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Potential for energy generation from anaerobic digestion of food waste in Australia

Xian Fang Lou, Jaya Nair and Goen Ho

Abstract
Published national and state reports have revealed that Australia deposits an average of 16 million Mg of solid waste into landfills yearly, of which approximately 12.6% is comprised of food. Being highly biodegradable and possessing high energy content, anaerobic digestion offers an attractive treatment option alternative to landfilling. The present study attempted to identify the theoretical maximum benefit of food waste digestion in Australia with regard to energy recovery and waste diversion from landfills. The study also assessed the scope for anaerobic process to utilize waste for energy projects through various case study scenarios. Results indicated anaerobic digestion of total food waste generated across multiple sites in Australia could generate 558 453 dam^3 of methane which translated to 20.3 PJ of heating potential or 1915 GW$_e$ in electricity generation annually. This would contribute to 3.5% of total current energy supply from renewable sources. Energy contribution from anaerobic digestion of food waste to the total energy requirement in Australia remains low, partially due to the high energy consumption of the country. However its appropriateness in low density regions, which are prevalent in Australia, may allow digesters to have a niche application in the country.

Keywords
Anaerobic digestion, food waste, waste management, renewable energy, Australia

Introduction

Alternative waste disposal strategies to landfilling for solid waste, such as recycling for inorganic materials and composting for green waste, are becoming increasing common in Australia. However, for putrescible waste such as food waste, landfilling remains the most common practice. Approximately 2.1 million Mg of food waste is landfilled in Australia every year (ABS, 2010a). This not only consumes valuable land but also results in emissions of greenhouse gases (GHG) (Lou and Nair, 2009a). Consequently, there has been a strong push towards waste diversion from landfills in the country (ABS, 2010a). Anaerobic digestion presents a promising option for the rapid degradation of putrescible waste. It not only reduces waste volume but also helps mitigate GHG emissions, as opposed to landfilling without landfill gas capture, and can generate a source of renewable energy through biogas [a mixture of methane (CH_4) and carbon dioxide] which is the end product of the digestion process. Furthermore, with a biodegradability potential of over 90% and CH_4 yields varying from 0.35 to 0.64 m^3 kg VS^{-1} (Chynoweth et al., 1993; Mate Alvarez, 2002; Rajeshwari et al., 2001; Rao et al., 2000), food waste presents itself as an appropriate substrate for this technology.

An advantage of anaerobic digesters over alternative waste disposal and energy generation strategies is their ability to be undertaken at different scales, from micro-scale applications to centralized facilities. This is one of the contributing factors to its widespread application in various countries (Arsova, 2010; Chen et al., 2010). Despite its popularity in certain countries, such as Europe (Kelleher, 2007), China (Chen et al., 2010) and India (Klavon et al., 2011), the uptake of food waste anaerobic digestion in the decentralized or centralized form has been scarce in Australia with only a handful of centralized plants being developed in the last decade with four centralized plants in Sydney and one to be commissioned in Perth. The first Australian digester designed for food waste digestion was developed by EarthPower Technology and commenced operation in 2003. The other three digesters are operated by Global Renewables (commenced 2004), ArrowBio (commenced 2009) and AnaerCo (to be ready in 2012) (Finstein and Zadik, 2008). On the other hand, decentralized digesters remain limited and undocumented in Australia.

Despite a late start for food waste digesters in Australia, recent developments in waste management (ZeroWaste WA, 2006), climate change mitigation (DCCEE, 2010) and renewable energy policy (Commonwealth of Australia, 2010) frontiers, provide an opportunity for the possible expansion of the technology in Australia. Hence, this study aims to examine the potential of

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treating food waste using anaerobic digestion in terms of waste diversion from landfill and energy generation in Australia.

Estimating the potential energy generation from food waste digestion in Australia

Biogas generation potential through anaerobic digestion of food waste was estimated based on a derivative of Matteson and Jenkins (2007), who used the expression [Equation (1)] to approximate the potential energy derived in California. This expression is suitable for an overall approximate of energy generation for a large area. This expression was also used by Lai et al. (2009) to estimate the potential of food waste for power generation in Taiwan.

$$CH_4 = q \cdot f_{vs} \cdot b \cdot g \cdot c_{CH_4} \qquad (1)$$

where CH_4 is the volume of CH_4 produced (dam^3); q is the available amount of food waste (Mg); f_{vs} is the ratio of volatile solids to total solids (unitless); b is the volatile solids biodegradability for food waste (unitless); g is the biogas yield (dam^3 Mg VS^{-1} destroyed); C_{CH_4} is the volume concentration of CH_4 in biogas (m^3 m^{-3})

Power generation potential from the combustion of biogas associated with food waste was estimated by Matteson and Jenkins (2007) as:

$$E_{AD} = \frac{1}{3600} \cdot q \cdot f_{vs} \cdot b \cdot g \cdot c_{CH_4} \cdot Q_{CH_4} \cdot \eta_e \qquad (2)$$

where E_{AD} is the electric energy potential (MW$_e$ year^{-1}); Q_{CH_4} is the volumetric heating value of CH_4 (MJ m^{-3}); η_e is the engine generator efficiency of biogas (unitless).

Heat generation potential from the combustion of biogas associated with food waste is estimated from a derivation of Equation (2) as:

$$H_{AD} = \frac{1}{1000} \cdot q \cdot f_{vs} \cdot b \cdot g \cdot c_{CH_4} \cdot Q_{CH_4} \qquad (3)$$

where H_{AD} is the heating potential (TJ year^{-1}).

An average value, gathered from cited literature, for each parameter is provided in Table 1 to estimate the energy potential of CH_4 generated from food waste.

Food waste in Australia is generated from the municipal, commercial and industrial sectors, with the minimum quantity of putrescible waste coming from the construction and industrial sector DCCEE (2012). The quantity and composition of food waste in total landfilled solid waste, in each state and Australia as a whole are presented in Table 2 (DCCEE, 2010). These figures thus highlight the potential quantity of food waste that could be diverted from landfills in individual states.

It is interesting to note that Northern Territory (NT) is the stand-out state with the highest amount of food waste generated per capita (176 kg capita^{-1} year^{-1}) (Table 2), which is well above the national average of 92 kg capita^{-1} year^{-1}. In contrast, Tasmania (TAS) showed the lowest amount of food waste generated per capita while having the highest composition of food waste in the landfill waste stream. The lower percentage food waste in Western Australia (WA) is attributed to a larger proportion of waste deriving from the construction and demolition waste. However, the amount of food waste generated per capita remains higher than the country's average. Although the primary course of action is to continually reduce the quantity of waste entering the landfill (ZeroWaste, 2006), states are also presented with the opportunity to derive energy benefits that may be obtained through anaerobic digestion.

As a nation, Australia generates approximately 2 051 200 Mg of food waste per year (Table 2). Utilizing the Matteson and Jenkins' (2007) method, Australia offers the potential to generate 558 453 dam^3 of CH_4 which equates to 20 272 TJ year^{-1} (or 20.3 PJ year^{-1}) of heating energy or 1915 GW$_e$ year^{-1} of electricity across multiple sites and energy generation units.

Due to the Australia's high energy consumption of natural gas (1233 PJ year^{-1}) and electricity (939 PJ year^{-1}) (Commonwealth of Australia, 2011), 100% diversion of Australia's food waste into anaerobic digesters may substitute only up to 1.65 and 0.74% of Australia's entire gas and electricity requirement, respectively. With the present population size standing at 22 408 000 people, full conversion of food waste into energy would be able to provide each person with 24.9 m^3 CH_4 year^{-1} or 85.5 KW year^{-1}. Currently, renewable energies contribute 8.7 % of total energy consumption in Australia (ABS, 2010b). Assuming a 50% diversion rate of current food waste generated, this could increase

Table 1. Gathered averages for parameters presented in Equations (1) and (2).

Symbol	Value	Reference
f_{vs}	0.84	Matteson and Jenkins (2007); Lai et al. (2009) ; Zhang et al. (2007)
b	0.83	Chynoweth et al. (1993); Davidsson et al. (2007); Kayhanian (1995); Rao et al. (2000); Zhang et al. (2007)
g	0.55	Chynoweth et al. (1993); Davidsson et al. (2007); Rao et al. (2000); Zhang et al. (2007)
c_{CH4}	0.71	Davidsson et al. (2007) ; Rao et al. (2000); Zhang et al. (2007)
η	34%	Baky & Eriksson (2003); Lai et al. (2009); Matteson and Jenkins (2007)
Q_{CH4}	36.3 MJ m^{-3}	–

Table 2. Percentage and amount of food waste landfilled in each Australian's state: this also illustrates the potential of this waste source to be diverted from landfill.

State	Percentage composition of food waste in solid waste landfilled	Amount of food waste landfilled (Mg year^{-1})	Amount of food waste landfilled per person (kg capita^{-1} year^{-1})
Victoria (VIC)	11.30	617 771	111
New South Wales (NSW)	11.40	593 712	82
Queensland (QLD)	12.30	346 245	77
Western Australia (WA)	8.80	237 248	103
South Australia (SA)	12.20	152 744	94
Northern Territory (NT)	12.30	40 432	176
Tasmania (TAS)	17.50	32 826	65
Australian Capital Territory (ACT)	14.50	30 222	84
Australia	12.60	2 051 200	92

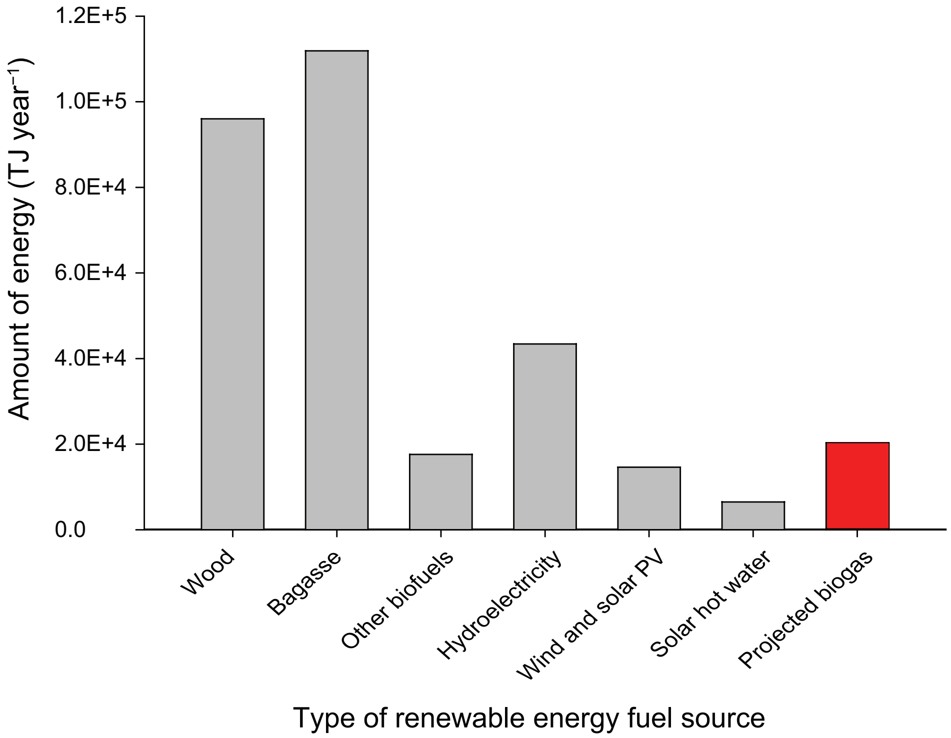

Figure 1. Comparison of current renewable energies supply and the projected energy generated from anaerobic digestion of food waste (in red).

energy generation from biofuels by approximately 19.6% and make up approximately 3.5% of total renewable energy supply (Figure 1).

It should be noted that in order to achieve the maximum of the stated benefits, good source separation of food waste is required. Any impurities from inorganic materials such as plastics and metals, commonly found in the municipal and commercial waste streams, can lead to a decrease in gas yield of up to 60% (Muthuswamy and Nemrow, 1990; Sengupta et al., 1981) and cause mechanical malfunctions (Polprasert et al., 1986). Source separation of food waste from the general waste stream might be more achievable at food industries where the majority of the waste stream is comprised of food waste as compared with an unsorted municipal waste stream.

Potential of waste diversion and energy generation for individual states

Assuming the current amount and composition of food waste generated, a breakdown of the annual potential energy generated from the anaerobic digestion of food waste for each state is presented in Table 3. Equations (1) to (3) were utilized to derive each of these values. It should be once again noted that the values presented below are the theoretical benefits that food waste digestion may offer and the actual benefits may be lesser or even wanting relative to other waste management practices.

From Table 3, it can be seen that with the exception of Victoria (VIC), the higher the population in each state, the higher the potential energy generation. However, the potential of energy generation

Table 3. Annual potential energy generation with regards to CH$_4$, heating and electrical energy generation from the diversion of food waste into anaerobic digesters.

State	Population ('000 person)	Potential CH$_4$ generation ('000 dam^3 year^{-1})	Potential of electrical energy (GW$_e$ year^{-1})	Potential of heating energy (PJ year^{-1})
VIC	5548	168.2	576.6	6.1
NSW	7239	161.6	554.2	5.9
QLD	4516	94.3	323.2	3.4
WA	2296	64.6	221.4	2.3
SA	1625	41.6	142.6	1.5
NT	230	11	37.7	0.4
TAS	508	8.9	30.6	0.3
ACT	359	8.2	28.2	0.3
Australia	22 342	558.5	1915	20.3

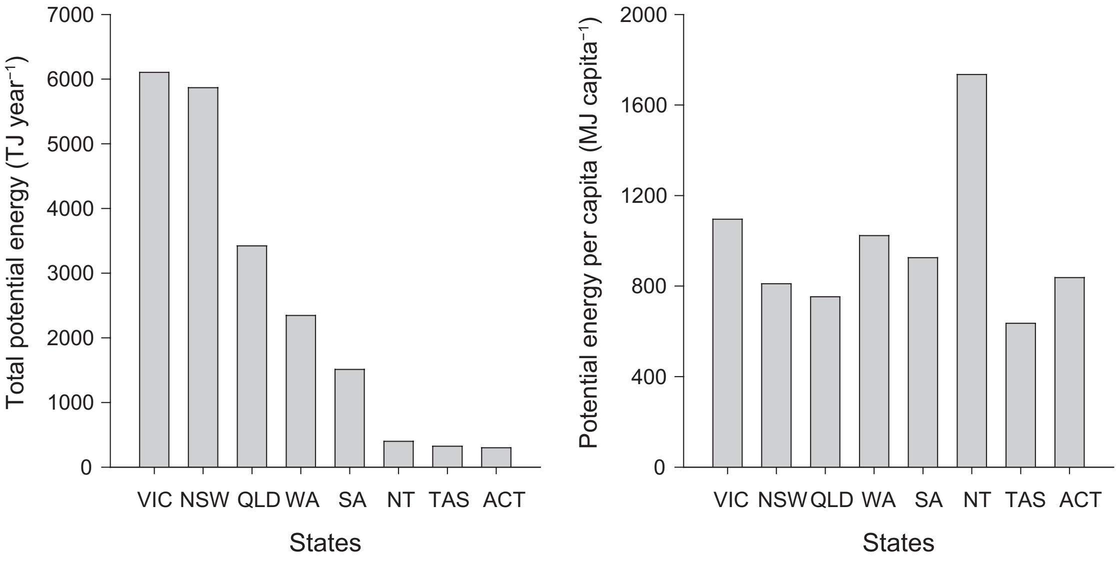

Figure 2. Total potential energy generation (left) and energy generation capita^{-1} (right) for each Australian states based on 100% diversion into landfills.

per capita does not follow the same trend owing to the differences in waste generation per capita from each state (Figure 2).

An important factor influencing the potential uptake of food waste digestion is the availability and distribution of food waste. Centralized facilities would be more feasible in metropolitan areas where there is a high population density and hence food waste density, whereas decentralized facilities would be more appropriate for low-density areas such as rural and regional Australia. Currently, the majority of Australians live in major cities, with a small percentage living in the remote or very remote regions (Figure 3).With the exception of the NT, all other states have less than 7% of their population living in remote or very remote areas, although the percentage living in regional areas are substantial for all states except the Australian Capital Territory (ACT) (ABS, 2010d). In the NT a substantial 44% of the population is living in remote or very remote communities with the remaining 56% living in the outer regional areas. The low population density of the NT (Figure 3), coupled with the high energy potential per capita (Figure 2 right) makes decentralized digestion of food waste an attractive option. This would be particular beneficial as more than 20% of the population of the NT was deemed too remote for connection to the grid (DPIFM, 2006). Conversely, it would be beneficial for high population density states such as the ACT and VIC to consider the implementation of centralized facilities to help alleviate the shortage of valuable land for landfills.

Case studies: scenarios and assessments

Realistically, not all available food waste can be recycled due to various reasons. For example, food waste composition for certain applications may not be proportionally sufficient to justify an alternative waste treatment facility. However, there remain numerous applications, which generate high quantity and composition of food waste that would justify such a facility. This section discusses the feasibility of anaerobic digesters in some of these applications using scenario analysis.

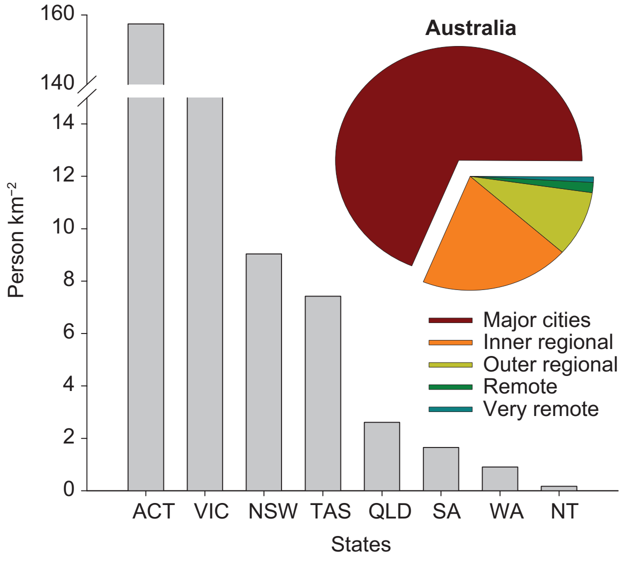

Figure 3. Population density of individual states and the areas of population distribution for Australians (Areas in Australia are classified as major cities, inner regional, outer regional, remote or very remote according to the remoteness structure under the Australian Standard Geographical Classification (ABS, 2012)).

The application of digestors for food waste treatment vary from small-scale digesters suitable for household and community levels to centralized digesters treating waste from one or several suburbs. In this section, common food waste generation facilities are taken as examples for the assessment of applications of anaerobic digestors as a waste treatment and energy recovery strategy. The scenarios will be assessed according to scale of operation: (1) decentralized household, (2) decentralized community and commercial and (3) centralized scenarios. It should be noted that the ranges of waste generated for each application vary widely and hence energy generation estimates will vary accordingly. Where possible, each case study presented in this section will be based on actual sites in Australia as an attempt to provide a realistic estimation of waste generation as best as possible.

Household scenarios

The estimations of the daily waste disposal and gas production characteristics for various Australian household sizes presented in Table 4 were based on the assumption that municipal waste production was 606 kg capita^{-1} year^{-1} (ABS, 2010c) with food waste composition of 26% (DCCEE, 2010). The daily CH_4 generations were calculated using Equation (1) from the daily amounts of food waste generated by each household.

It was calculated that a household can expect to generate 0.12 m^3 CH_4 capita^{-1} day^{-1}. Surveys indicated that an average household in Australia uses approximately 21 000 MJ of gas year^{-1}, which roughly equates to 1.48 m^3 CH_4 day^{-1} (Holloway and Bunker, 2006). This means a domestic digester will be able to provide 21.1% of the total gas requirements of a household.

Reported biogas consumption for cooking varied between 0.30 and 0.41 m^3 capita^{-1} day^{-1} with an average consumption of 2.9 m^3 day^{-1} of biogas for a typical family of six (NAS, 1977). However, the consumption rate will depend on many factors such as country, economic growth, the family lifestyle, etc. For example, 3 m^3 of gas was considered to be sufficient to meet the cooking and lighting needs of a family of five in Kenya, which translated to 0.6 m^3 biogas capita^{-1} day^{-1} (Mugo and Gathui, 2010). Ilori et al. (2000) reported the average cooking energy demand in Nigeria was 0.26 m^3 biogas capita^{-1} day^{-1}, and Nigaguna (2007) reported 0.85 m^3 biogas day^{-1} for a family in India. Calculations of the typical yield of a domestic household in Australia (0.12 m^3 CH_4 capita^{-1} day^{-1}), suggests that the average yield from a domestic digester would not be able to provide a family with its entire energy requirement. This can be seen through Ferrer et al. (2011) who reported that household digesters were able to ensure 2 to 3 h of cooking, corresponding to 40 to 60% of fuel requirements for cooking in families of three to five members. Voegeli et al. (2009) also estimated that 2 kg kitchen waste produced by a household of five members would be able to generate 0.2 m^3 biogas allowing 45 min of burning, which represented a third of the average cooking time for a family in Tanzania.

Table 4. CH4 generation and application potential of digesters in various household sizes.

	Household size (person^{-1})				
	1	2	2.6[a]	4	5
Daily FW generation (kg day^{-1})	0.43	0.86	1.12	1.73	2.16
Daily CH_4 generation (m^3 day^{-1})	0.12	0.24	0.31	0.47	0.59
Hours of burning from 1 stove (h day^{-1})[b]	0.26	0.52	0.67	1.03	1.29
Lighting via 1 lamp (h)[c]	3.01	6.03	7.84	12.05	15.07

[a] Average Australian household size of 2.6 person (ABS, 2010a).
[b] Assume gas consumption rate 0.25 m^3 CH_4 h^{-1}.
[c] Assume gas consumption rate of 0.039 m^3 CH_4 h^{-1}.

Alternatively, the gas can be used for lighting purposes where approximately 3 h of lighting per person could be provided using a biogas lamp (Table 4), assuming a gas consumption rate of 0.039 m^3 CH_4 h^{-1}. This would be particularly attractive to regions not connected to the electrical grid and would be less costly than a household-level generator. Although provision of lighting can help improve living standards in the household, fuel consumption to provide illumination via biogas lamps is considerably less efficient as compared to electric lamps (Dutt, 1994). Therefore, it would be preferable to utilize biogas generated from household-scale digesters for cooking purposes, unless lighting needs are imperative.

Community and commercial scale scenarios

Waste generations from community applications are similar to those from the domestic sector and are similarly classified under municipal solid waste while commercial waste belongs in the sub-category of commercial and industrial waste. The diverse nature of waste generation by the commercial sector is important when examining waste generation. Some operations such as fruit and vegetable wholesalers can produce approximately 97% food organic whereas others such as hotels and restaurants can have 60 to 70 wt.% food organic but have a more diverse mixture of waste types (Waste Audit & Consultancy Services, 1999). Therefore, general statements on the management of food waste from the commercial and industrial sector will be inaccurate. However, there are many businesses for which anaerobic digestion may prove to be a beneficial technology. In this section, scenarios in which anaerobic digestion may be appropriate such as lifestyle village, a mine site village, a prison facility and a university student complex are presented. Commercial application presented included a restaurant, a supermarket, a food supplier and a motel. The results of digester performance for community and commercial-scale scenarios are illustrated in Table 5.

From the case studies, it appears that decentralized systems would be preferable for small-scale applications such as household and community applications, and for commercial activities which generate a high percentage of putrescible waste. It is recommended that smaller commercial applications such as restaurants and supermarkets utilize the biogas generated directly for heating purposes instead of electricity generation. This is mainly attributed to the disproportionately higher electricity demands from these facilities as compared to possible energy generated from the digester. Using the example provided in Table 5, the average of a large, medium and small restaurant will generate 76 kg day^{-1} which equates to 751.1 MJ day^{-1}. Using a six-burner commercial gas cooker with an energy consumption of approximately 282 MJ h^{-1}, this would allow a restaurant to utilize all gas stoves continuously for roughly 2.7 h which is a reasonable supplement to their daily gas use. Furthermore, the restaurant would be able to save on waste disposal costs.

As for larger applications such as a prison facility, a motel or a mine site village, opportunities for electrical generation becomes feasible. As seen in several market digesters in India, electricity generation was often attempted when digesters exceeded 25 m^3 (Heeb, 2008). Heeb documented the lighting of 12 electrical lamps for 3.5 h day^{-1} based on a daily load of 86 kg day^{-1} fish waste. Due to the high rate of electrical consumption by larger applications and the need for a constant reliable supply of electricity, it would be unfeasible for the digester to be the standalone energy source. However, the amount of waste diverted from landfill and external benefits continues to make the digester an attractive option.

Community scenario I: lifestyle village. A sustainable lifestyle village located in the south of WA will be used to illustrate a scenario in which a digester may be operated to serve a community. This lifestyle village is situated near an estuary with a capacity of approximately 1300 residents in 389 tenements (Lou and Nair, 2009b). The village, spreading over 16 acres of farmland, has implemented an onsite waste management strategy in which recyclables are collected at an asset recovery centre, green waste are composted and the rest are brought to the landfill. The village generates approximately 24.9 Mg of organic waste per year of which 10.8 Mg comprises food waste.

Calculations showed the lifestyle village would be able to generate 8.1 m^3 CH_4 day^{-1}. The villagers may choose to either utilize this CH_4 for cooking/heating purposes or to generate electricity, the latter of which translated to 27.6 kW day^{-1}. Logistically, dividing the gas produced to each household in the village would not be feasible. Unless the gas is used at a central facility, it would be more convenient to utilize the gas for electricity generation to power street lamps instead. Considering the biggest power cost for councils is street lighting coupled with the recent 30% spike in street lighting tariffs in the 2011 state budget in Western Australia; having an alternative source of power for street lighting would be an attractive option (Thomas, 2011). Assuming installation of 80 W florescent street lamps, the digester will be able to power 34 lamps for 10 h (between 2000 and 0600 h) each day. With the current street lighting tariffs ($0.4596 day^{-1} for a conventional 80 W mercury vapour lamp with a dawn switch off plan) (DoF, 2012), this would amount to an annual savings of AU$5703 for the village. In this case study, the sustainable village is located near the estuary, hence extra caution will have to be taken with regards to effluent management. As seen in previous studies (Burke, 2001; Heeb, 2009), effluent quality remains high in nutrients and chemical oxygen demand. As a result, it would be recommended for effluent to be released into the sewage instead of applying it on land to prevent groundwater or estuary contamination.

Community scenario II: university residential complex. The second scenario involves a university-owned residential complex, also known as a student village. It provides accommodation and three daily meals to the residents, seven days a week. A detailed waste audit was performed in the kitchen and the cafeteria and it was found that the average food waste generated in the kitchen was approximately 35 kg day^{-1} and the cafeteria generated approximately 81 kg day^{-1} from 803 students, totally 116 kg day^{-1} (Burgess et al., 1992).

Calculations revealed CH_4 generation of 31.6 m^3 day^{-1}, all cooking requirements are centralized in the kitchen area. Hence, the gas produced can be used for direct cooking purposes by the kitchen staff. Although the gas generated is insufficient to cater for all gas requirements of the kitchen; assuming a gas consumption rate of 45 MJ h^{-1} for a commercial cook top, the digester would be able to provide sufficient gas to power three such burners for 8.5 h each. Alternatively, 108.3 kW of electricity can be generated per day to power 135 lamps (assuming 80 W mercury vapour lamps) to light the walkways of the student village for 10 h each day between 2000 and 0600 h. With all food preparation and dishwashing performed by the kitchen staff, scrapping all uneaten food into a particular bin for use in the digester would be logistically feasible to organize and operate each day.

Table 5. Performance of community and commercial scale case studies in Australia.

Lifestyle village		Mine site village	
Case study overview Lifestyle village located in Mandurah, housing approximately 1300 residents or 389 tenements (Lou and Nair, 2009b)		Case study overview CloudBreak mining village in Western Australia with approximately 1300 workers on site each day (Nair et al., unpublished, 2008)	
Description	Unit	Description	Unit
Food waste generation (kg day^{-1})	29.6	Food waste generation (kg day^{-1})	807
CH_4 generation (m^3 day^{-1})	8.1	CH_4 generation (m^3 day^{-1})	219.7
Heating value (MJ day^{-1})	292.6	Heating value (MJ day^{-1})	7975.5
Electricity generated (kW_e day^{-1})	27.6	Electricity generated (kW_e day^{-1})	753.2
Prison facility		University student complex	
Case study overview Prison facility located in Western Australia metropolitan accommodating approximately 820 inmates at any given time (Lou and Nair, 2009c)		Case study overview University residential complex with an attached kitchen providing accommodation and three daily meals to its 803 students every day of the week (Burgess et al., 1992)	
Description	Unit	Description	Unit
Food waste generation (kg day^{-1})	1364	Food waste generation (kg day^{-1})	116
CH_4 generation (m^3 day^{-1})	371.4	CH_4 generation (m^3 day^{-1})	31.6
Heating value (MJ day^{-1})	13 480.3	Heating value (MJ day^{-1})	1146.4
Electricity generated (kW_e day^{-1})	1273.1	Electricity generated (kW_e day^{-1})	108.3
Restaurant		Supermarket	
Case study overview Average of a large, medium and small size restaurant (Newell et al., 1992)		Case study overview Average of three supermarkets belonging to Woolworth and IGA (Newell et al., 1992)	
Description	Unit	Description	Unit
Food waste generation (kg day^{-1})	76	Food waste generation (kg day^{-1})	248.2
CH_4 generation (m^3 day^{-1})	20.7	CH_4 generation (m^3 day^{-1})	67.5
Heating value (MJ day^{-1})	751.1	Heating value (MJ day^{-1})	2451
Electricity generated (kW_e day^{-1})	70.9	Electricity generated (kW_e day^{-1})	231.5
Grocery distributor		Motel	
Case study overview Grocery distributor generating 16 Mg raw food waste year^{-1} (Lott, 2010).		Case study overview 80 rooms capacity motel with an average occupancy of 58.5% (ABS, 2011)	
Description	Unit	Description	Unit
Food waste generation (kg day^{-1})	43.8	Food waste generation (kg day^{-1})	70.5
CH_4 generation (m^3 day^{-1})	11.9	CH_4 generation (m^3 day^{-1})	19.1
Heating value (MJ day^{-1})	432.9	Heating value (MJ day^{-1})	693.3
Electricity generated (kW_e day^{-1})	40.9	Electricity generated (kW_e day^{-1})	65.5

Commercial scenario I: motel in regional Australia. The first commercially operated scenario presented here is an 80-room capacity small motel. A motel was chosen as they, together with similar type establishments such as private hotels, guesthouses and caravan parks, represent the bulk of tourist-based accommodation – approximately 57% out of a total of 4216 establishment of hotels, motels and serviced apartments in Australia (ABS, 2011). Anaerobic digesters are probably less suitable for hotels and resorts (19%) in comparison with smaller hotels and motels for a number of reasons. Firstly, hotels and resorts tend to have higher room capacities and hence higher waste generation which require large digesters. This is likely to pose space availability issues due to the prime locations of larger hotels and resorts. In contrast, motels, guesthouses and caravan parks are smaller in operation and they operate in abundance in regional Australia where land is more readily available. The average annual occupancy rate for motels and guesthouses is 58.5% although the occupancy rate, and hence waste generation, varies with season. Australian surveys by the Florida Energy Extension Service (undated) and Sustainability Victoria (2006) found that a hotel generates an average of 0.26 to 12.92 kg of waste per room with an average of 11% food waste, and a national survey performed in Ireland estimated an average of 20.4 kg food waste generation per bed night sold per week (DEHLG, 2009). Due to the large variation in the available data, an average of 1.5 kg food waste per room was used for energy estimation purposes.

Calculations showed that the motel can expect to generate 19.1 m^3 CH_4 day^{-1} which equates to 693 MJ day^{-1} or 65.5 kW day^{-1}. While statistics with regards to energy consumption of Australian hotels are available (City of Melbourne, 2007; Commonwealth of Australia, 2002), there are no available statistics with regards to motels/guesthouse. Surveys from the Commonwealth of Australia (2002) revealed that energy consumption has a strong correlation with accommodation type and suggested a benchmark estimate of 35 000 MJ $room^{-1}$ $year^{-1}$ or 750 MJ m^{-3} $year^{-1}$ for service-orientated accommodations (hotels and resorts) and 95 000 MJ $room^{-1}$ $year^{-1}$ or 1050 MJ m^{-3} $year^{-1}$ for business hotels. In contrast, a survey performed in New Zealand found that the average energy use of purpose-orientated accommodation (motels, guesthouse, caravan parks) were 5122 MJ $room^{-1}$ $year^{-1}$ or 323 MJ m^{-3} $year^{-1}$ (Becken, 2000). The same survey found that New Zealand hotels consumed an average of 730 MJ m^{-3} $year^{-1}$, which was similar to that reported in the Australian survey; hence the average energy use for motels can be used with confidence (Becken, 2000). This highlights the difference between energy consumption and the type of accommodation. It was also found that 33% of the total energy consumption of purpose orientated accommodation was from gas consumption and 66% from electricity. Thus, assuming an energy consumption of 5122 MJ $room^{-1}$ $year^{-1}$, utilizing the biogas for heating can replace 62% of the motel's gas requirements (Commonwealth of Australia, 2002). Alternatively, gas can be used for electricity generation to help supplement purchased grid electricity. Assuming an energy consumption of 5122 MJ $room^{-1}$ $year^{-1}$, of which 66% is utilized from electricity; this equates to an energy requirement of 949 KW $room^{-1}$ $year^{-1}$. With a potential electricity generation of 65.5 kW day^{-1}, the digester will be able to supplement a maximum of 31.5% of the motel's total electricity demand.

A digester may be especially beneficial for operations in regional Australia where waste management services may not be as efficient as that available in the metropolitan region. Having an alternative source of energy can also serve as a back-up energy provider in case of a power blackout. Out of the 4216 temporary accommodation type facilities operating in Australia, around 60% of all international and domestic visitors' nights in Australia are spent outside capital cities (Prosser et al., 2000); thus creating a potentially large scope for such applications in purpose-orientated accommodation such as motels, guesthouses and caravan parks operating in regional Australia.

Commercial scenario II: grocery distributor. Due to a lack of data with regard to waste generation from an Australian food wholesaler, a case study from a grocery wholesaler from the Portland metropolitan area in Oregon, United States, will be used (Lott, 2010). At this grocery wholesaler with 86 employees, a total of 812 Mg waste is produced annually, 16 Mg of which is comprised of raw food. On-site observations suggest fruits and vegetables comprised the majority of the raw food stream. A daily food waste production of 43.8 kg day^{-1} (Lott, 2010) would result in 27.2 m^3 CH_4 generated per day, which can be used for heating or electricity generation purposes. For grocery distribution-type operations, the majority of energy consumption is derived from electricity instead of gas usage where the primary energy consumption by end use is the refrigeration system followed by lighting then space heating purposes, the last of which uses gas (E Source Companies, 2002). Assuming the biogas generated is used for space heating purposes, 988 MJ of gas can be expected each day; alternatively, 93.3 kW day^{-1} of electricity may be generated.

Assuming an average waste bulk density of 71.2 kg m^{-3} (Newell et al., 1993), and six operating days, the wholesaler would expect to generate an average of 537 L of raw waste per day. Although retail vegetable waste can be a cheap source of feedstock, the Waste Management Board of Australia discourages this practice due to risks to the stock or public (Zero Waste, 2006) and any food waste generated by the facility should be removed from the site daily. Based on bin fees and charges of a Perth metropolitan council (City of Melville, 2012), this would amount to an approximate annual savings of AU$6024. Gas savings coupled with savings from waste collection would amount to AU$8161 $year^{-1}$. Despite these savings, it has been reported that food waste disposal for grocery distributors accounts for approximately 0.5% of total variable costs making it a relatively lower priority when compared to other cost drivers such as labour and energy cots (Lott, 2010). Therefore, in order for such an installation to be successful, it would require an alternative push factor such as acting in accordance with the company's sustainability policies. In addition, to ensure efficient digester performance, it was generally found that intensive education programmes were necessary to control contamination – as waste needs to be source separated. This would be especially challenging for a range of reasons, such as time, space, high staff turnover, language/cultural barriers, etc (Waste Audit & Consultancy Services, 1999).

Centralized scenarios

Table 6 provides the results of two case studies representing centralized plants. The first case study represents the town of Port Hedland, the largest town in the Pilbara region of Western Australia, with a population of approximately 14 000 residents or 6000 tenements. A waste audit of two hundred 240 L domestic garbage bins revealed the total putrescible waste generated was 19.06 kg $household^{-1}$ $week^{-1}$, which constituted 56.6% of the total domestic waste generated by weight (Dallywater Consulting, 2005). Currently, all waste generated at the town of Port Hedland are directed to the local landfill.

Calculations suggest source separation and treatment of food waste from the municipal solid waste stream can help divert 12 949 kg day^{-1} from the local landfill. Anaerobic digestion of this waste can generate 3525 m^3 CH_4 day^{-1}, which is able to generate

Table 6. Performance of centralized anaerobic digesters: case studies in Australia.

Rural town site	
Case study overview The town of Port Hedland has approximately 14 000 residents or 6000 tenements within three town sites (Dallywater Consulting, 2005)	
Description	Unit
Food waste generation (kg day^{-1})	12 949
CH_4 generation (m^3 day^{-1})	3525
Heating value (MJ day^{-1})	127 973
Electricity generated (kW$_e$ day^{-1})	12 086
Metropolitan council	
Case study overview Kerbside collection from a town council in Tasmania of approximately 38 714 tenements (RPDC, 2006)	
Description	Unit
Food waste generation (kg day^{-1})	20 821
CH_4 generation (m^3 day^{-1})	5669
Heating value (MJ day^{-1})	205 772
Electricity generated (kW$_e$ day^{-1})	19 434

approximately 12 MW$_e$ day^{-1} or 2 kW person^{-1} day^{-1}. Assuming an operational electricity consumption of 180.1 MJ Mg^{-1} digested and an operational diesel consumption of 0.020 L Mg^{-1} digested in a centralized digester (Baky and Eriksson, 2003), this would amount to an approximate operational requirement of 3313 MJ day^{-1} which represented 2.6% of the total output energy.

The second case study represents a council within the metropolitan region in Tasmania. This particular metropolitan council receives approximately 21 Mg waste day^{-1} from 38 714 tenements, generating 5669 m^3 CH_4 day^{-1} and an output of 19.4 MW$_e$ day^{-1}, which equates to approximately 1.8 kW person^{-1} day^{-1}. Both results from the two centralized case studies are comparable to OFMSW digesters in Austria and Finland where the former is a 750 m^3 plant producing an average of 1845 m^3 CH_4 day^{-1} (Illmer and Gstraunthaler, 2009) and the latter being a 1500 m^3 plant generating 5500 m^3 CH_4 day^{-1} at mesophilic conditions (Rintala and Jarvinen, 1996). Unlike the decentralized digesters discussed in the previous sections, centralized digesters require a significantly higher capital, operational and maintenance cost. In addition to the high capital cost, the connectivity of such towns and councils to the electrical and gas grid coupled with the current low fuel cost may be a major inhibiting factor with regard to the uptake of the technology in the area. Furthermore, with regards waste collection from a large demographic, a comprehensive and efficient method of waste separation and collection would be required in order to ensure an efficient digestion process. The large quantities of effluent discharge would also be a separate management issue.

Economic considerations

The cost of installing, operating and maintaining a digester is one of the major factors which determine the feasibility of such an application. Due to the lack of data in Australia, economic data from other similar income brackets as Australia has been used. The main costs of a digester are the capital cost, project development cost and operational cost. Capital costs include equipment, landscaping and construction work, which is greatly dependent on the scale and technicality of the plant. A survey by British Biogen (2000) indicated capital cost values between AU$6200–14 430 per kW$_e$ of electricity generating capacity. The same report stated a small continuous stirred tank reactor plant (150 m^3) could cost AU$124 000–144 300 while a large centralized plant (10 000 m^3) could cost AU$6.2–8.2 million (British Biogen, 2000). A 416 m^3 farm-based anaerobic digester located in Texas installed with heat exchangers, a mixer and a 100 hp engine coupled to a 65 kW generator incurred an investment cost of AU$149 300 and an annual operating cost of AU$24,413 compared to an economic benefit of AU$9600 (Engler et al., 2003). However, for small-scale plants, such as household and community plants, a simple low-cost digester can be constructed cheaply. A feasibility study of a community-based, fixed-dome digester of 9 m^3 fed with food waste in Melbourne, Australia reported an investment cost of AU$3000 and labour cost of AU$2000 (Hessami, 1996). Levis et al. (2010) reported the cost of operating a centralized anaerobic digestion is between AU$77 and AU$140 Gg^{-1} of capacity in the United States whereas British data found the cost to vary between AU$18 720–26 735 year^{-1} for a farm-scale digester and more than AU$206 000 year^{-1} for centralized plants. This is comparable to mass burn waste-to-energy facilities which cost between AU$77 and 190 per Gg of capacity (Levis et al., 2010).

In comparison to digester cost, landfilling cost in Australia is significantly lower. In 2005, the Waste Management Association of Australia (WMAA, 2006) estimated the private cost of a large best practice landfill in an Australian capital city at around AU$25 Gg^{-1} and Wright Corporate Strategy (2009) placed a value at around AU$50 Gg^{-1}; where private cost includes the cost for landfill establishment, operation and post close management. However, the private cost for smaller landfill sites tend to be higher, for example, AU\$40 Gg^{-1} for the Cairncross landfill in Hastings Council, and AU\$40–50 Gg^{-1} at the landfill sites in Great Lakes Council (IEC, 2004). The private cost of landfills decreases exponentially with the increase in the amount disposed, with a sharp decrease at the size of approximately 200 Mg $year^{-1}$ (BDA Group, 2009). However, the full cost of disposing putrescible waste to landfills in Australia, should include the costs of greenhouse gas emissions, other atmospheric emissions, leachates and dis-amenity, which brings the cost to AU\$40–100 Gg^{-1} (BDA Group, 2009). Regardless, the cost of landfilling remains lower in comparison with centralized digesters. Furthermore, the WMAA has suggested that landfills should not be at the base of the waste hierarchy if their private plus environmental costs are less than alternative strategies (WMAA, 2006), making it challenging to justify the construction of a centralized plant financially.

However, with respect to simple decentralized digesters, the capital and operating cost will be vastly reduced due to the simplicity of the system, built without continuous control and minimal mechanical parts. Murphy (2004) found that a low-cost digester incurred approximately 4 to 7.5% of the capital cost for a farm-scale plant, as there are no moving parts and little operating labour. Utilization of the generated gas can save AU\$3.50 GJ^{-1} of otherwise grid supplied gas. Furthermore, the cost of installing appropriate low-cost digesters, in inaccessible parts of rural and/or remote Australia would be most likely cheaper than operating a small-scale landfill. Regardless, as adeptly pointed out by Wilkinson (2011), although there is considerable application of small and centralized digesters in Australia, the emergence of new incentives to encourage such investment is necessary to propel its further adoption.

Conclusion

Anaerobic digestion offers an alternative strategy to landfilling of food waste in Australia. A potential of 2 051 200 Mg $year^{-1}$ of food waste may be diverted from landfills in Australia into anaerobic digesters offering the opportunity for energy recovery as heat and/or electricity and to mitigate greenhouse gas emissions. Anaerobic digestion of food waste generated in Australia could potentially produce 558 453 dam^3 CH_4, which can generate approximately 20.3 PJ $year^{-1}$ of heating potential or electrical generation amounting to 1915 GW_e $year^{-1}$ across multiple sites and energy generation units. Due to the high energy demands in many Australian applications, the percentage energy contribution from anaerobic digestion remains low. Fifty percent diversion of total food waste into energy recovering digestion facilities would be able to contribute to 3.5% of total current energy supply from renewable energy sources. Applications of decentralized facilities would also be able to utilize digesters' energy as a supplementary source of fuel only but not exclusively. However, the availability of such systems would be particularly beneficial to rural and remote communities, where 31% of Australians reside, where connection to waste disposal and energy systems are limited. For the further expansion of food waste digesters in the country, appropriate policies, governmental incentives and low capital costs would be required. Effective source separation of waste and effluent management would also need to be in place to ensure efficient operations and minimal adverse environmental impact from the operation of the digester, respectively.

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