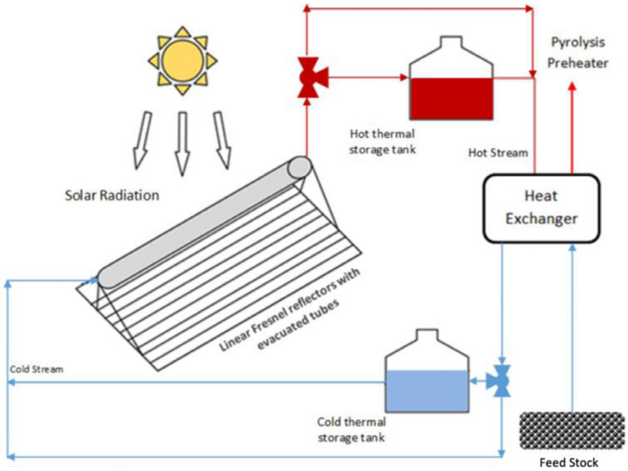


Fig. 4. Zeaiter et al. (2018) Fresnel CSP system for solar-driven pyrolysis (Qureshi et al., 2018).

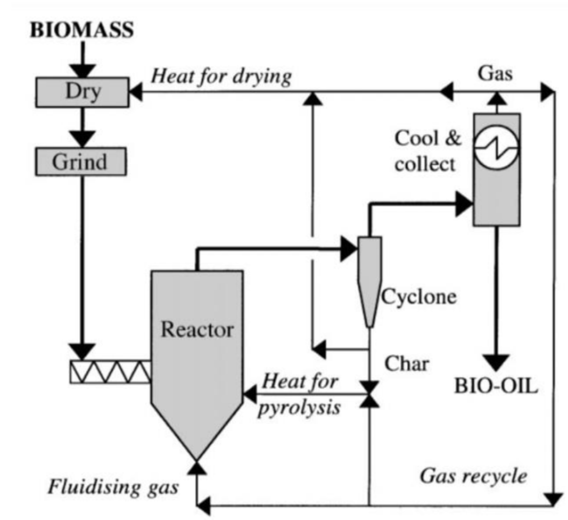


Fig. 5. Bridgewater et al.'s (1999) Fluidized bed layout for fast pyrolysis.

plus the successful conversion of biomass to separable bio-oil led Rony et al (2018) to conclude that solar energy is a viable means of replacing electrical heat for producing value-added materials from bioresources (Rony et al., 2018). The most common solar pyrolysis reactor design in literature is typically a quartz glass reactor that absorbs heat from a point concentration system, with published works as recently as 2019 (Rony et al., 2018; Zeng et al., 2017; Rony et al., 2019). As per Sobek and Werle (2019) the purpose of this type of reactor design is to investigate kinematice, the influence of process temperature on product yields, and biomass energy upgrade factor (Sobek and Werle, 2019). Currently there are no commercial-scale solar pyrolysis reactors and very little research into the upscaling of solar-driven pyrolysis systems. However, Zeaiter et al (2018) recently described a solar-pyrolysis reactor driven by linear Fresnel reflectors Zeaiter et al. (2018) with potential for implementation on a large-scale. This study cites low cost and high operating temperatures as the reason for choosing Fresnel reflectors. Such a system would heat a pyrolysis reactor via heat transfer fluid (HTF) rather than heating the reactor directly with sunlight. Zeaiter et al.'s Fresnel system is shown below in Fig. 4. Note that it is specified that the feed stock is fed into the heat exchanger before entering the pyrolysis reactor/preheater. This type of system can utilize a conventional pyrolysis reactor. Unlike solar-driven pyrolysis reactors, conventional pyrolysis reactors are very well documented, and vary in scale. As per Bridgwater et al. (1999), the most common type of pyrolysis reactor is the fluid bed. This study attributes the fluid bed's popularity to its ease of operation and readiness to scale up. The main concept behind the fluid bed is the condensation of vapours produced from the pyrolysis process, which produces liquid fuel product. Bridgewater's layout for fluidized bed pyrolysis technology is shown in Fig. 5 Evidently the fluidized bed is old technology, however it is still relevant today with multiple papers utilizing the technology as recently as 2018–2019 (Fuentes-Cano et al., 2018; Brandão et al., 2018; Chandler and Resende, 2019). In terms of new and current research into pyrolysis reactors, pyrolysis gasifiers that take advantage of the process' syngas output are being investigated. Chen et al. (2019) proposes a two-stage pyrolysis gas combustion apparatus. The advantage specified for this set up include the decoupling of pyrolysis and combustion process, which offers operational degrees of freedom as well as prevents back mixing. The diagram of Chen et al.'s system is shown in Fig. 6. The inclusion of such a system to a pyrolysis reactor would allow for the utilization of gas products, as well as the production of bio-oil. For a solar-driven design, this type of system could provide its own supplementary power in times of low solar exposure. From this reviewed work, it becomes apparent that the most appropriate combination of technology subsystems for a commercial solar-driven pyrolysis reactor are a combination of Fresnel reflectors, fluidized bed reactor, and gas combustion system. It is critical to understand that despite the various advantages and disadvantages of these reactor types; with respect to a solar thermal implementation, these reactors utilize open-loop control. This means that during operation, amounts of feedstock are being input into the reactor without concern for maximizing fuel production, despite it being known that feedstock feed rate and reactor heat rate greatly affect fuel production. This provides research opportunity to develop a close-loop control system for solar driven pyrolysis reactors that can take environmental parameters to accomplish achieve optimal feed and heat rates. With the review of both modelling and components of solar-driven pyrolysis having been completed, the next chapter will justify the particular combination.

4. Solar-driven pyrolysis combination in an Australian context

There was found to be no current literature that discussed the combination of CSP and pyrolysis over other RES/waste-to-fuel combinations (for example, PV and gasification). Therefore, before solar-driven biomass pyrolysis can be further analysed for producing biofuel in Australia, it must first be assessed against other possible solutions. Table 2 weighs the economics and performance of common energy sources from literature. The economic parameters were project capital cost ($AUD/kW), and the annual operations/maintenance costs ($AUD/yr). Capacity (MW) was compared for all technology types except solar PV, which was measured in W/m^2. Because of the extreme scalability of PV, it was better to provide the energy per square metre.

Table 2 shows that coal accounts for 63% of Australia's energy generation, with the use of black coal rising 6% in 2017 (Geoscience Australia, 2017). Despite its established use and reasonable capital and maintenance costs, it was disregarded as an option due to its non-renewable nature. Australia is a historically water-sparse country (Hoekstra et al., 2012), so it is important that minimal use of water be considered a high weighted requirement. This leaves PV and wind as the main competitors to CSP as potential RES waste-to-fuel drivers. Both PV and wind

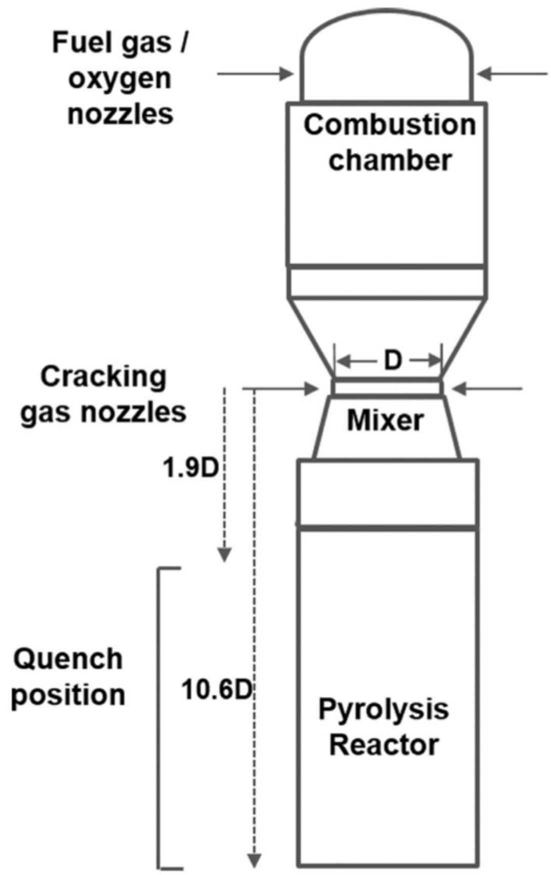


Fig. 6. Chen et al. (2019) gas reactor diagram.

Table 2
Economic and performance parameters for common types of generation.

Technology	Capital cost \$AUD/kW (Elliston et al., 2016; Hydropower: Technology Brief, 2015)	Operation and maintenance cost O&M (\$AUD/yr) (Elliston et al., 2016; Hydropower: Technology Brief, 2015)	Typical capacity (MW)	Typical capacity (W/m^2)
Black coal	3038	59	>1000 (Climate Change Authority, 2016)	N/A
Central receiver CSP	4778	84	10–200 (Anon, 2012a)	N/A
On-shore wind	1809	38	2 per turbine (Anon, 0000a)	N/A
PV (single axis)	2278	35	N/A	120 (Anon, 2012b)
Geothermal	7234–11,071	199–234	2–113 (Anon, 2013)	N/A
Hydro	2834–5668	63	0.5–50	N/A

are lower in capital and maintenance costs and can easily be scaled to match the capacity of an equivalent CSP facility. In the case of wind power, (Needham, 2009) stated that Australia is not well-endowed with wind resources, with most of the current installed capacity existing in the Southern regions of the country (Needham, 2009). Additionally, Australia's attitude towards wind power has made attaining social license to operate difficult in recent years. This decreased the amount of potential installed wind capacity. Australian policy has also been hostile towards wind power at times depending on government (Vorrath, 2015). This left solar PV as the remaining alternative to CSP. The Australian Energy Council (2018) cites an installed PV capacity in Australia of 6401 MW (including both residential and large facilities) (Anon, 2018). Compared to CSP, the only notable capacity is a 150 MW plant currently being installed in South Australia (Solar reserve, 2017). So PV is a much more well established technology in Australia than CSP and has a lower capital and O&M cost. However, the use case must be considered. Had this paper focussed on electricity-to-grid generation, than PV would appear the more attractive option. However, the context for this technology was to be used to provide input energy to a thermochemical reaction. The main advantage that CSP possesses over PV in this case is the direct transmission of thermal energy. Additionally, CSP has the added advantage of cheaper energy storage options. Consider CSP's extensive use of HTF and molten salt storage. This technology is rated to a capacity of up to 60 MW for a cost of 30–60 \$USD/kWh (Chen et al., 2009). The storage options for PV as a whole are more expensive and lacking in storage. In terms of battery storage, lead–acid, NiCd, Li-ion, and NaS technology may range from 50 kW–100 MW for a much greater cost, in the range of hundred to thousands of \$USD/kWh (Chen et al., 2009). Other potential PV storage technology such as flywheels and super capacitors are both unable to match HTF storage in terms of both capacity and cost (Chen et al., 2009). Therefore, while the capital cost of PV is lower than CSP, the cost of storage is far higher. This makes CSP more attractive for a highly capital cost dependent system such as a solar-driven pyrolysis facility. Focussing on the thermochemical side of the technology: pyrolysis is not the only reaction path for converting waste into useable energy. Table 3 provides an overview of common alternative thermochemical routes from literature.

This shows that gasification is the most energy rich process as its products possess the highest cumulative HHV. In fact, the two most energy rich processes are the ones predominantly utilized for gas production; digestion and gasification. Digestion (commonly known as AD, or "anaerobic digestion") is a complex fermentation process where organic matter is broken down to produce methane and carbon dioxide (Bajpai, 2017). Interestingly, pyrolytic gas has a low HHV compared to the other gases found in the different thermochemical processes. Gasification is similar to pyrolysis in that biomass is upgraded in hydrogen content. The difference is that gasification produces gaseous products under the presence of a medium such as oxygen or supercritical fluids (Basu, 2018). Gasification also produces H2 and CO, which can be used as a base for liquid fuel production (Basu, 2018). It should be noted however that pyrolysis offers a more direct approach to the production of liquid fuel. So any of these thermochemical processes may be used in conjunction with CSP technology. Pyrolysis however is particularly attractive in its ability to produce three chemical states of fuel, allowing for greater versatility and operational flexibility. As discussed in reactor design section of this paper, current technological trends would allow for the simultaneous utilization of both the bio-oil and gas products (Chen et al., 2019; Bridgwater et al., 1999). Torrefaction is typically used to upgrade the energy of wood, turning it into "torrefied wood", and is described as mild pyrolysis process carried out at temperatures

Table 3
Summary of common waste to fuel processes.

Process	Reaction(s) (Chuayboon et al., 2019; Bajpai, 2017; Basu, 2018)	Major product(s)	Highest heating value (MJ/kg) (Raveendran and Ganesh, 1996; Waldheim and Nilsson, 2001; Keipi et al., 2014; NIST Chemistry WebBook, 2018)
Pyrolysis	$C_xH_yO_z \rightarrow \Sigma C_aH_bO_{c\ (liquid)} + \Sigma C_dH_eO_{f\ (gas)} + C_gH_hO_i$ (char) + C (char)	Char Liquid Gas	24.1 24.9 16.6
Gasification	$C_xH_yO_z + (x - z)H_2O \rightarrow (y/2 + x - z)H_2 + xCO + C_aH_bO_c$	H_2 (gas) CO (gas) CH_4 (gas)	141.8 12.6 55.5
Torrefaction	$C_xH_yO_z$ + heat → char + CO + CO_2 + H_2O + vapours	Various solids in the form of char	21.2–23.2
Digestion	Hydrolysis $C_6H_{10}O_4 + 2H_2O \rightarrow C_6H_{12}O_6 + H_2$ Acidogenesis $C_6H_{12}O_6 \rightarrow 2CH_3CH_2OH + 2CO_2$ $C_6H_{12}O_6 + 2H_2 \leftrightarrow 2CH_3CH_2COOH + 2H_2O$ + $C_6H_{12}O_6 \rightarrow 3CH_3COOH$ Acetogenesis $CH_3CH_2COO^- + 3H_2O \leftrightarrow CH_3COO^- + H^+ + HCO^-{}_3 + 3H_2$ $C_6H_{12}O_6 + 2H_2O \leftrightarrow 2CH_3COOH + 2CO_2 + 4H_2$ + $CH_3CH_2OH + 2H_2O \leftrightarrow CH_3COO^- + 3H_2 + H^+$ Methanogenesis $CH_3COOH \rightarrow CH_4 + CO_2$ $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ $2CH_3CH_2OH + CO_2 \rightarrow CH_4 + 2CH_3COOH$	CH_4 (gas) Syngas (gas)	39.7 55.0

ranging from 225 to 300 oC (Prins et al., 2006a). Torrefaction can be used in conjunction with gasification to achieve an outcome similar to two-stage pyrolysis gasification (Prins et al., 2006b). The main difference being that this process must be carefully controlled at temperatures below 300 oC to avoid tar formation, and there is no liquid fuel produced (Prins et al., 2006b). Therefore, when considering the context of a CSP-driven thermochemical process, pyrolysis still represents the best choice in terms of operational versatility in terms of being able to selectively produce the most in-demand fuel type, whether it be char, bio-fuel, or gas. So to summarize the justification of process selection, concentrated solar is the most suitable technology to drive a thermochemical process and pyrolysis presents the end-user with the best trade-off of versatility to HHV. With the process justified, the implementation of this technology in Victoria will now be considered.

5. Solar and waste resources and solar-assisted pyrolysis feasibility in Australia

The Australian continent has the highest level of solar irradiance in the world (Solar Energy and Government, 2020). Despite this, Australia's current solar usage only accounts for 0.1% of its energy consumption (Solar Energy and Government, 2020). Victoria itself is a highly developed and wealthy state, capable of initiating and maintaining large-scale energy projects. One of the challenges facing solar energy in Victoria however is the fact that the regions with the highest solar radiation are located in remote desert regions in the North-West and centre of the continent (Solar Energy and Government, 2020). This can be seen in Fig. 7, which shows a colour-map of the continent's direct normal solar irradiance (DNI) (Direct Normal Radiation, 2020).

This does not infer implementing CSP in Victoria is unfeasible. Figs. 8 and 9 compare the annual average DNI of the Australian state of Victoria to the German federal state of North-Rhine Westphalia. Though this region possess noticeably lower DNI levels than Victoria, in 2008 Germany commissioned an experimental 1.5 MWe solar tower in Jülich (Hennecke et al., 2008). The purpose of this plant was not to generate power for an end user, but to experimentally verify the functionality and to quantify the performance of the plant's storage subsystem (Anon, 0000b). Additionally, Philibert (2005) recommends a minimum 2000 kWhm^2 for a viable commercial CSP plant (Philibert, 2005) . It can be seen in Fig. 3 that the major population centre of Victoria (Melbourne city) is quite close to the inside the 2000 kWhm^2 boundary. This locations is therefore sufficient to generate the temperature requirements for a commercial fast pyrolysis facility, which Badger et al. (2006) states as being 500 °C (Badger and Fransham, 2006). For reference, the Jülich solar tower itself could generate up to 700 °C (Anon, 0000b), noting that the city lies within a 1000 kWhm^2 region. Temperature is not the most important parameter, the power capacity of the system must be considered as well. Taking the Jülich case and assuming a thermal to electric efficiency of 10%, the thermal capacity of this facility was 4.5 MWth. Noting that Jülich is located in a region of 1000 kWhm^2 DNI and assuming a linear relationship between DNI and power capacity, this means an equivalent CSP facility located around the Australian coast could produce up to 9 MWth. Important to note is that literature does not provide a minimum power requirement for pyrolysis biofuel production. Ganesh and Banerjee (2001) cites a 5 MWe upper limit due largely to economic restrictions. So in terms of solar resources, while Victoria is not well-endowed as other Australian regions, it still possesses double the available DNI of the example case in Jülich. Australia's waste management is heavily dependent on landfill (Waste, 2010). The Australian Bureau of Statistics predicts that as Australia's population and economy grows, so too will its waste output as a result of the increased production and purchasing power (Waste, 2010). So not only is Australia's growing energy demand becoming a concern, but also the amount of waste it produces. Waste to fuel systems have a positive net impact on both of these issues, as they are able to take waste and convert it into useable energy. This is unlike other RES technology, as it involves the upgradation of waste materials. Australia produces massive amounts of waste per annum. In 2011, 48 Mt (million-tonnes) of

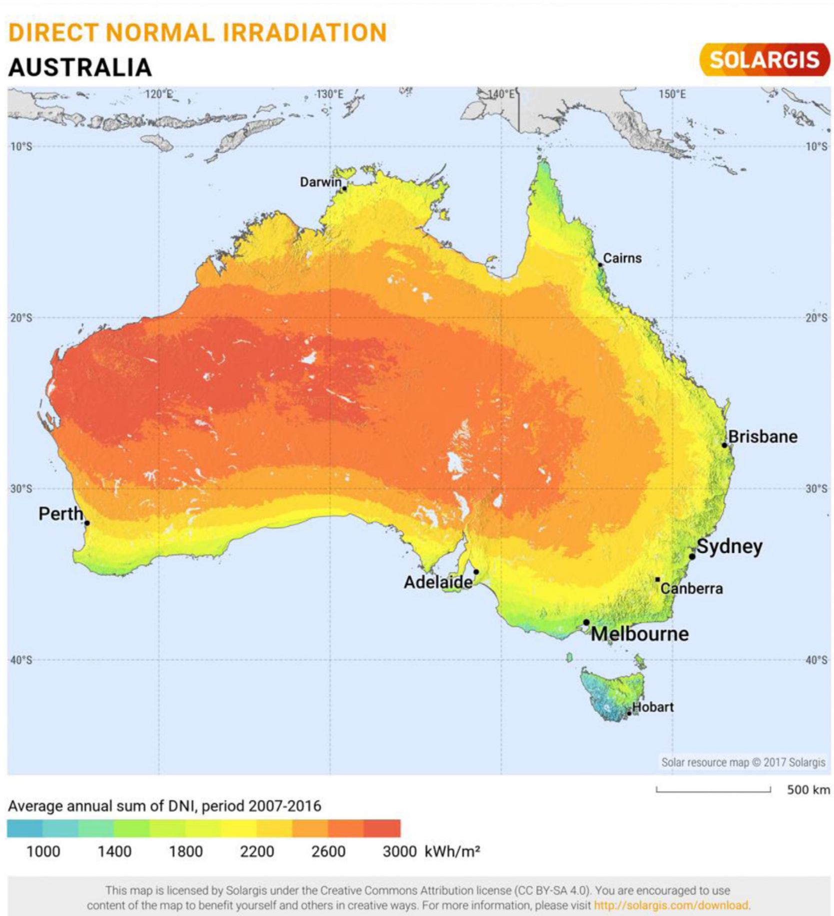


Fig. 7. Australian continental DNI, Note that Victoria possesses relatively lower DNI compared to more remote locations.

waste was produced, up from the 44 Mt produced in 2007 (Anon, 0000c). From the National Waste Reporting 2013, the Department of Environment and Energy categorizes solid waste into three major streams: municipal solid waste (MSW), commercial and industrial (C&I), and construction and demolition (C&D) (Anon, 0000c). MSW is primarily waste collected from households and councils and includes biodegradable and recyclable material. In 2010–11, 14 Mt of MSW was generated nationally of which 51% was recovered. C&I is waste that is produced by institutions and businesses such as schools and restaurants. In 2010–11, 15 Mt of C&I waste was generated, of which 59% was recovered. C&D waste refers to waste produced by demolition and building activities, such as road and rail construction. 18 Mt of C&D waste was produced in 2010–11, with a recovery of 66%. Importantly, this report specifies that the majority of waste recovered is categorized as recycling; with only a small percentage recovered as energy (0.32 to 6.26% depending on waste category). This report assumes that most of the unrecovered waste ends up in landfill, which can vary in composition from mixed (in the case on MSW) to homogeneous (in the case of C&I). MSW is of particular interest as it has been widely used in the production of bio-fuels (Sipra et al., 2018), with pyrolysis listed as a potential conversion technology in Tareen et al.'s (2018) review paper of biomass energy (Khan Tareen et al., 2018). MSW is a type of biomass which mainly consists of food waste, paper, plastics, wood, textiles, metals, and glass (EPA, 0000). Sipra et al. (2017) states that given MSWs have a versatile chemical composition, they have a heat value of 20.57 MJ/kg, which gives them great potential as a source of bio-energy. However, one of the major design challenges for biofuel production is feedstock composition and source. Most methods for biofuel production (save digestion, which mainly utilizes food waste) use woody matter such as rice husk and saw dust for feedstock. It is important that the feedstock be uniform to ensure controlled calorific content. This is a problem as no extensive research into the specific content of Australia's landfill has been performed. The National Waste Report does not provide insight into the content or composition of C&D, C&I or MSW. The most recent effort to characterize Australia's MSW comes from Hla et al. (2015), who assessed the City of Greater Brisbane's MSW composition (Hla and Roberts, 2015). Hla et al. argues that because of the heterogeneous nature of MSW, the results of this study can be extrapolated for the other Australian capital cities.

Fig. 10 shows a breakdown of Hla et al.'s results on MSW composition. It can be seen that wood and paper waste make up the bulk of Australia's MSW. This bodes well for pyrolysis because, as stated above, most interest in this technology has to do with the conversion of cellulose, lignin, and hemicellulose based materials into fuel. This shows that MSW has an appropriate composition for a pyrolysis waste to fuel facility. The composition of MSW/landfill is not the only important factor to consider. The location of landfill sites must be taken into account as transportation costs can quickly accumulate over large distances. Pearman (2018) computed the overhead of truck transportation to be 0.13–1.35 $AUD/km/t depending on truck type. From this, Pearlman deduces that the cost of transporting a tonne of biomass 500 km is $AUD 672 for rigid trucks, and $AUD 96 for articulated trucks (Pearman, 2018). Obviously, as capital and OM costs play

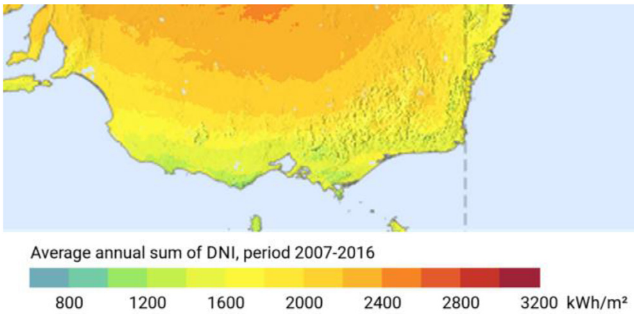


Fig. 8. Victorian DNI (Pitz-Paal, 2007).

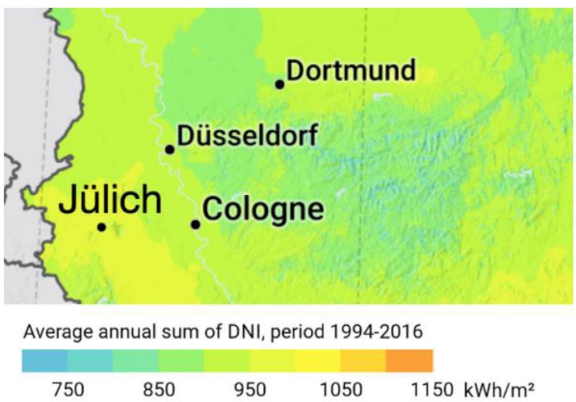


Fig. 9. North-Rhine Westphalia *DNI* (Pitz-Paal, 2007).

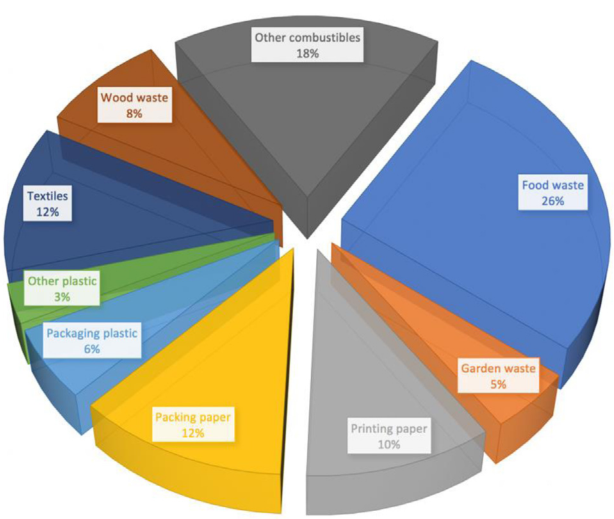


Fig. 10. Break down of MSW composition of Greater Brisbane.

a large role in both the CSP and pyrolysis side of the technology, articulated trucks would therefore be the preferred means of feedstock transportation. From here, it is now important to consider landfill locations and accessibility. Taking landfill location data from the Environmental Protection Authority Victoria, Fig. 11 shows the location of landfill sites relative to the DNI for the state of Victoria. This landfill data was filtered to exclude hazardous (asbestos) and non-biomass (ceramic or glass) wastes, and overlaid on the DNI map of Victoria. This shows that landfill locations are densest around the state's population centres (such as Geelong and Melbourne), while most sites are scattered across

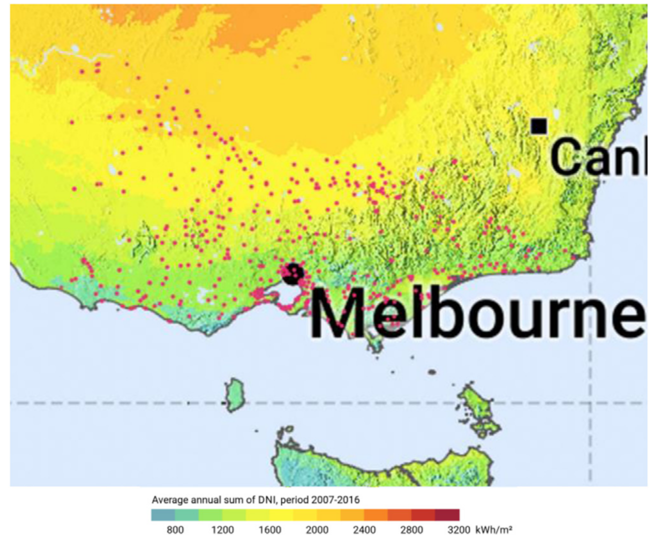


Fig. 11. Location of landfill site in the state of Victoria (Victorian Landfill Register, 2018), overlaid on the SOLARGIS map of Australian DNI (Climate Change Authority, 2016).

the entire state. Fig. 11 shows that the majority of landfill sites are located within the 1400 to 1600 kWh/m^2 DNI bands. Regions of higher DNI and therefore greater solar efficiency have a greater scattering of landfill sites, meaning the feedstock would need to be transported over greater distances. Longer transportation increases the overall use of fossil fuels throughout the system lifecycle. The landfill site density can be roughly broken down into three categories: city, regional, and rural. This is shown in Fig. 12; which shows the Victorian landfill site map colour-coded into these categories. City, coloured in pink, encompasses the densely clustered landfill sites located immediately around the state's population centres. Regional, coloured in purple, encompasses the lightly clustered landfill sites located near or around small towns that are within a reasonable driving distance (no more than several hours drive) of the major population centres. Rural encompasses the rest of the landfill sites, spread out over a greater distance. Comparing this figure with the one above, the northern areas of the rural region will offer the highest DNI, while regional will only offer a slightly higher average DNI than the city. Waste sources are more clustered in the regional and city regions, making for more available feedstock with lower transportation costs. From this analysis it is apparent that Victoria's densest waste streams come from locations of lower DNI, and that the transportation of waste equals accumulating operating costs as per Pearman (2018). While the CSP side of the technology benefits from high DNI, it has been noted that the upper power limit for pyrolysis specified by Ganesh and Banerjee (2001) means that excessive DNI may not be required, however maximization of DNI would still be advised for the benefit of heat storage. Therefore, a solar-driven pyrolysis facility in Victoria would benefit from a location that balances the distance to sources of feedstock with DNI. Overall, upon review of the literature and data pertaining to Victoria's solar irradiance and waste generation, it appears that the country is a strong candidate for a commercial solar-assisted pyrolysis facility.

6. Discussion

A review of solar-driven pyrolysis was conducted along with a justification of the technology combination and where it fits in the context of providing a waste to energy source for Victoria.

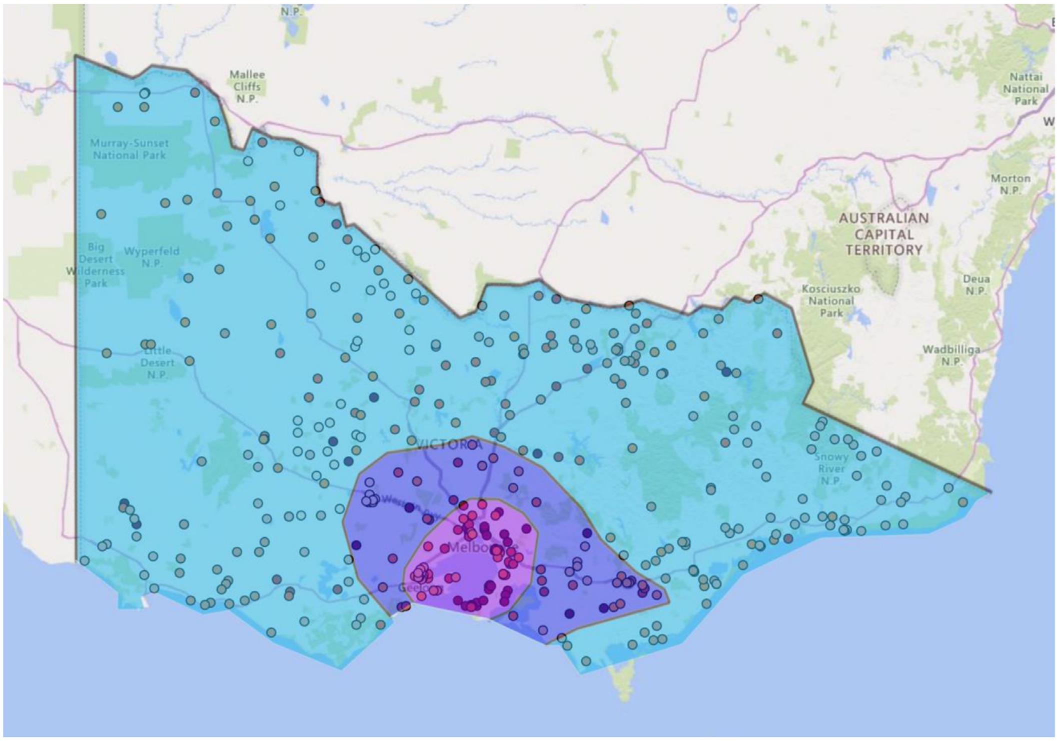


Fig. 12. Break down of regions, categorized as: City, Regional, Rural. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 4
Table of system requirements for a solar-driven pyrolysis facility in Australia.

Requirement	Units	Direction	Threshold value
Direct normal irradiance	kWh/m^2	up	2000
CSP operating temperature	°C	up	>400 °C
CSP capacity	MWe	up	5
Thermal variance of CSP	°C	down	Unknown
Distance to feedstock	km	down	Unknown
Heating value of fuel produced	MJ/kg	up	24.9
Reactor temperature variance	°C	down	Unknown
Reactor feed rate variance	kg/s	down	Unknown
Liquid fuel production	Litres/year	up	134 million
Total capital cost	$AUD	down	200 million
Operations and maintenance cost	$AUD/year	down	9.6 million

A range of technologies and sub-technologies were summarized. The most suitable combination of technologies were chosen for the Victorian conditions by system analysis. From the insights in previous chapters, a list of technical requirements for a Victorian solar-driven pyrolysis facility were tabulated in Table 4. These requirements list the essential parameters and thresholds that pertain to the Victorian environment. This table includes the units that quantify the requirements, as well as the direction they need to travel to have a positive system impact. For example, in the first entry of Table 4, DNI is measured in kWh/m^2. The direction is listed as 'up', which implies the amount of DNI should be maximized. An entry of 'down' in the direction column implies a value should be minimized.

All requirements from Table 4 were generated based off previously discussed aspects of the technology from this paper. DNI and feedstock proximity were covered in the above chapter, where it was shown that Victorian is capable of meeting both requirements. In order to reduce operating cost, the governing unit (km) should trend down. Thermal variance of CSP was listed as a requirement instead of operating temperature. This is an important requirement, as it is one of the main research bottlenecks currently plaguing the technology (Chintala, 2018). This parameter is caused by solar intermittancy. In addition to solar intermittancy, other parameters such as feed stock input rate are known to effect the operating temperature and heat rate of pyrolysis reactors. The rationale for this is that under high waste feed rates sufficient heat cannot reach be delivered, therefore having a negative impact of fuel production (Qingang et al., 2013). So alongside thermal variance, reactor feedrate variance and reactor operating temperature variance are included. These three parameters (thermal variance, feedrate variance, temperature variance) make up the control system gap that is currently missing in solar-driven pyrolysis literature. Additionally, the type of feedstock and its HHV will also impact the quantity and quality of fuel produced. Liquid product yield can vary from 22.6–62 wt% depending on feedstock (Chintala, 2018). Stable reactor feed variance is a requirement for a continuous process, as this was previously cited to be the more favourable over batch processes. Threshold values have been provided where possible for these parameters. The DNI and capacity parameters have been assigned threshold values of 2000 kWh/m^2 and 5 MWe respectively based off the previous discussion on power and capacity. Economic threshold values pertaining to fuel production, capital, and OM costs have been extrapolated from Wright et al. (2010) economic study of a fast pyrolysis biomass plant. Threshold values marked as 'unknown' are due to there not being sufficient literature or research. For example, no literature has established a minimum operational thermal variance for a large scale pyrolysis facility. The same goes for feed stock proximity, reactor temperature variance, and reactor feedrate variance. With the system requirements established, the various sub-technologies can be assessed against one another in order to determine the most suitable combination for the Victorian environment. This analysis is detailed in Table 5 below, and ranks each sub-technology within relevant categories. For example, the CSP column contains four types of technology, and are therefore ranked between 1 and 4, 1 being the technology best

Table 5
Ranking of the different technologies against the system requirements. Note that 'x' mean that the requirement does not pertain to a technology, and 'o' means that the requirement pertains to the technology, however there are too many variables involved to determine an exact ranking.

Technology/ Requirements	Direct normal irradiance	CSP operating temperature	CSP capacity	Thermal variance of CSP	Feed-stock distance	Heating value of fuel produced	Reactor temperature variance	Reactor feed rate variance	Liquid fuel production	Total capital cost	O&M costs	Total score (handicap)
CSP:												
Parabolic trough collectors (PTC)	x	3	o	=1	x	x	=1	x	o	2	2	9
Parabolic Dish Collector (PDC)	x	1	o	=2	x	x	=2	x	o	3	3	11
Fresnel reflector	x	4	o	=2	x	x	=2	x	o	1	1	8
Solar Tower Collectors (STC)	x	2	o	=1	x	x	=1	x	o	4	4	13
Feed system:												
Hopper	x	x	x	x	x	x	x	2	x	2	2	6
Screw	x	x	x	x	x	x	x	1	x	1	1	3
Conveyor belt	x	x	x	x	x	x	x	3	x	4	4	11
Pinch valve	x	x	x	x	x	x	x	4	x	3	3	10
Feedstock transportation:												
Rigid trailer	x	x	x	x	x	x	x	x	x	x	2	2
Articulated trailer	x	x	x	x	x	x	x	x	x	x	1	1
Waste type:												
MSW	x	x	x	x	x	1	2	x	1	x	x	4
C&D	x	x	x	x	x	=2	=1	x	=2	x	x	5
C&I	x	x	x	x	x	=2	=1	x	=2	x	x	5
Facility location (by region)												
City	3	x	x	x	1	x	x	x	x	x	2	6
Regional	2	x	x	x	2	x	x	x	x	x	1	5
Rural	1	x	x	x	3	x	x	x	x	x	3	7

able to meet the requirement and 4 being the least suited/unable. This analysis utilizes handicap ranking, so the lower the score a technology receives, the more suitable it is for implementation in Victoria. The handicap is calculated by adding the rows. For example, looking at the first row of Table 5 (Parabolic Trough Collectors), this would score $3 + 1 + 1 + 2 + 2 = 9$. From this requirements analysis, Fresnel reflectors are the strongest candidate of the CSP types. As described in the CSP chapter of this review, parabolic dish collectors are able to generate extremely high temperature, but are limited by cost and space requirements, while Fresnel reflectors are able to be implemented in great number at a relatively low capital and O&M cost. The feed system was ranked based off information from Fig. 3. The screw feeder was determined as the most appropriate feed technology, due to its low cost and reliability, which importantly translates to consistent feed rate. Feed stock transportation was determined solely off of running costs. As discussed in the above chapter, this means that articulated trucks will be the most cost efficient means of feed stock transportation. Waste type was ranked based on its consistency, and ability to be turned into liquid pyrolytic fuels. Ryu (2010) notes that C&D wastes are mostly incombustible and a high percentage is recycled. MSW outranks C&I waste, as it is more combustible (Hla and Roberts, 2015). Facility location was based off the three regions discussed in the previous section: city, regional, and rural. As described, Rural possesses the highest DNI, while city has the highest feed stock source density. A more detailed evaluation of each technology is given in Table 6. Overall Regional was ranked as the most appropriate location, due to its balance between DNI, and feed stock distance. Additionally, running and maintaining a waste to fuel facility close to a densely populated city would be likely to drive up O&M costs, due to higher rates, and limited space availability. Overall, this analysis shows that the most appropriate pyrolysis waste to fuel facility for Victoria will be one powered by Fresnel reflectors, with a reactor fed by a screw feeder. MSW should be the favoured feedstock type, and the most affordable means of delivery to the facility will be with articulated truck. This facility should be sited in a regional location, as this will provide the best trade-off between DNI and distance from feedstock sources. From the analysis of solar irradiance and waste generation, it has been extrapolated that the state of Victoria is a strong candidate for a commercial solar-assisted pyrolysis facility. However, based off literature review of solar-driven pyrolysis, it is apparent that key research bottlenecks must be addressed before a full-scale project can be considered. Chintala (2018) specifies the following issues (Chintala, 2018): uniform distribution of heat flux across the biomass feed inside the pyrolysis reactor, heat losses from the surface of the reactor, high wind speeds causes significant heat losses from the exposed surfaces of the reactor, high capital cost, reactor design for the effective thermochemical conversion of biomass feedstocks, pyrolysis reactor materials compatibility, variation in solar flux with respect to time throughout the day/season, the ability for pyrolysis reactor to operate under solar transience. The most notable issue from those listed are the ones that effect the operational performance of the pyrolysis reaction. Chintala suggests that an autonomous control system could solve this issue. This type of technology is viable with today's technology, and the method used could be similar to the machine learning process utilized by Islam et al. for maximum power point tracking in PV systems (Islam et al., 2018). Temperature, heating rate, feed rate, biomass particle size, and vapour residence times have a drastic effect on pyrolysis product output (Qureshi et al., 2018). These operating parameters have been found to have a drastic effect on both the quality and quantity of liquid biofuel produced from pyrolysis (Sharma et al., 2015; Akhtar and Saidina Amin, 2012). For solar-driven pyrolysis, temperature and heating rate are exogenous processes which are impossible to control. Biomass feed rate, particle size, and vapour residence times are endogenous, as it is possible to directly control these parameters. In addition to solar DNI and wind speed, relative humidity and ambient temperature have also been found to affect the performance of solar concentration technology (Kalogirou, 2004). Focusing on these exogenous and endogenous operating parameters, a system can be envisioned that optimizes the performance of a solar-driven pyrolysis reactor by forecasting the exogenous time series parameters and autonomously adjusts the endogenous ones accordingly. Forecasting time series parameters for RES systems is a well-established route for performance optimization (Das et al., 2018; Flores et al., 2012; Seyedmahmoudian et al., 2016). For solar RES systems, the two popular types of parameter forecasting are machine learning and statistical methods. It has been found that artificial neural networks (ANNs)

Table 6
Detailed evaluation of the assigned ranking from Table 5.

Relative rank from Table 5/Evaluation and data	Evaluation				
CSP:	CSP Operating temperature	Thermal variance of CSP	Reactor temperature variance	Total capital cost	O&M costs
1. Fresnel reflector 2. PTC 3. PDC 4. STC	It is apparent that point concentration systems are capable at operating at far higher temperatures than linear concentration systems (Needham, 2009), with PDCs capable of reaching 3000 Celsius, while Fresnels are only capable of operating up to 500 Celsius	Given that point concentration systems are able to achieve higher operating temperatures, logically, they should be able to better cope with days of lower solar exposure than their linear counterparts	This follows from the last requirement. Lower thermal CSP variance will lead to lower reactor thermal variance	Fresnel systems are lower in capital cost than PTCs and are more easily scaled to suit land size requirements (Cau and Cocco, 2014). PDCs are known to be expensive and incompatible with current thermal storage systems (Zhang et al., 2013). STCs are the highest costing system out of all four types of reflector assessed in this report (Elliston et al., 2016)	Fresnel technology uses simpler components than PTCs (Cau and Cocco, 2014), while point concentration systems require complex control systems (Cau and Cocco, 2014) making for higher complexity and therefore maintenance costs.
Feed system:	Reactor feed rate variance	Total capital cost	O&M costs		
1. Screw 2. Hopper 3. Pinch valve 4. Conveyor belt	Screw-type feeders are the most consistent due to their self-sealing nature and therefore ability to resist backpressures (Qureshi et al., 2018). Hopper and pinch valves are less preferable due to feed inconsistencies from rat holes and actuator problems respectively. Conveyor belt are more suited to long distance feed stock transportation (Qureshi et al., 2018)	From Qureshi et al. (2018), Screw and Hopper feed systems are low cost and energy efficient. Pinch Valve and Conveyor belt systems are cited as being the least cost and energy efficient (Qureshi et al., 2018)	Rankings based off of energy efficiency, as cited in Qureshi et al. (2018)		
Feedstock transportation:	O&M costs				
1. Articulated trailer 2. Rigid trailer	Articulated trailers are simply a more cost efficient mode of feedstock transportation. Pearman (2018) computes a cost difference of $AUD 576 per 500 km between the two				
Waste type:	Heating value of fuel produced	Reactor temperature variance	Liquid fuel production		
1. MSW 2. C&D/C&I	MSW is typically presorted into landfill, garden, and recyclable waste (Anon, 0000c) and possesses a higher concentration of degradable material than C&D	C&I and C&D outperform MSW in this requirement due to their homogeneity (Anon, 0000c), which leads to a more consistent feedstock and therefore reactor stability	Liquid fuel production would be maximized due from a higher concentration of degradable material, which can be found in MSW		

(*continued on next page*)

perform well at DNI prediction, while autoregressive methods are best for forecasting this issue. This type of technology is viable with today's technology, and the method used could be similar to the machine learning process utilized by Islam et al. for maximum power point tracking in PV systems (Islam et al., 2018). Temperature, heating rate, feed rate, biomass particle size, and vapour residence times have a drastic effect on pyrolysis product output (Qureshi et al., 2018). These operating parameters have been found to have a drastic effect on both the quality and quantity of liquid bio-fuel produced from pyrolysis (Sharma et al., 2015; Akhtar and Saidina Amin, 2012). For solar-driven pyrolysis, temperature and heating rate are exogenous processes

Table 6 (*continued*).

Relative rank from Table 5/Evaluation and data	Evaluation		
Facility location (by region)	Direct normal irradiance	Feedstock distance	O&M costs
1. Regional 2. City 3. Rural	Based on the analysis seen in Fig. 11 (Climate Change Authority, 2016) rural areas will on average have a high DNI exposure, followed by regional, then city. Looking at Fig. 8, the difference between rural and city can be up to ∼1200 kWh/m^2	From Fig. 11 analysis, it is evident cities are the best positioned for easy access to waste sources, followed by regional, then rural areas	This is based on transportation costs of feed stock within these environments. It is easier to waste streams from cities, however in terms of transportation, cities suffer greatly from traffic congestion. Distances to waste and therefore cost will be greatest with rural areas unless a pyrolysis facility is located intentionally close to a single waste site. Regional areas benefit from close proximity to waste, but with reduced traffic conditions

which are impossible to control. Biomass feed rate, particle size, and vapour residence times are endogenous, as it is possible to directly control these parameters. In addition to solar DNI and wind speed, relative humidity and ambient temperature have also been found to affect the performance of solar concentration technology (Kalogirou, 2004). Focusing on these exogenous and endogenous operating parameters, a system can be envisioned that optimizes the performance of a solar-driven pyrolysis reactor by forecasting the exogenous time series parameters and autonomously adjusts the endogenous ones accordingly. Forecasting time series parameters for RES systems is a well-established route for performance optimization (Das et al., 2018; Flores et al., 2012; Seyedmahmoudian et al., 2016). For solar RES systems, the two popular types of parameter forecasting are machine learning and statistical methods. It has been found that artificial neural networks (ANNs) perform well at DNI prediction, while autoregressive methods are best for forecasting temperature, wind, and precipitation (Marquez and Coimbra, 2011; Perez et al., 2010; Voyant et al., 2017). So, for future work in solar-driven pyrolysis systems, a forecasting model for the multiple exogenous performance parameters can be developed. The forecasted data can then be fed into a control system that will adjust the endogenous parameters to achieve optimal biofuel output. For example, when a downward trend in time series DNI is predicted, the feed rate would be decreased to compensate for the lower reactor temperature, as the feed rate affects the heat transfer inside a biomass reactor (Chintala, 2018). Implementing a control scheme capable of doing this will contribute to the negation of the impact of environmental transience on this type of RES. Before this can occur however, a model of a solar-driven pyrolysis system must be developed. There is currently no model for such a system, however the mathematics for both solar concentration and pyrolysis are very well established in literature (Abnisa et al., 2013; Agrawal, 1992; Alén et al., 1996; Anuar Sharuddin et al., 2016; Boukis, 1997; Bridgwater, 2003; Butti and Perlin, 1980; Cau and Cocco, 2014; Chintala, 2018; Chrissafis, 2009; Chuayboon et al., 2019; Chueh et al., 2010; Couper et al., 2010; Cronshaw, 2015; Deepak et al., 2016; Demirbas, 2000, 2004; Dijan et al., 2016; Douani et al., 2013; Duffie and Beckham, 2013; Elliston et al., 2016; Encinar and González, 2008; Fan et al., 2011; Gao et al., 2003b; Geoscience Australia, 2017; Solar reserve, 2017; What is Lignin?, 2016; Gharbi et al., 2011; Green and Perry, 2008; Holdren, 1991; Hoshi et al., 2005; Isahak et al., 2012; Jahirul et al., 2012; Jebasingh and Joselin Herbert, 2016; Jomaa et al., 2015; Kalogirou, 2004; Kan et al., 2016; Kayacan and Doğan, 2008; Kreith and Kreider, 1978; Kumar and Singh, 2014; Lede, 1999; Meinel and Meinel, 1976; Morales et al., 2014; Ngoh and Lim, 2016; Peterseim et al., 2013; Quoilin, 2007; Qureshi et al., 2018; Rony et al., 2018, 2019; Shafiee and Topal, 2009; Shafizadeh, 1982; Sharma et al., 2015; Smolders et al., 2006; Sobek and Werle, 2019; Sùrøm et al., 2001; Tian and Zhao, 2013; Van de Velden et al., 2010; Viikari et al., 2009; Vyazovkin et al., 2014; Weldekidan et al., 2018; Zeng et al., 2017; Zhang et al., 2013; Zhou et al., 2006; Department of the Environment and Energy, 2017; Kple et al., 2017; Needham, 2009; Pitz-Paal, 2007), so creating a model that combines the two should be a straight-forward task.

Conclusion

Solar-driven pyrolysis is a promising technology for a renewable means of converting MSW waste into liquid fuel. This study showed the combination of CSP and pyrolysis to be superior to other combinations of energy generation/biofuel production through comparative analysis of capital/OM costs, capacity, fuel type output, and energy efficiency. Mainly, pyrolysis was shown to have an advantage over processes such as gasification because of the energy density of liquid fuel per unit volume, and CSP was shown to possess high energy transfer efficiency through thermodynamic principles. By combining GIS solar data with the Victorian landfill registry, this study showed that Victoria's high magnitude of direct normal irradiance and waste sites makes it an attractive candidate for the implementation of solar-driven pyrolysis. It was stipulated that as Germany demonstrated the ability to implement CSP in an area of low DNI, Victoria should have greater locational flexibility for CSP, therefore giving greater access to waste resources. This would drive down the overhead waste transportation costs. From these assessments, a table of technical system requirements was compiled to analyse the available technology and deduce the best solution for the Victorian environment. It was found from this analysis that the combination of systems most capable of meeting the requirements would be a system located in Victoria's regions. This was because of the 1200 kWh/m^2 difference in DNI between city and rural location, where regional areas represented a good trade-off between feed stock distance and solar exposure. Fresnel reflectors would be best suited to meet the requirements because of their cost effectiveness and their operating temperature of 250–500 °C falling within the range of slow pyrolysis. MSW was decided as the most suitable waste source due to its organization and heating value. Articulated trucks for feedstock transportation was found to be the favourable due to only costing $AUD 96 per 500 km. Screw feeders were found to be preferable due to their self-sealing nature and affordability. After this systems analysis was carried out, it was then proposed that future work on solar-driven pyrolysis be based on the forecasting of performance parameters in order to increase pyrolytic fuel output, as doing so would make the technology more attractive, and therefore likely to be adopted by the Victorian energy sector. Forecasting environmental parameters with machine learning or statistical analysis is already a proven method for RES intermittency negation, so it makes logical sense that a system such as solar-driven pyrolysis would benefit in the same way. While solar-assisted pyrolysis for the production of bio-fuels is a promising technology whose key requirements are met by the Victorian climate and waste culture, there are still important technological and economic milestones that must be addressed before widespread implementation can be carried out.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The Australian Federal Government is acknowledged for supporting this work through the provision of RTP funding.

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