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ORIGINAL RESEARCH

# Energy potential from the anaerobic digestion of food waste in municipal solid waste stream of urban areas in Vietnam

**Hoa Huu Nguyen · Sonia Heaven · Charles Banks**

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**Abstract** Anaerobic digestion (AD) was introduced in Vietnam more than 10 years ago, but at a small scale to deal with agricultural wastes, manure, etc. Despite its many advantages, AD does not yet make a significant contribution to resolving Vietnams urban waste issues due to a lack of information, data and experience. This paper, using an energy model of food waste digestion, provides a usable source of information regarding energy potential of food waste generated from urban areas in Vietnam in forms of electricity, heat, and upgraded biogas under two different scenarios. Results show that if food waste is separated from the municipal solid waste (MSW) stream and sent to AD plants, total available energy equivalent each day is about 19, 20 and 45 GWh in 2015, 2020, and 2025, respectively. This could contribute between 2.4 and 4.1 % of the electricity demand of Vietnam, as well as double this amount of energy in the form of heat. Alternatively, upgraded biogas could contribute approximately 2.2–4.7 % of fuel consumption for transportation. This suggests AD is a promising method to treat MSW in cities, especially when considering the problematic aspects of other current waste disposal methods such as: landfilling, composting and, incineration.

**Keywords** Anaerobic digestion · Food waste · Aspen Plus · Energy · Biogas · Vietnam

H. H. Nguyen (✉) · S. Heaven · C. Banks
Water and Environmental Engineering Group,
Faculty of Engineering and the Environment,
University of Southampton, Southampton, UK
e-mail: hhn1g10@gmail.com

H. H. Nguyen
University of Civil Engineering, Hanoi, Vietnam

## Introduction

Urban waste generation and disposal are a growing global issue, as more people are moving from rural areas into cities. In Vietnam, the generation of MSW is growing rapidly, in parallel with urbanisation. The composition of MSW is mainly food waste which is a highly biodegradable material and can be digested with AD to produce biogas. This can then be used to generate heat, electricity, and biofuels. However, in Vietnam food waste is mostly treated with other components in the MSW stream by landfilling. The disadvantages of this treatment can be clearly seen: direct landfilling of MSW has been known to create lasting detrimental impacts to the environment (emissions to the atmosphere, hydrosphere, risk in landfill stability, and scarcity of land). In comparison AD is a better method to treat biogenic wastes from an ecological and economic point of view. It is also receiving increased attention as a promising option for energy recovery to help mitigate against energy shortages. However, applying AD technology has been neglected by the Vietnam government when formulating national strategies to deal with MSW problems due to a lack of information, data, and experience. To date, sources of information about the achievable energy from food waste created in cities in Vietnam using AD technology is unavailable. The purpose of this paper, hence, is to provide estimates of energy potential from food waste in the municipal solid waste stream of urban areas in Vietnam through AD in forms of heat, electricity, and upgraded biogas using an energy model developed at the University of Southampton, UK.

Results from estimations can be used as a source of data for evaluation of the AD method as a treatment of food waste in MSW streams from the energy recovery point of view. Furthermore, it can help Vietnam government and industry decision makers to establish more effective and sustainable MSW management strategies.

## Background

### Population growth and increased urbanisation in Vietnam

Urbanisation in Vietnam has been increasing rapidly along with the country's economic growth. In 2000, the number of cities and towns in Vietnam was 649 but this has increased to 715 in 2005 and 755 in 2010. The growth in the number of people moving from rural to urban areas is the main driver in the expansion of Vietnams urban population. As of 2009, the urban population was 25.59 million, accounting for 29.74 % of the total population; this expanded to 26.22 million (30.17 %) a year later.

According to MONRE [1], it has been estimated that in 2025 the urban population in Vietnam will double to 52 million, accounting for 50 % of Vietnams total population. This rapid urbanisation has put pressure on the government in dealing with environmental problems, including solid waste management in cities; and this is exacerbated by the limited space for treatment of wastes by traditional methods. For Vietnam to develop sustainably more effort is required to solve this challenge.

### Quantity and composition of MSW in Vietnam

According to recent reports, urban areas currently contain 30 % of the country's population but produce about 42–46 % of total solid wastes. The waste is mainly generated from households, buildings, commercial activities, and other sources similar to households; from commercial enterprises such as offices, hotels, retail, institutions; and from municipal services such as street cleaning, etc. The municipal waste generated daily in Vietnam from 2007 to 2010 is presented in Table 1 [1].

The proportion of food waste can be estimated based on the municipal waste generation rate, population growth in urban areas and the organic fraction. Table 2 shows estimates for the predicted generation of food waste in cities for 2015, 2020 and 2025.

MSW in Vietnams urban areas is mainly composed of food waste, paper, plastic, wood, metal, and glass, with some hazardous household waste such as electric light bulbs, batteries, etc. [1]. Composition of MSW from some of the main cities in Vietnam between 2009 and 2010 is presented in Table 3. The data have been adapted from JICA [4] and MONRE [1]. As can be seen, food waste accounts for a very large proportion of the MSW stream, ranging between 54 and 77 % depending on the city.

**Table 1** MSW generation in Vietnam from 2007 to 2010

| Contents | 2007 | 2008 | 2009 | 2010 |
|---|---|---|---|---|
| Urban population (million) | 23.80 | 27.70 | 25.50 | 26.22 |
| % of Vietnam's population | 28.20 | 28.99 | 29.74 | 30.17 |
| Municipal waste generation rate (kg $cap^{-1}$ $day^{-1}$) | ~0.75 | ~0.8 | 0.95 | 1.0 |
| Total MSW per day (tonnes $day^{-1}$) | 17,682 | 20,849 | 24,225 | 26,220 |
| Total food waste per day[a] (tonnes $day^{-1}$) | 10,945 | 12,905 | 14,995 | 16,229 |

[a] Estimated from data provided by the MONRE [1]

**Table 2** Estimation of MSW and food waste generation in Vietnam for the 2015, 2020 and 2025

| Contents | 2015 | 2020 | 2025 |
|---|---|---|---|
| Urban population (million)[a] | 35 | 44 | 52 |
| % of Vietnam's population | 38 | 45 | 50 |
| Municipal waste generation rate (kg $cap^{-1}$ $day^{-1}$)[b] | 1.2 | 1.4 | 1.6 |
| Total MSW per day (tonnes $day^{-1}$) | 42,000 | 61,600 | 83,200 |
| Rate of MSW collected (% of total MSW) | 85[c] | 90[c] | 100[d] |
| Total MSW collected per day (tonnes $day^{-1}$) | 35,700 | 55,440 | 83,200 |
| Total food waste collected per day (tonnes $day^{-1}$)[e] | 21,420 | 33,264 | 49,920 |

[a,d] Data taken from the GWP [2]

[b] According to the MONRE [1]

[c] According to the GWP [3]

[e] Assumed that food waste fraction in MSW stream is 60 %

### The problems with landfilling

One of the most common treatment methods which is applied widely in cities across Vietnam to deal with almost all types of MSW is landfilling. It is considered the simplest, and in many cases the cheapest, method of disposal. The stabilising solid waste produces leachate and landfill gas which can be used for heat and electricity generation. This process has many significant economic and environmental problems, however, including: limited space for landfill sites; cost of waste burial; cost of transporting the waste; the contamination of groundwater with pollutants; and the emission of greenhouse gases to the atmosphere [7]. Due to space limitations landfill sites will have to be located further from the cities, considerably increasing transportation costs.

**Table 3** Composition of MSW from some of the main cities in Vietnam 2009 - 2010

| Components | Hanoi (Nam Son) | Hanoi (Xuan Son) | Haiphong (Trang Cat) | Haiphong (Dinh Vu) | Hue (Thuy Phuong) | Danang (Hoa Khanh) | HCM (Da Phuoc) | HCM (Phuoc Hiep) | Bacninh (Ho) | Average |
|---|---|---|---|---|---|---|---|---|---|---|
| Food waste[a] | 53.81 | 60.79 | 55.18 | 57.56 | 77.1 | 68.47 | 64.50 | 62.83 | 56.9 | 61.9 |
| Paper | 6.53 | 5.38 | 4.54 | 5.42 | 1.92 | 5.07 | 8.17 | 6.05 | 3.73 | 5.20 |
| Textile | 5.82 | 1.76 | 4.57 | 5.12 | 2.89 | 1.55 | 3.88 | 2.09 | 1.07 | 3.19 |
| Wood | 2.51 | 6.63 | 4.93 | 3.70 | 0.59 | 2.79 | 4.59 | 4.18 | – | 3.74 |
| Plastic | 13.57 | 8.35 | 14.34 | 11.28 | 12.47 | 11.36 | 12.42 | 15.96 | 9.65 | 12.15 |
| Leather and rubber | 0.15 | 0.22 | 1.05 | 1.90 | 0.28 | 0.23 | 0.44 | 0.93 | 0.20 | 0.60 |
| Metal | 0.87 | 0.25 | 0.47 | 0.25 | 0.40 | 1.45 | 0.36 | 0.59 | – | 0.58 |
| Glass | 1.87 | 5.07 | 1.69 | 1.35 | 0.39 | 0.14 | 0.40 | 0.86 | 0.58 | 1.37 |
| Porcelain | 0.39 | 1.26 | 1.27 | 0.44 | 0.79 | 0.79 | 0.24 | 1.27 | – | 0.81 |
| Soil and sand | 6.29 | 5.44 | 3.08 | 2.96 | 1.70 | 6.75 | 1.39 | 2.28 | 27.85 | 6.42 |
| Cinder | 3.10 | 2.34 | 5.70 | 6.06 | – | 0.00 | 0.44 | 0.39 | – | 2.58 |
| Hazardous waste | 0.17 | 0.82 | 0.05 | 0.05 | – | 0.02 | 0.12 | 0.05 | 0.07 | 0.17 |
| Sludge | 4.34 | 1.63 | 2.29 | 2.75 | 1.46 | 1.35 | 2.92 | 1.89 | – | 2.33 |
| Others | 0.58 | 0.05 | 1.46 | 1.14 | – | 0.03 | 0.14 | 0.04 | – | 0.49 |
| Total | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | |

[a] Food waste can be considered as the organic fraction of MSW when it does not contain irrecoverable paper residues [5, 6]

There is no simple solution to the waste issue, but it obviously requires alternative methods to shift the paradigm.

## Anaerobic digestion technology

Anaerobic digestion (AD) is a series of natural processes in which microorganisms break down biodegradable material (organic matter) in the absence of oxygen, producing biogas and a stabilised digestate. Compared to landfilling and composting there are ecological and economic benefits of using AD to treat biogenic wastes [8]. Compared to landfilling, anaerobic digesters are fully enclosed systems and allow all the biogas to be collected, reducing gas emissions which can be harmful to the environment. Previous studies [9] indicated that AD has an improved energy balance in comparison with composting. While the AD produces biogas which can be used for energy production, the composting produces mostly carbon dioxide which has no energy value [10, 11].

The most important by-product of the AD process is biogas. The biogas produced from the AD process is considered as a renewable energy source because under controlled conditions, the biogas produced (consisting mainly of methane and carbon dioxide) can be used for energy production, helping to replace fossil fuels. It can be burnt directly to produce heat for heating and other purposes. Another method is to use the gas in combined heat and power (CHP) plants which again present opportunities for heat use, including supply to public buildings, horticultural glasshouses, and small-scale industry at a community level. A more recent method becoming increasingly popular is to upgrade biogas, resulting in pure methane for gas grid injection, provision of a low-pressure gas supply to the community or for use as a vehicle fuel. Gas upgrading is usually reserved for large installations, but the ability to do this at a smaller community or private enterprise scale would greatly extend the potential applications.

## Food waste as a high energy source for anaerobic digestion

Food waste is a typical type of organic matter containing high potential for energy production through anaerobic degradation. Some characteristics of food wastes that have been reported in the literature are presented in Table 4, showing moisture content of 70–90 %, volatile solids to total solids ratio (VS/TS) of 85–95 %, and carbon to nitrogen ratio (C/N) of 9–36.4.

Digestion of food waste produces a highly desirable value of methane potential. Studies showed that the methane yield through anaerobic digestion is among the range of 350–435 mL/g $VS_{added}$ depending upon hydrolic retention time (HRT), operational conditions, reactor types, and composition of input food waste [18, 21–23]. Because of the benefits in terms of energy saving, environmental espects and waste management, biogas production from food waste, together with other renewable organic sources i.e. agricultural waste has been suggested as an ideal

**Table 4** Characteristics of food wastes listed in literature

| Source | Characteristics | | | Countries | Sources of reference |
|---|---|---|---|---|---|
| | Moisture content (%) | VS/TS (%) | C/N ratio | | |
| A dining hall | 79.5 | 95 | 14.7 | Korea | [12] |
| University cafeteria | 80.03 | 93.55 | NA | Korea | [13] |
| A dining hall | NA | 94 | 18.3 | Korea | [14] |
| A dining hall | 84.1 | 95.6 | NA | Korea | [15] |
| University's cafeteria | 87.6 | 89.3 | 9.2 | Korea | [16] |
| Segregated domestic food waste | 77 | 92 | 14 | England | [17] |
| Separated from MSW of San Francisco | 69.1 | 85.43 | 14.8 | USA | [18] |
| University restaurant | 81.9 | 94.47 | 13.2 | Korea | [19] |
| Emanating from fruit and vegetable markets, household and juices centres | 85 | 88.5 | 36.36 | India | [20] |

*NA* not available

solution for waste management and energy recovery in coming decades.

### Development of anaerobic digestion worldwide and in Vietnam

It is widely accepted that the first AD plant with biogas collection system to power gas engines was built in Matunga, Bombay, India in 1897 [24]. Since the turn of the 20th century it has become a widely used process and can be found around the world where there are sources of high organic matter from agriculture-by-products. From the 1990s until recently research in AD has developed exponentially because of the global shortage in energy and urgent focus for renewable energy. Biogas plants around the world have increased at the rate of 20–30 % each year with the most experienced and well-developed markets being in Germany, Denmark, and Austria [25]. In developing countries AD technology also flourishes as a waste-to-energy solution, but on a smaller scale and in a decentralised manner. For example in China, in 2002, there were about 11 million digesters, this has almost doubled to more than 19 million in 2006 [26]. In India, the total number of family size biogas plants installed in 2005 was under 4 million, compared to 12 million in 2010 [27].

Biogas production was introduced to Vietnam over 10 years ago. By the end of 2006, more than 18,000 domestic biogas plants had been installed in 10 provinces in Vietnam with support from the Netherlands government. This investment, however, is only to deal with agricultural wastes, manure, etc. at the household or household-group levels [28]. When it comes to MSW, AD has been disregarded by the government.

The National Environment Report of Vietnam [1] indicated that strategies from now to 2025 will focus on methods to recover energy and materials from MSW in cities. Recently, the Vietnam Government again emphasised that it is necessary to develop waste management systems in which solid wastes are classified at source, collected, reused, renewed, and treated with progressive technologies to boost technological innovation in waste-to-energy processes [29]. Thus, waste-to-energy technologies could not only help to provide a solution to this problem but also meet the national energy consumption policy for sustainable development [1].

## Methods and tools

### Method

To estimate energy potential from the anaerobic digestion of food waste in municipal solid waste stream of urban areas in Vietnam, below steps were carried out.

- Investigate, collect data from published National Environment Reports.
- Estimate food waste generation based estimation of population in the next milestones and strategies on food waste management of urban area system in Vietnam up to 2025.
- Develop a model for simulation of food waste digestion system in terms of mass and energy balance.

### The energy model of anaerobic digestion of food waste

A mass and energy balance model of the anaerobic digestion system based on stoichiometric approach was deliberately built in Aspen Plus flowsheeting software [30]. Aspen is an interactive and flexible process modelling tool for conceptual design, optimisation, process operational improvement, and asset management for chemical industries. The Aspen system has a library of various common industrial operations which are called built-in modules. By interconnecting the modules using material, work and heat streams, process flowsheets can be constructed. Each module in Aspen provides an integrated FORTRAN and Excel environment for calculation or customisation [30].

The energy model used in this work incorporates an updated investigation on food waste aspects conducted by researchers from the University of Southampton, UK and partners in Austria, Finland and India. Details of components in system such as mixing, heating, biogas upgrading, etc. can be found in [31]. In this paper, only brief introduction has been introduced.

*Biogas production estimation*

For the energy and mass balance purposes and to limit the complexity, a kinetic free equilibrium model using Aspen plus has been developed. A theoretical stoichiometric method based on Buswell equation is an easy way to estimate products of the anaerobic digestion process (e.g. biogas, digestate). This method has been applied widely in a number of studies [32–37], etc.

Symons and Buswell [38] represented an equation for overall process of anaerobic degradation, known as the "Buswell equation":

$$C_cH_hO_oN_nS_s + yH_2O \rightarrow xCH_4 + (c - x)CO_2 + nNH_3 + sH_2S$$

where: $x = \frac{1}{8}(4c + h - 2o - 3n - 2s)$ and $y = \frac{1}{4}(4c + h - 2o + 3n + 3s)$

The validation of this theoretical approach in terms of methane yield and other products for further energy calculation can be found in [31].

*Model boundary*

To determine how much energy is used in an AD plant and how much is generated, a boundary is required to determine which elements are inputs and which are outputs from the system. Figure 1 shows the main elements of an AD plant which have been taken into account in this study.

There are four main components in our model, including Digester unit, CHP unit, Upgrading unit and Boiler unit. Almost all components of that units modelled by unit operation blocks existed in the Aspen such as reactors, separators, compressors, pumps etc. When the built-in models do not meet calculation purposes, extra steps have been done to involve required subroutines for the simulation. In this study, FORTRAN subroutines in calculator blocks, Excel models have been implemented.

*Assumptions*

The AD process is very complicated and depends upon a variety of parameters such as the composition and size of feedstock, operational conditions, the trace of tars, and heavy substances, etc. [39]. To make this model simpler, basic assumptions have been made:

1. The amount of biogas produced can be predicted using Buswell's Equation [40] which still has been used worldwide,
2. The digesters work at optimum conditions (adequate temperature, pH, mixing, etc.),

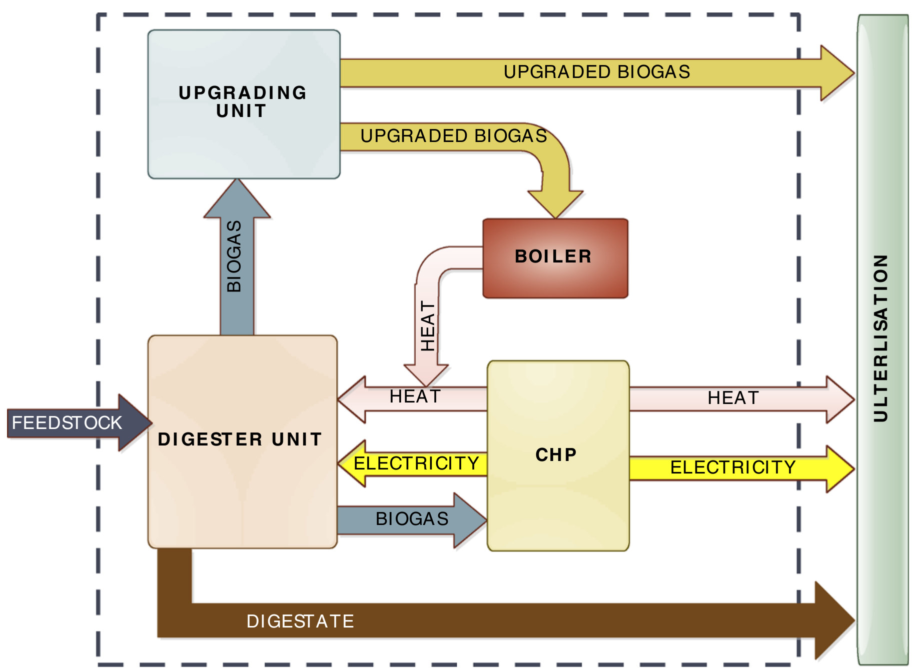


**Fig. 1** System boundaries (inside the *dashed line*)

3. The main impurities are $H_2S$ and $NH_3$, other trace gases are minor and can be neglected.

*Physical property method*

The NRTL global property method which is integrated in Aspen has been used. Gas components i.e. $O_2$, $H_2S$, $CO_2$, and $CH_4$ are assumed to obey Henry's law for calculating their solubility in the liquid phase [41]. Due to the difficulties in determining the exact particulates in food waste, for the mass and energy balance purposes, an empirical formula has been used. Themelis and Kim [42] used data conducted by Kayhanian and Tchobanoglous [43] to propose a formula for food waste: $C_6H_{9.6}O_{3.5}N_{0.28}S_{0.2}$ which was used in this study.

*Model description*

In digester tanks feedstock is fed to a digester where digestion takes place in the absence of oxygen. Gas created from the digestion process (raw biogas) is treated to reduce $H_2S$ levels to prevent mechanical corrosion before feeding to the CHP and boiler for the generation of heat and electricity, or to upgrading unit for biofuel production. Both thermal and electrical energy are required to sustain on-site energy requirements, the surplus energy is used for off-site purposes. In some cases, when the demand for heat for internal use exceeds the amount of heat generated by the CHP, a boiler unit is used to make up for this deficiency. In the upgrading unit, carbon dioxide and unwanted compounds are separated from the raw biogas to make the purified biogas which composition meets the requisite standard of vehicle fuel or natural gas.

Figure 2 illustrates the modeled AD system. Eight Aspen blocks have been used to simulate the AD system (see Table 5).

## Scenarios

### Assumptions and specifications

Although currently food waste is collected in combination with other components of MSW, the national waste management strategies recently emphasised separation of food waste from MSW for energy recovery [1, 29]. Hence, this paper assumes that all collected food waste is separated from the MSW stream and will be treated at centralised biogas plants. The estimated amount of food waste generated in 2015, 2020, and 2025 as in Table 3 will be used. The seasonal average temperature in Vietnam is taken as 22 °C in the winter and 27 °C in the summer [44].

As mentioned, biogas can be utilised in the forms of heat, electricity, vehicle fuel, natural gas, fuel cells, etc. Among these, electricity and vehicle fuel are currently the most suitable for use in Vietnam, and therefore these two were used in the scenarios to estimate the possible energy from food waste. These scenarios consider parameters which directly affect the overall energy consumption in operation of the AD plant, such as: ambient temperature, total input food waste, heat loss, etc. The digester has been assumed to be able to operate at both mesophilic and thermophilic conditions (35 and 42 °C, respectively). The required digester volume is also increased by 10 % for gas storage. Other assumptions made in the model are summarised in Table 6.

### Setting scenarios

Scenario 1 was chosen to obtain the maximum possible usable energy in the form of heat and electricity, by sending all biogas generated from digesters to the CHP unit. The surplus heat and electricity after internal uses (for pumps, mixers, compressors, etc.) is assumed to be sold for commercial purposes.

In scenario 2, only a certain amount of raw gas is fed to a CHP unit to produce an adequate amount of electricity for internal uses. The remaining raw gas is then sent to an upgrading unit to enhance the methane content and remove impurities to achieve vehicle fuel standards. The upgraded gas will then be dried and compressed to approximately 200 atm ready for utilisation. When the heat generated by the biogas sent to the CHP unit is less than the internal heat requirement, a boiler unit is added to the system. In this design, the boiler takes cleaned biogas from the upgrading unit.

## Results and discussion

The amounts of biogas and digestate derived from the AD of food waste for different years under the two scenarios are shown in Table 7. As can be seen from Table 7, the biogas generated in 2025 is about 9,850 tonnes/day which is two times greater than in 2015 and more than the total biogas generated in 2020.

Results from running scenario 1 (Table 8) show that energy in the form of heat produced from the CHP unit is about two times greater than the electricity generated. This reflects the fact that the efficiency of heat from CHP units is about 65 % whereas in electric power it is around 35–43 % [45–47]. From these figures electricity generated that can be sent to the grid could contribute between 2.4 and 4.1 % of the total electricity demand in Vietnam in 2015 and 2025, respectively. The heat produced can also be

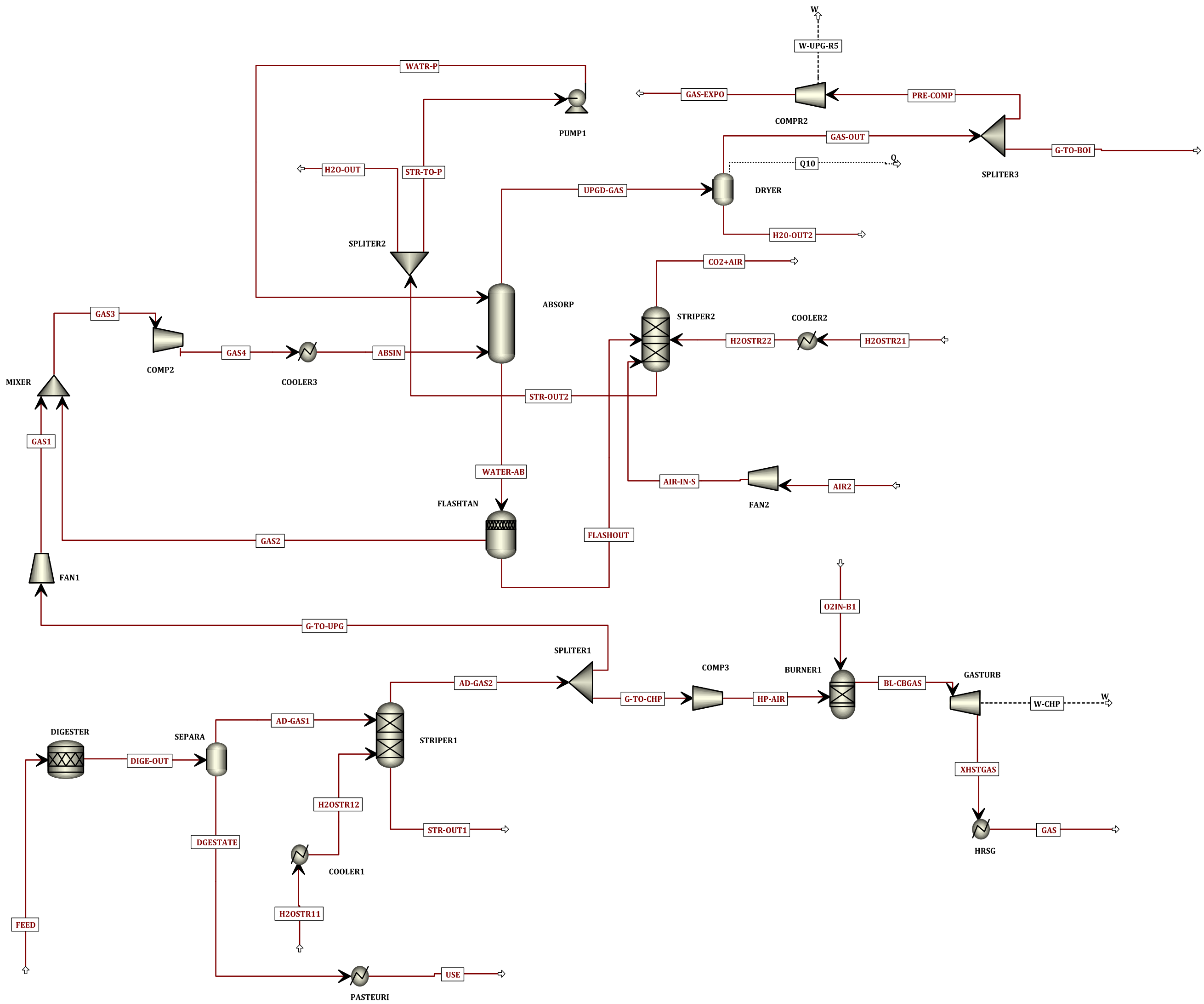


**Fig. 2** The Aspen plus modelling of Anaerobic Digestion plant

**Table 5** Description of Aspen plus unit operation models

| Aspen ID | Block ID | Description |
|---|---|---|
| RSTOIC | DIGESTER | Calculations for the digester based on the Buswell equation |
| FLASH | SEPARATOR | Separates digester output into gas and digestate |
| | FLASHTAN | Releases almost $CH_4$ and some $CO_2$ in liquid from the absorber |
| HEATER | COOLER1, COOLER2 COOLER3 | Cools down the temperature of water streams |
| | HRSG | Heat Recovery Steam Generator |
| RADFRAC | STRIPER1, STRIPER2 | Model of Stripers |
| | ABSORBER | Model of Absorber |
| FSPLIT | SPLITER, SPLITER2, SPLITER3 | Divides feed based on splits specified for outlet streams |
| COMPR | COMP1, COMP2, COMP3, COMP4 | Changes stream pressure to meet the pressure requirement when energy-related information, such as power requirements |
| | FAN1, FAN2 | Generates pressure enough for the feeding |
| | GASTURB | Generates electricity as an isentropic turbine |
| RGIBBS | BUNNER1 | Equilibrium reactor with Gibbs energy minimization |
| PUMP | PUMP1 | Changes stream pressure to meet the pressure requirement |

**Table 6** AD plant operational parameters

| Parameters | Unit | Values |
|---|---|---|
| Digester temperature | °C | 35/42 |
| Pasteuriser temperature | °C | 70 |
| Ambient temperature | °C | 22/27 |
| Total food waste (wet) | $\times 10^3$ kg day$^{-1}$ | 21,420/22,260/49,920 |
| Time in pasteuriser | hour | 1 |
| Loading rate | kg VS m$^{-3}$day$^{-1}$ | 3 |
| TS in food waste | % | 27.8 |
| VS in food waste | % | 25 |
| Overall heat transfer coefficient of digesters surroundings | | |
| Wall | W m$^{-2}$K | 0.275 |
| Floor | W m$^{-2}$K | 0.823 |
| Roof | W m$^{-2}$K | 0.931 |

**Table 7** Biogas generated, gas lost and digestate from food waste in different years

| Contents | Unit | Years | | |
|---|---|---|---|---|
| | | 2015 | 2020 | 2025 |
| Food waste | tonnes day$^{-1}$ | 21,420 | 22,260 | 49,920 |
| Gas generated | tonnes day$^{-1}$ | 5,858 | 6,088 | 13,654 |
| Biogas available | tonnes day$^{-1}$ | 4,221 | 4,397 | 9,853 |
| Biogas composition | | | | |
| $CH_4$ | % | 61.6 | | |
| $CO_2$ | % | 37.6 | | |
| $H_2S$ | ppm | 2,055 | | |
| Digestate | tonnes day$^{-1}$ | 15,561 | 16,171 | 36,265 |

used for heating/cooling in buildings [48, 49] or other industrial purposes in urban areas.

In the second scenario (Table 9), upgraded biogas with a methane content of over 97 % (clean gas) can be used as fuel for trucks, buses, etc. According to Vietnam's national energy development strategy [51], it is estimated that the fuel requirement for transportation in 2020 will be 23 million tonnes, increasing to around 30 million tonnes in 2025. Assuming 1 kg fuel (diesel) is equal to 11.5 kWh [52] then upgraded biogas can replace about 2.2 and 4.75 % of anticipated daily fuel use for transportation in 2020 and 2025, respectively.

Because of the high average ambient temperature, the heat requirements for internal uses such as for heating the digester, pasteurising etc. are small compared to those in cooler climates [53–55]. Therefore, use of the surplus biogas for on-site electricity generation in a CHP plant will produce a large amount of surplus heat. This is potentially available for export. Waste heat can also be used for cooling as well as for industrial purposes and work in these areas is important to effective use of the renewable energy.

The embodied energy in the biogas plants was not included in this study, as it is normally quite small relative to the net energy flows in the operation of the plant [56]. Future work could include the embodied energy, specifically for Vietnam, to give a more comprehensive overall energy balance.

## Conclusion

Due to the strong economic growth and urbanisation in recent years, Vietnam faces many environmental challenges. In particular solid waste management in cities has been promoted as the big issue. Solid waste generation in Vietnam is increasing dramatically, mainly generated from households, buildings, commercial activities and other sources whose activities are similar to those of households and commercial enterprises such as wastes from offices, hotels, supermarkets, shops, institutions, and from municipal services such as street cleaning, etc. The main component of MSW is food waste which is a source of a very high potential of energy.

Results from running scenarios in an energy balance model based on Aspen Plus show that if the food waste in

**Table 8** Scenario 1: Energy potential in the form of heat and electricity

| Contents | Unit | 2015 | | | | 2020 | | | | 2025 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Digestion temp. | | M | M | T | T | M | M | T | T | M | M | T | T |
| Ambient temp. | | W | S | W | S | W | S | W | S | W | S | W | S |
| Heat and electricity for external uses | | | | | | | | | | | | | |
| Heat | GWh | 12.6 | 13.0 | 12.3 | 12.6 | 13.1 | 13.5 | 12.7 | 13.1 | 28.2 | 29.0 | 27.5 | 28.3 |
| Electricity | GWh | 6.85 | 6.85 | 6.85 | 6.85 | 7.10 | 7.10 | 7.10 | 7.10 | 14.8 | 14.8 | 14.8 | 14.8 |
| Electricity demands of Vietnam p.a[a] | GWh | 241 | | | | 301 | | | | 360 | | | |

[a] Adapted from World Bank [50]; *M* mesophilic condition (35 °C), *T* thermophilic condition (42 °C), *S* average temperature in summer (27 °C), *W* average temperature in winter (22 °C)

**Table 9** Scenario 2: Energy potential in the form of upgraded biogas

| Contents | Unit | 2015 | | | | 2020 | | | | 2025 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Digestion temp. | | M | M | T | T | M | M | T | T | M | M | T | T |
| Ambient temp. | | W | S | W | S | W | S | W | S | W | S | W | S |
| Heat and electricity for external uses | | | | | | | | | | | | | |
| Heat | GWh | 3.06 | 3.74 | 2.90 | 3.58 | 3.23 | 3.90 | 3.03 | 3.75 | 7.50 | 9.09 | 7.23 | 8.76 |
| Energy potential of upgraded biogas | GWh | 16.03 | 16.11 | 16.04 | 16.95 | 16.85 | 16.74 | 16.74 | 16.95 | 37.33 | 37.36 | 37.65 | 37.67 |

*M* mesophilic condition (35 °C), *T* thermophilic condition (42 °C), *S* average temperature in summer (27 °C), *W* average temperature in winter (22 °C)

the MSW stream from cities in Vietnam could be separated, it could be a significant source of energy in the form of heat, electricity, or biofuel. This can be achieved in the future through changes in people's behaviour and enforcement of environmental laws. The total surplus exportable energy generated from biogas plants working at standard conditions each day in any form of heat, electricity or purified gas, after allowing for plant operating demand is about 19, 20 and 45 GWh in 2015, 2020, and 2025, respectively.

Results from modelling show that when food waste is separated from the MSW stream and sent to AD plants, it could contribute between 2.4 and 4.1 % of the electricity demand of Vietnam, with about two times this energy also in the form of heat. Alternatively upgrading this biogas could contribute approximately 2.2–4.7 % of fuel consumption for transportation. This suggests AD is a promising method to treat MSW in cities, especially when considering the problematic aspects of other waste disposal methods such as: landfilling, composting, and incineration.

If the organic waste component in the MSW stream of cities in Vietnam could be separated, then AD offers a source of energy generation with many economic benefits. This could provide a contribution towards dealing with the dramatic increases in costs associated with energy supply, waste disposal, space for landfilling, and the increasing public concerns with environmental issues.



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