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Indicative Energy Technology Assessment of Hydrogen Processing From Biogenic Municipal Waste[†]

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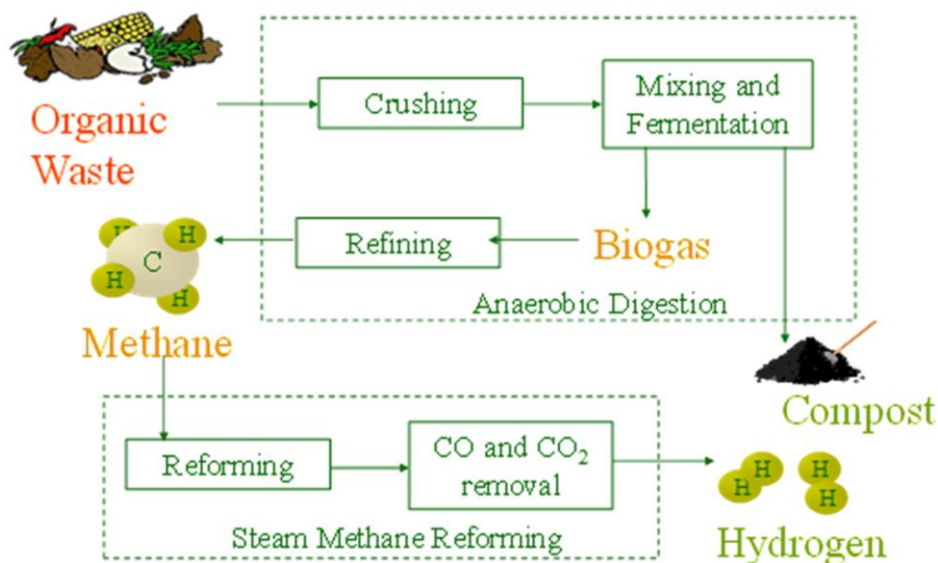
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ABSTRACT

An indicative appraisal has been undertaken of a combined *Anaerobic Digestion* and *Steam Methane Reforming* process to produce sustainable hydrogen from organic waste. The anaerobic digestion plant was based on the plant in Tilburg (The Netherlands), and was modelled from the kerbside organic waste collections through to methane production. Data on biogenic waste was obtained from a collection trial in a municipal area in the UK. This was scaled-up to match that of a Tilburg-like anaerobic digestion plant. The waste collection trials enabled the catchment area for an anaerobic digestion plant on a commercial scale to be estimated. A thermodynamic evaluation of the combined process included energy and exergy analysis in order to determine the efficiency of each process, as well as to identify the areas that lead to inefficiencies. The overall energy efficiency is 75% and the overall exergy efficiency is 60%. The main energy losses were associated with compressor inefficiencies. In contrast, the main exergy consumption was found to be due to the fermentation in the digestion tanks. Other hydrogen process efficiencies vary from 21% to 86%, with the higher efficiencies belonging to non-renewable processes. However, the sustainable hydrogen produced comes from entirely renewable sources (biogenic waste) and has the benefit of near-zero carbon emissions in contrast to fossil fuels. Finally, the case study included an indicative financial assessment of the collection to processing chain. A discounted payback period of less than 20 years was estimated with a modest annual charge for householders.

GRAPHICAL ABSTRACT



KEYWORDS: Hydrogen production, Biogenic municipal waste, Steam methane reforming, Anaerobic digestion, Technology assessment, Thermodynamic analysis

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NOMENCLATURE

Abbreviations

AD	Anaerobic Digestion
Bathnes	<i>Bath and North East Somerset</i> unitary authority (in the South West of England)
BEIS	(the UK) Department for Business, Energy and Industrial Strategy
CCC	(the UK) Committee on Climate Change
CCS	carbon capture and storage
CO	carbon monoxide
CO ₂	carbon dioxide
CH ₄	methane
DCF	discounted cash flow
DECC	(the former UK) Department of Energy and Climate Change
DOE	(the US) Department of Energy
EERE	(the US) Office of Energy Efficiency & Renewable Energy
EFA	ecological or environmental footprint analysis
EfW	energy from waste
EU	European Union
Fe ₂ O ₃	hydrated iron oxide
GHG	'greenhouse' gas
hh	household
HMT	(the UK Government or) Her Majesty's Treasury
H ₂	hydrogen
H ₂ O	water vapour
H ₂ S	hydrogen sulphide
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LNG	liquefied natural gas

MEA	monoethanolamine
MSW	municipal solid waste
NG	natural gas
NPV	net present value
OECD	Organisation of Economic Co-operation and Development
OPEX	operating expenditure
O ₂	oxygen
pH	a quantitative measure of the acidity of aqueous or other liquid solutions
SMR	Steam Methane Reforming
TDR	test discount rate
UK	United Kingdom of Great Britain and Northern Ireland
UNESCO	United Nations Educational, Scientific and Cultural Organization
WACC	weighted average cost of capital
WMO	World Meteorological Office

Symbols

• **Financial Appraisal**

I	capital investment
N	number of years (or physical plant life)
R	annual return on investment
r	discount rate

• **Thermodynamic Analysis**

E	exergy
H	enthalpy
h	specific enthalpy
I	irreversibility (always ≥ 0)
m	mass flow across the system inlet or outlet
N	number of moles of species
Q	heat transfer
S	entropy
T	‘absolute’ or thermodynamic temperature
W	work transfer

Greek letters

Δ	change in a property (typically between inlet and outlet of the system)
ϵ	specific exergy
η	First Law or energy efficiency

Θ	thermodynamic quality
μ	chemical potential
ψ	‘exergy’ efficiency
<i>Subscripts</i>	
g	gas (or vapour)
i	chemical species
in	inlet boundary
lost	property loss
o	reference environmental state (or ‘dead state’)
out	process or system outlet boundary
p	process or device

1. INTRODUCTION

1.1 The Challenge of Anthropogenic Climate Change

The threat of anthropogenic (i.e., human-induced) climate change is the dominant challenge to the energy sector globally. The most recent (2013) scientific assessment by the *Intergovernmental Panel on Climate Change* (IPCC) asserts [1] that it is ‘extremely likely’ that humans are the dominant influence on the observed global warming since the mid-20th Century. Carbon dioxide (CO₂) emissions, the principal ‘greenhouse gas’ (GHG) having an atmospheric residence time of about 100 years, mainly arises from the use of fossil-fuelled [coal, natural gas and oil (petroleum)] power stations and road vehicles, as well as for heating in buildings and industrial processes. Changes in atmospheric concentrations of GHGs affect the energy balance of the global climate system. Human activities have led to dramatic increases since 1950 in atmospheric CO₂; concentrations have risen from 330 ppm in 1975 [1] to about 408 ppm in 2018 [2]. The 2015 *Paris Agreement* on climate change aims to keep global temperatures “well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels” [3]. Indeed, the IPCC in their subsequent ‘special report’ on the implications of keeping temperatures down to 1.5°C [4] argued that humanity has just 12 years to respond to the climate change challenge (i.e., by about 2030 rather than 2050 presently incorporated in international agreements), if it wishes to keep global warming to 1.5°C above pre-industrial levels. However, *bottom-up* national pledges received in connection with the Paris Conference for GHG mitigation efforts are expected to result in a warming of around 2.7°C, even if fully implemented [3]. So the world still faces a significant test of reducing GHG emissions further in order to bring global warming into line with the aspirations in the *Paris Agreement*.

Concern over the impacts of global warming (more recently termed ‘global heating’ by some climate scientists) led the British Government to introduce a legally binding aim of reducing the nation’s ‘targeted GHG emissions’ overall by 80% by 2050 in comparison to a 1990 baseline [5] in their 2008 *Climate Change Act* [6]. This initiative led the way globally, and subsequent pathways for achieving such levels of GHG savings are now known as “deep

decarbonisation” in much of the industrialised world (see, for example, Spencer *et al.* [7]). [The upper end, 2°C global warming target agreed at the *Paris Agreement* [3] is broadly consistent with the 2050 UK GHG emissions target.] It led the British Government’s independent *Committee on Climate Change* (CCC), established under the 2008 *Climate Change Act*, to monitor a series of ‘carbon budgets’ stretching out to 2050 [8]. They require a rapid transition (reduction) in GHG emissions towards an energy system that delivers high quality energy services through low-carbon technologies and processes, that are also secure and at competitive prices. Nevertheless, in 2018, the UK Government asked the CCC to give it advice on the possible tightening of the 2050 target in light of the *Paris Agreement* [3]. Its subsequent report [9] advocated a new emissions target for the UK: net-zero GHGs by 2050, i.e., balancing emissions with CO₂ removal. The CCC argued that this target is “achievable with known technologies, alongside improvements in people’s lives, and within the expected economic cost that Parliament accepted when it legislated the existing 2050 target for an 80% reduction from 1990” [9]. They also advised that the steepest reductions in GHG emissions must occur before 2030. But the CCC viewed current UK climate change policy as being insufficient to meet even the existing 2050 targets [9], i.e., an 80% reduction against the 1990 baseline. The *Climate Change Act* was subsequently amended by the UK Government in June 2019 in order to target a reduction of all GHG emissions to net zero by 2050. A few other countries in Europe have adopted even more stringent net-zero target timescales: 2030 (Norway), 2035 (Finland), 2040 (Iceland) and 2045 (Sweden). However, these Nordic nations are relatively well placed in terms of low carbon energy resources (various combinations of biomass, hydroelectric and geothermal schemes, as well as nuclear power plants in the cases of Finland and Sweden) that makes rapidly securing a net-zero target rather easier than in other countries within northern, central and southern (Mediterranean) Europe. The larger European nations, such as France, Germany, Italy, Spain and The Netherlands, have recently followed the UK example of setting a 2050 target date or supporting its introduction across the *European Union* (EU).

1.2 Hydrogen Energy Options on the Transition Pathway to a Low Carbon Future

Hydrogen (H₂) is potentially a low or zero-carbon energy carrier; depending on its means of production. The notion of the so-called ‘hydrogen economy’ (see, for example, Hoffman [10]), whereby H₂ is produced on a large scale (typically by the electrolysis of water) and then used as an energy carrier or intermediary, was popular in the aftermath of the oil crises of the 1970s. Member states of the *Organisation of Economic Co-operation and Development* (OECD) became anxious about the security of fuel supplies, and began to examine what might substitute for oil in the transport sector. These worries largely evaporated in the 1980s and 1990s with the collapse in the spot price of oil to effectively pre-1973 levels in real terms. In any case, H₂ was perceived to have a number of technical and safety (flammability and steel embrittlement) problems when contrasted with the alternatives. In recent years, its attraction as a climate change mitigation option has become apparent.

The *Royal Society* (of London) recently published a policy briefing that evaluated the prospects for generating sustainable hydrogen (H₂) at scale [11]. The *Royal Society* was founded in 1660 as an ‘invisible college’ of natural philosophers and physicians. It is now the

UK's national academy of science, and has adopted a mission to "recognise, promote, and support excellence in science and to encourage the development and use of science for the benefit of humanity". Over recent years it has produced a number of 'policy briefs' on critically important issues related to the development of science and technology, as well as their implications for the wider world. These have provided government, business and community decision-makers with the necessary background on which they can formulate policy based on independent scientific evidence. In their hydrogen policy brief [11] the *Royal Society* identified a number of processes for obtaining low carbon H₂ for tackling climate change and poor (mainly urban) air quality. The document itself was developed via discussions at a specialist workshop and a number of subsequent expert contributions of best available evidence. Options for producing low carbon H₂ included 'thermochemical routes' [such as *Steam Methane Reforming* (SMR) and *Coal/Biomass Gasification*]; biological routes [such as *Anaerobic Digestion* (AD), *Photo Fermentation*, and *Bioelectrochemical Systems*]; 'electrolytic routes' (such as those utilising an *Alkaline Electrolyser*, *Solid Oxide Electrolyser*, and *Polymer Electrolyte Membrane Electrolyser*); and finally a suite of innovative technologies under the umbrella title of 'solar to fuels' (or 'artificial photosynthesis'). In the context of the present study, the two relevant technologies are:-

- *Steam Methane Reforming* (SMR): The process conventionally uses natural gas and steam to generate H₂, and the UK currently produces around 26.9 TeraWatt-Hours (TWh) annually. SMR plant vary between 150 and 440 MegaWatts (MW) with a typical energy efficiency of about 70%. However, this process continues to emit CO₂ emissions unless used together with *Carbon Capture & Storage* (CCS) [11-15]. Some 71-92% of carbon can be captured in this way, although the higher rates will be required for SMR to be a long-term prospect. Upstream CO₂ emissions tend to limit the capture rate depending on the origin of the natural gas resources. Pipelines from the Russian Federation, for example, have been shown to be particularly leaky [16].
- *Anaerobic Digestion* (AD): The process utilises microbes to convert biomass to H₂ at lower temperatures and with relatively simple technology. The *Royal Society* [11] suggest that this route is presently feasible at a laboratory and small pilot scale. It may have other difficulties, such as the range of biomass or biogenic wastes that can be utilised and their biochemical accessibility. Improved microbial processes and biorefineries [17,18] are being developed that are likely to yield greater H₂ output.

The *Royal Society* policy briefing [11] challenges the idea that conventional SMR is the only solution for producing H₂ at scale over the next 30 years. Each of the technology routes was reviewed in terms of their best available evidence and the prevailing uncertainties. It goes on to outline the technological readiness of each route and the challenges that have to be faced in bringing them to commercial realisation.

1.3 The Issues Considered

Sustainable development is desirable and, hopefully, attainable on a global scale. However, it is less obviously applicable on a city scale [19], where the term 'sustainable cities' is sometimes used synonymously with concepts such as urban autonomy, self-reliance or self-

sufficiency. Thus, Doughty and Hammond [19] used *environmental footprint analysis* (EFA) to study the sustainability of cities by placing them in their broader geographic context. They examined the 18th Century ('Georgian') city of Bath as a sustainability case study. It was found to exhibit an environmental footprint that is greater than its surrounding hinterland or 'bioregion', and some twenty times larger than its own land area. Bioregional thinking attempts to emphasise the interdependence of cities and their natural surroundings. Berg [20] (1990) argued that in order for cities to become more sustainable, they should secure a reciprocal dependence between their urban settlement and the surrounding bioregion. However, at current rates of consumption, the footprint of cities far exceeds their natural catchment [19-21]. The least restrictive interpretation of a sustainable community would be one that is both resource efficient and relied only on products of sustainable production. Thus, cities only survive because they are linked by human, material and communications networks to their hinterlands or bioregions [19].

Commercial H₂ production is almost entirely via the steam reforming of natural gas at the present time. Sustainable production of H₂ may follow either a direct biological route, biological production of methane (CH₄) followed by reforming, or gasification of biomass. Other possible sustainable sources are electrolysis using electricity from wind (e.g., Dutton *et al.* [22] and Hoffman [10]) or solar sources and photocatalytic splitting of water. However, the main priority of the present study is the biological routes. The aim here was to provide an indicative appraisal of a H₂ production plant using thermodynamic and other methods of analysis of the biochemical process. Thermodynamic (energy and exergy) analysis gives rise to differing insights into the relative performance of various process chains. The thermodynamic property known as 'exergy', for example, reflects the ability of undertake 'useful work', but does not represent well heating processes within an energy sector. Methods of analysis employed in the present study are similar to those set out in detail within a related work by Hammond [23], Hammond [24] and Hammond & Mansell [25]. This was followed by a financial appraisal of the technology on a *discounted cash flow* (DCF) basis, and a brief qualitative review of its likely environmental burdens. The facility appraised used synthetically produced CH₄ as a feedstock, generated via *Anaerobic Digestion* (AD) of organic *municipal solid waste* (MSW), followed by its *Steam Methane Reforming* (SMR); see Fig. 1. The novelty of the study is in the synthesis of the H₂ production and the municipal sourcing of biogenic waste on a community-scale. Here the 'Unitary Authority' of *Bath & North East Somerset* (*Bathnes*) in the South West of England (UK) is adopted as a typical source of MSW. This was scaled-up to match that of a Valorga-type AD plant, based on that constructed in Tilburg (The Netherlands). The *Bathnes* area consists principally of the UNESCO World Heritage City of Bath and its surrounding bioregion. It was selected because the *Bathnes* Council had previously carried out a novel trial to evaluate waste collection. This study is 'indicative' in the sense of being a simplified evaluation and illustration of the performance of the combined AD-SMR hydrogen processing system from biogenic MSW in the light of imperfect information. Such assessments provide a valuable evidence base for developers, policy makers, and other stakeholders across the developed world. Thus, lessons learned can be drawn for other industrialised nations attempting to decarbonise their energy

systems, although local circumstances will determine potential country- and region-specific applications

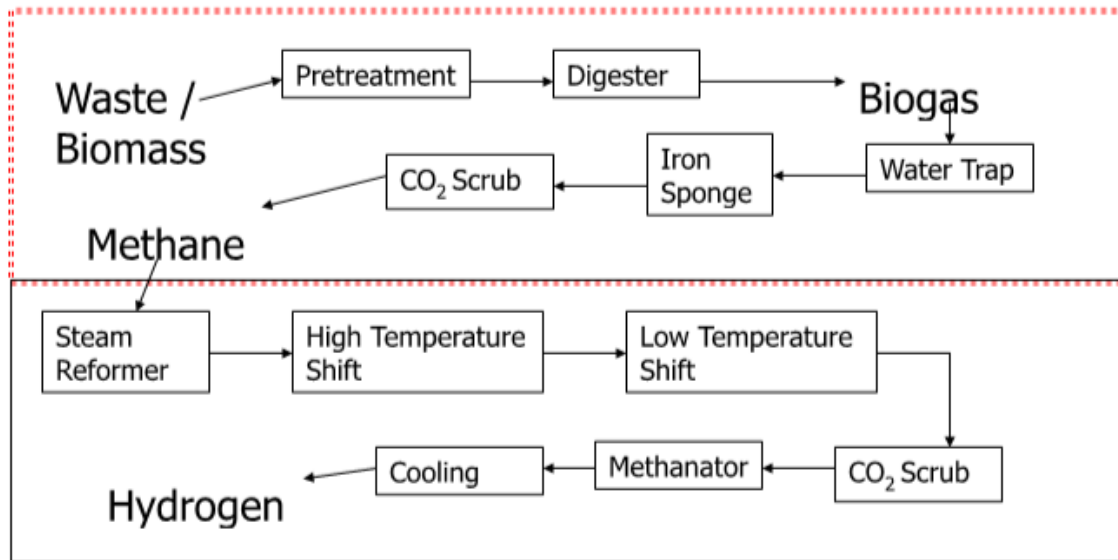


Fig. 1. A schematic representation of a combined AD-SMR processing system utilising biogenic municipal waste as a feedstock. (*Upper section*: anaerobic digestion (AD) stage; *Lower section*: steam methane reforming (SMR) stage).

2. THE BIOREGIONAL CASE STUDY: BATH & NORTH EAST SOMERSET (UK)

2.1 Historical Development

Doughty and Hammond [19] described the historical development of the city of Bath from pre-Roman times to the present day. They observed that its origins lay in its development as a Roman spa [26,27]. A quarter of a million gallons of hot spring water erupts from the ground in Bath, and was utilised by the Romans both for bathing and for the central heating of their dwellings. Davies and Bonsall [26] noted that “the economy of Bath was closely associated with the rural hinterland”. In the aftermath of this Romano-British era, Bath became successively a Saxon monastic town and then a Norman cathedral city. The local economy depended mainly on the wool trade until the end of the 15th Century [19,26]. Its hot baths were largely disused after the withdrawal of the Romans in the 5th Century, until their supposed medicinal properties became more widely recognised in the 16th Century as a cure for illnesses, such as leprosy, smallpox and infertility; leading to the growth of the city in medieval times.

The city of Bath expanded dramatically from the original medieval core to meet the needs of visitors, with new public spaces linked by terraced houses in the Palladian style (named after the Italian architect, Andria Palladio). These were built mainly in the period 1714-1830 when a succession of King Georges (I to IV) reigned over the United Kingdom, and the era is consequently known as 'Georgian' [19,26,28]. The characteristic soft, mellow (Oolitic) limestone was extracted from quarries on nearby Combe Down. Building in Bath really took

off from 1726 when the river between Bath and nearby city of Bristol (now the 8th-largest urban area in the UK in terms of population) was made navigable, and building materials could be imported into the city by water from Bristol. Construction of a canal network, and then the *Great Western Railway* (1840) linking the city directly with Bristol and London, facilitated trade with the Capital and other parts of the UK. Local government reorganisation in 1994 meant that the city became part of the unitary local authority of Bath & North East Somerset: the *Bathnes Council*. This brought together the City of Bath and the former rural district of Wansdyke [19]. The architectural heritage of the city was officially recognised by UNESCO in 1987, when it became one of some ten ‘World Heritage Sites’ in Britain at that time. Bath has a population estimated to be about 100,230 (in 2015), and the residents have an income that is generally higher than the UK average.

2.2 Human and Physical Geography

Bathnes covers an area of ~35,200 hectares (ha), and extends some 36 km east to west and 17 km north to south (see the geographic location illustrated in Fig. 2). Two thirds is so-called ‘green belt’ land that lies between the Cotswold and Mendip Hills; giving it a diverse and complex character. It represents an example of development on an urban scale, coupled with its surrounding ‘bioregion’. The *UNESCO World Heritage City of Bath* is the principal settlement in the district with a population estimated to be about 100,230 (in 2015), and the residents have an income that is generally higher than the UK average. It is complemented by a number of smaller urban communities scattered amongst its surrounding area (‘hinterland’ or bioregion). The local authority covers an area roughly equal to the old *County of Avon* (that existed over the period 1974-1996; see again Fig. 2), and has a varied geography including a number of river valleys and rolling hills. The population of the area has been slowly, but steadily, growing during recent decades, and stood at about 192,100 in 2018. Just over half the population live in the historic City of Bath with the other main centres of population being the towns of Keynsham, Midsomer Norton, and Radstock. The local authority seeks to develop a *systems approach* to achieve a ‘virtuous circle’ in terms of sustainability: balancing economic and social development with environmental protection [19]. It’s latest corporate strategy aims to address the challenge of the “climate and nature emergency”, whilst “improving people’s lives” in the community. The *Bathnes Council* therefore intends to improve public infrastructure, including the environmental performance of its buildings, transport and local renewable energy generation over the coming decades.

3. METHODS AND MATERIALS

3.1 Biochemical Processing

3.1.1 Anaerobic Digestion (AD)

Anaerobic digestion is a biological process that takes place in the absence of oxygen [29,30].



Fig. 2. The Bioregion of *Bath & North East Somerset (Bathnes)*.
Source: Doughty & Hammond [19].

Bacteria are cultivated in a controlled atmosphere and feeds on organic material, breaking it down and releasing a synthetic gas, commonly known as biogas. It is used in many parts of the world to generate biogas, and is technically well developed. The process is employed widely in so-called developing countries where the biogas is either used for cooking, or refined and sold as synthetic *natural gas* (NG) to provide an income for a local community [30]. The process is also quite widely employed in Europe to help combat the growing problem of waste generation from landfill sites [29]. The organic fraction of biogenic waste is digested in tanks that are vastly reduced in volume compared to the waste that enters landfill sites. The methane content of biogas is high, although it has a significant proportion of CO₂ and trace amounts of contaminants, such as hydrogen sulphide (H₂S) [29,30]. Removal of the

dilutant CO₂ and contaminants yields a synthetic gas of very similar composition to NG, i.e., principally methane (CH₄). NG is a naturally occurring gas mixture with a lower carbon content than other fossil fuels, such as coal or oil. The biogas created during AD, if refined to remove any contaminating substances, can be used as a substitute for NG and hence as a feedstock for the SMR process. If *energy from waste* (EfW) were used to create this synthetic gas, and then the net CO₂ release into the atmosphere would be reduced in comparison to NG usage.

There are many different types of digesters available, but all follow essentially the same stages [29-31]:

- Hydrolysis/Liquefaction
- Acetogenesis
- Methanogenesis

During the first stage fermentative bacteria convert the complex organic matter, such as cellulose, into soluble molecules like sugar, amino acids and fatty acids. The second stage uses acetogenic bacteria (acid formers) to convert the products of the first stage to simple organic acids, such as acetic acid and propionic acid, CO₂ and H₂. In the third stage bacteria called methanogens produce methane. This is done either by splitting acetic acid into CO₂ and CH₄ or by reducing CO₂ with H₂. Limited concentrations of hydrogen in the digestion tank restricts the second method and so splitting acetic acid produces the bulk of the CH₄. There are two types of bacteria that create methane, thermophilic and mesophilic, and each have optimum environmental conditions in which they thrive. The bacteria chosen for the digestion process is dependent on the climate and digester type.

There are many different types of digesters, each of which can be classified in terms of the total solids contents of the slurry fed into the tanks. Low solids systems typically contain less than 10% solids, medium solids contain between approximately 15-20%, and high solids range from about 20-40% [32]. Furthermore, digesters can be classified into single-stage and multi-stage reactors, as well as batch and continuous flow reactors. Single-stage reactors make use of a single tank where the three stages of digestion all take place, whereas multi-stage reactors separate the acetogenesis and methanogenesis stages via the use of two tanks. Batch reactors are used when the tank is loaded with slurry and unloaded at the end of the retention time. In continuous flow systems feed is constantly fed in and digestate is continually discharged. The digestion products differ depending upon various factors such as the temperature, pH level, composition of the feedstock, carbon/nitrogen ratio, organic load rate, retention time and mixing [32]. These need to be optimised according to the time of year to account for climate changes and variations in organic composition in order to produce the highest yield of methane.

The Valorga digestion system analysed in the present study was a high solids, single stage, continuous flow system that uses mesophilic bacteria, and is illustrated schematically in Fig. 3 [33]. It was based on a commercial-scale AD plant in Tilburg (The Netherlands). *Municipal solid waste* (MSW) from five surrounding municipalities was sent to the digestion plant at Tilburg, which separated the organic matter and recyclable waste. The pre-sorting section of

the AD plant sorts the organic fraction of the waste from other materials, which were sent to be recycled or to landfill sites. Waste was hand sorted to remove large non-organic particles, passed through a rotating drum sifter and ferrous materials were removed with a magnet. A conveyor belt transported the waste to the pre-treatment unit. Electrically driven rotary sheers in the pre-treatment unit reduced the organic waste particle size to a maximum of 10 cm

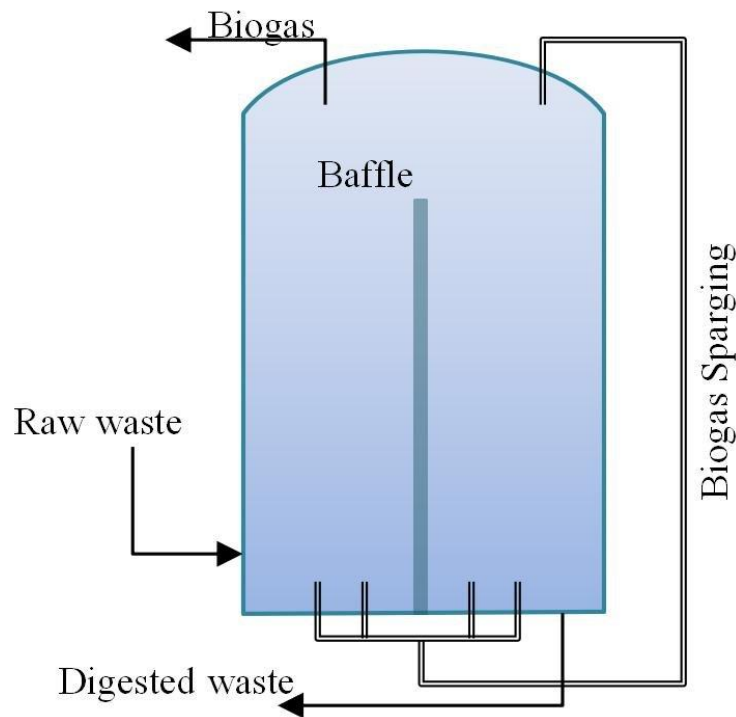


Fig. 3. A schematic representation of a *Valorga* AD processing tank.

Source: Elsharkawy *et al.* [33].

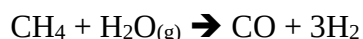
across. The conveyor belt moved the organic matter to the mixer, where it was dissolved with process water, fermented matter, and the micro-organisms responsible for fermentation. A solids piston pump transferred the mixture into the digestion tanks. The digestion process was carried out in two tanks, each with a volume of 3,300 m³, under mesophilic conditions at 38°C. At Tilburg the digestion tanks had the capacity to process 52,000 tonnes of organic matter per year, but operated at 80%, processing 40,000 tonnes of waste annually. The Tilburg *Valorga*-type plant digested the organic matter in vertical cylindrical vessels with a partition across two-thirds of their diameter [31-35]. Digestate was extracted from the tanks by gravity after a retention time of approximately three weeks, and then dehydrated with the aid of electrically-driven screw presses before being transported on a conveyor belt to a composting hall. The separated liquid was passed through a centrifuge to remove the suspended solids, before the bulk was stored in a process water tank to be heated with steam and mixed with the incoming organic waste. Residual waste water was passed through a belt filter press where any remaining solid matter was removed, before being pumped to a sewerage treatment plant. The filter cake was transported to the compost hall with the rest of

the digested solids. Finally, the digested matter was stored for four weeks under aerobic conditions to stabilize. The remaining material was considered to be a high quality compost.

3.1.2 Steam Methane Reforming (SMR)

Steam methane reforming is one of the most important hydrogen generation processes, because it is associated with low emissions [36,37]. The feedstock is typically desulfurized *natural gas*; a fossil fuel (although potential other sources include biogenic waste, liquefied petroleum gas, naphtha and refinery offgas). Consequently, the H₂ produced using this fuel is not a renewable or low carbon energy carrier. However, adopting CH₄ from renewable sources of energy could enable this process to contribute towards the attainment of a sustainable energy economy. Rosen [36] undertook a classic study of the thermodynamic performance of the process in which he examined the energy and exergy flows through the system. His aim was to identify potential areas for improving the effectiveness of the SMR process. The analysis was evaluated in order to understand the energy and exergy calculation procedure so that it could then also be applied appropriately to the AD process described above. The six main steps involved in the SMR process (see again Fig. 1) are summarised [37] as:

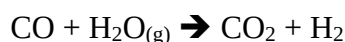
- *Reforming.* Methane is first purified before being reacted with water vapour to produce a synthesis gas containing hydrogen and carbon monoxide according to the following endothermic reaction:



Methane fuel is combusted in air to produce the heat required for this process and also steam for compression and carbon dioxide scrubbing:



- *High-Temperature Shift.* 94% of the carbon monoxide (CO) from the raw synthesis gas is reacted with water over a high temperature catalyst according to the following exothermic reaction:



The high temperature gas exiting this reaction is used to pre-heat the methanator and boiler feeds.

- *Low-Temperature Shift.* 83% of the remaining carbon monoxide is reacted with water according to the same reaction used in the high-temperature shift block, over a low-temperature catalyst.
- *Carbon Dioxide Scrub.* The synthesis gas is compressed to 3.5 MPa before the carbon dioxide is removed. The scrubbing unit uses *monoethanolamine* (MEA) as a solvent to absorb the carbon dioxide leaving 0.1% by volume in the resulting gas.
- *Methanation.* The methanation reaction uses some of the hydrogen produced in the reforming reaction to convert the remaining carbon monoxide into methane and water:



- *Cooling.* Cooling water reduces the temperature of the gas and it is dried to result in a gas consisting of 97% hydrogen by weight.

The datum for the enthalpy and entropy values were set to coincide with the dead state of the process, which was set by Rosen [36] as 298 K and 1 bar. The SMR process enables flexible use of different feedstocks, designs that may be optimized for the highest efficiency, yield the lowest *operating expenditure* (OPEX), or lowest total life-cycle cost. Different degrees of modularization and standardization can be applied to meet specific project requirements.

3.1.3 The Combined AD-SMR System

AD is primarily a waste treatment method, widely used on mainland Europe and in America to reduce the volume of waste sent to landfill sites. It is a fermentation process which breaks down biodegradable organic matter into compost. The bacteria responsible for the fermentation give off a synthetic gas (i.e., biogas), which consists primarily of CH₄ and CO₂. In contrast, SMR is a process that has been used for several years to generate H₂ from NG (CH₄). The combined AD-SMR process that was appraised is illustrated schematically in Fig 1. Here the AD plant studied was modelled on a full-scale facility operating in Tilburg (The Netherlands). The analysis performed on the SMR processing plant implies that 3.92 kmol of hydrogen is produced from 1 kmol of methane. The analysis performed on the AD plant that produces methane from municipal solid waste indicated that an average of 11.5 kmols of methane is produced per day. This suggests that if this quantity of methane were processed each day in the SMR plant, then 45 kmols of H₂ would be generated. One mol of H₂ is equivalent to 2.016 grams, and therefore 91 kg of hydrogen would be produced per day, or 33,171 kg of H₂ per year.

3.2 Biogenic Municipal Waste in a UK Context

In the present study, the ‘Unitary Authority’ of Bath & North East Somerset (*Bathnes*) in the South West of England (UK) is adopted as a typical source of MSW. It was selected because the *Bathnes* Council had carried out a novel trial to evaluate waste collection. Their intention was to determine the best method for collecting waste, and the type of response from differing household (hh) types and areas. ‘Bin lorries’ – special-purpose vehicles for the collection of domestic (and commercial) waste – were weighed in the trials to determine the amount of waste that was collected. These waste collection trucks (or ‘dust carts’) have a six tonne (t) dry weight, and during the trials increased up to 16 t when loaded; hence they collect up to 10 t of waste. However, this is not the maximum capacity as research from other trials in the country report trucks collecting up to 16 t of waste. If the lorries were to be used to collect waste for a commercial-scale project, then they would need to be carried out five days a week; accounting for public holidays that equates to 250 days per year. Therefore one truck would be able to collect 4000 t of compostable waste per year, assuming that they only collect one load per day.

Details of *Bathnes* household waste obtained from the collection trial are presented in Fig. 4. These results could be used to estimate the catchment area for an anaerobic digester on a commercial scale. The bulk of the waste consists of material that can be recycled or composted. If fine quality, sorted biogenic waste could be extracted, then an AD plant could

produce both a good yield of biogas and high-grade compost. This compost would be a potentially valuable product from the AD plant that could compliment high plant efficiency. The current UK Government strategy for waste management is to reduce the amount of waste produced, reuse anything that can be used again, and then recycle as much waste as possible. Landfill use has declined over the past few years, but it still remains an important waste disposal technique in Britain. Waste recycling is rising with the backing of the central government, as well as targets and standards set by the EU. Thus, research into composting schemes to recycle the organic element of municipal solid waste is necessary to improve the current recycling rates of the UK.

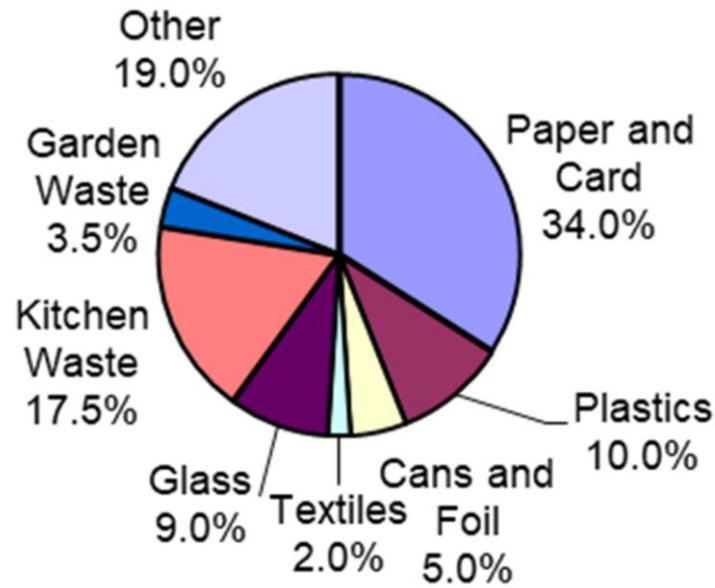


Fig. 4. Dustbin waste composition for *Bath & North East Somerset (Bathnes)*.

3.3 Thermodynamic Analysis

3.3.1 Energy Analysis

In order to determine the primary energy inputs into a system, it is necessary to trace all the flows of energy across the ‘value chain’: a set of industrial activities that are performed in order to deliver a valuable product or service for the market. This is based on the *First Law of Thermodynamics*; representing the principle of conservation of energy, or the notion of an energy balance applied to the system [38,39]. The *First Law* is typically viewed in terms of a steady-state process for which the energy balance may be represented by [23-25]:

$$\sum (h + ke + pe)_{in} m_{in} - \sum (h + ke + pe)_{out} m_{out} + \sum Q - W = 0 \quad (1)$$

where m_{in} and m_{out} denote the mass flow across the system inlet and outlet respectively, Q represents the heat transfer across the system boundary, W is the work (including shaft work, electricity, and so on) transferred out of the system, and h , ke , and pe denote the specific values of enthalpy, kinetic energy, and potential energy respectively.

The *First Law* energy efficiency becomes:

$$\eta = (H_{\text{out}})_{\text{useful}} / H_{\text{in}} < 1 \quad (2)$$

where H_{in} represents the enthalpies of the various incoming flow streams for the system, and H_{out} the different enthalpies of the output.

3.3.2 Exergy Analysis

The traditional approach to energy analysis takes no account of the energy source quality in a thermodynamic sense. Electricity may be regarded as a high-grade source having a higher quality, or exergy, because it can undertake work. In contrast, low temperature hot water, although also an energy source, can only be used for heating purposes [23]. Consequently, Hammond and Stapleton [38] proposed to employ exergy analysis alongside traditional energy analysis in order to illuminate such issues. In the case of biogenic waste, the significance of energy quality depends on (i) whether the system output is in terms of fuel, heat, or electricity, and on (ii) the energy end-use.

Exergy is lost or degraded in every irreversible process or system. Consequently an exergy budget on a control volume can be formulated in an analogous manner to the *First Law* energy balance, *Equation 1*, as [38,40]:

$$\sum \varepsilon_{\text{in}} m_{\text{in}} - \sum \varepsilon_{\text{out}} m_{\text{out}} + \sum (E^Q - E^W) - I = 0 \quad (3)$$

where E^Q and E^W denote the exergy transfer associated with Q and W respectively, I is the system exergy consumption or ‘irreversibility’, and ε represents the specific exergy. Thus, the exergy loss or irreversibility rate [41] of the system is given by:

$$I \equiv \Delta E_{\text{lost}} = E_{\text{in}} - E_{\text{out}} > 0 \quad (4)$$

The exergy function itself is an ‘extensive’ property that is dependent on the mass or size of the system [25], which is defined by reference to a “dead” or equilibrium state (in terms of temperature T_o , pressure P_o , and species component μ_{io}):

$$E = (H - H_o) - T_o(S - S_o) + \sum_i N_i (\mu_i - \mu_{io}) \quad (5)$$

where S denotes the Clausius entropy and N_i is the number of moles of species i . Variations in species, or matter, concentration are reflected in the last term on the right hand side. An exergy efficiency, ψ , can be defined in an analogous manner to its energy counterpart, *Equation 2*, as [38]:

$$\psi = E_{\text{out}}/E_{\text{in}} = 1 - I/E_{\text{in}} < 1 \quad (6)$$

Comparison with the practical *First Law* or energy efficiency (defined by *Equation 2*) suggests that, in any real world system (which is irreversible) exergy is degraded and therefore the exergy efficiency is consequently less than unity. Van Gool [40,41] has noted that the maximum improvement in the exergy efficiency for a process or system is obviously achieved when ΔE_{lost} is minimised; see *Equation 4*.

Van Gool [42] suggested that the thermodynamic quality of a flow stream may be represented by the ratio of its exergy to enthalpy:

$$\Theta \equiv \frac{E}{H} \quad (7)$$

Thus, for electricity [24]: $\Theta = 1$

and for process heat [24]: $\Theta = \left(1 - \frac{T_0}{T_p}\right)$

In contrast to electricity (a high quality energy carrier with $\Theta = 1$ as indicated above), low temperature hot water ($\Theta \approx 0.2$) can only be used for heating purposes. The variation in van Gool's thermodynamic quality (Θ) with the process temperature ratio (T_p/T_0) is shown in Fig. 5. This was produced using the environmental datum temperature adopted by Hammond and Stapleton [38] for their energy analysis of the UK economy: -1°C (or $T_0 = 272\text{ K}$). They indicated that the exergy efficiency of various domestic heating appliances was quite sensitive to the choice of this reference temperature, when the process temperature is close to the selected environmental datum. However, the thermodynamic quality (Θ) is insensitive to the choice of this environmental temperature when plotted against the process temperature ratio [23]; as depicted in Fig. 5. Here a very wide variation in T_p/T_0 is displayed, and various heat sources are shown for comparison purposes. Their associated process temperatures span the range from liquefied natural gas (LNG) at about -50°C to the optical temperature of our Sun at around $+5500^\circ\text{C}$. Thus, exergy reflects the ability of a processing system to produce '*useful work*', but does not represent well *heating processes* [39].

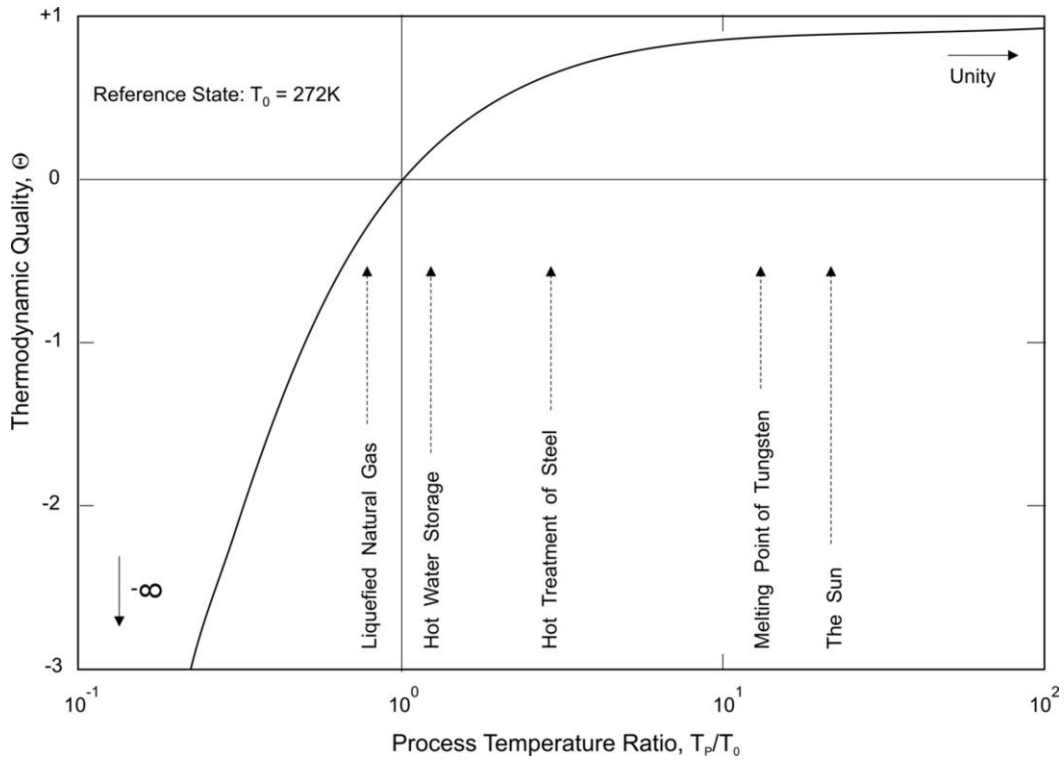


Fig. 5. Temperature dependence of thermodynamic quality.
Source: Hammond [23]; with a minor correction.

3.3.3 Thermodynamic Data and System Analysis

- **Anaerobic Digestion (AD)**

The energy use and exergy consumption in the AD plant (based on the *Valorga*-type digester [32-34] located in Tilburg, The Netherlands) are displayed in Tables 1 and 2 respectively. These are shown in terms of the irreversibility inherent in each of the various sub-processes and the percentage column in Table 2 indicates which sub-process consumes the most exergy. Clearly, the fermentation, biogas high pressure storage, and refining process show large energy and exergy losses. The balances for the biogas high pressure storage block show the largest energy and exergy losses of approximately 75%. However, this is due to the assumption that only 20% of the biogas is re-circulated to provide pneumatic mixing. Since the biogas re-circulates back to the low pressure gas storage tank, this assumption has no effect on the overall efficiency of the plant. However, there are considerable energy and exergy losses due to the inefficiencies in the compressor, which are approximately 38%. The energy and exergy losses in the refining process are also due to the compressor inefficiencies and amount to approximately 31%. The energy and exergy losses in the fermentation process of 30% and 39% respectively.

Table 1 Energy balance of each block for the *Anaerobic Digestion* (AD) process plant (based on one at Tilburg, The Netherlands).

	h_{in}	Q_{in}	W_{in}	h_{out}	Q_{out}	W_{out}	Sum	% Energy Lost
Sub-processes	kW	kW	kW	kW	kW	kW	kW	%
Waste Collection	10273	0.0	0.0	10273	0.0	0.0	0.0	0.0
Transport	10273	0.0	49.9	10273	0.0	0.0	49.9	0.5
Reception	10273	0.0	1.1	10273	0.0	0.0	1.1	0.0
Crushing	10273	0.0	35.4	10273	0.0	0.0	35.4	0.3
Mixing	18218	0.0	20.8	17960	0.0	0.0	279.3	1.5
Fermentation	17959	0.0	0.0	12585	0.0	0.0	5373.0	29.9
Biogas LP Storage	120	0.0	0.0	120	0.0	0.0	0.1	0.1
Biogas HP Storage	24	0.0	72.0	234	0.0	0.0	72.0	75.0
Refining	120	0.0	53.6	120	0.0	0.0	53.7	31.0
Dehydration	12466	0.0	21.6	12438	0.0	0.0	48.8	0.4
Centrifuge	9756	0.0	10.7	9710	0.0	0.0	56.3	0.6
Process Water Storage	7639	305.6	1.0	7945	0.0	0.0	1.0	0.0
Filter	1255	0.0	3.3	1251	0.0	0.0	7.5	0.6
Compost	3586	0.0	1.1	3586	0.0	0.0	1.1	0.0

The overall energy and exergy efficiencies of the AD plant was 34.2% and 27.6% respectively. Inputs to the system included the internal energy or exergy associated with the organic element of municipal solid waste, the energy or exergy inputs for transporting the waste from households to the digester plant, and the electricity inputs. The outputs of the

Table 2 Exergy balance of each block for the *Anaerobic Digestion* (AD) process plant (based on one at Tilburg, The Netherlands).

	h_{in}	Q_{in}	W_{in}	h_{out}	Q_{out}	W_{out}	I	% Exergy Consumed
Sub-processes	kW	kW	kW	kW	kW	kW	kW	%
Waste Collection	12903.1	0.0	0.0	12903.1	0.0	0.0	0.0	0.0
Transport	12903.1	0.0	49.9	12903.1	0.0	0.0	49.9	0.4
Reception	12903.1	0.0	1.1	12903.1	0.0	0.0	1.1	0.0
Crushing	12903.1	0.0	35.4	12903.1	0.0	0.0	35.4	0.3
Mixing	20458.9	0.0	20.8	20439.8	0.0	0.0	39.9	0.2
Fermentation	20438.9	0.0	0.0	12396.3	0.0	0.0	8042.6	39.3
Biogas LP Storage	119.6	0.0	0.0	119.6	0.0	0.0	0.0	0.0
Biogas HP Storage	23.9	0.0	72.0	23.9	0.0	0.0	72.0	75.1
Refining	119.6	0.0	53.6	119.6	0.0	0.0	53.7	31.0
Dehydration	12292.1	0.0	21.6	12291.1	0.0	0.0	22.5	0.2
Centrifuge	9608.6	0.0	10.7	9589.2	0.0	0.0	30.2	0.3
Process Water Storage	7535.1	229.2	1.0	7555.8	0.0	0.0	209.5	2.7
Filter	1238.0	0.0	3.3	1237.5	0.0	0.0	3.8	0.3
Compost	3586.1	0.0	1.1	3586.1	0.0	0.0	1.1	0.0

system only included the energy or exergy in the refined gas (CH_4) and the compost. Waste process water and the vented gases from the *Binax* CO_2 removal system were assumed to be lost during processing. Inputs for the dehydration sub-process include the energy/exergy content of the digestate, and work inputs for the centrifuge, screw press, pumps and belt filter press. The outputs were the energy/exergy content of the solids from the dehydration, centrifuge and filter sub-processes, as well as the liquid into the process water storage block. The water out of the belt filter press is considered to be waste.

The calorific value of the compost in the analysis was assumed to be the same as that from the Tilburg plant. However, the Tilburg plant collects and sorts all municipal solid waste, and the resulting compost contains 40% inorganic matter. Source sorted waste may result in a compost with a different composition and hence a different calorific value. Indeed, sorted waste can provide good quality feedstock for either composting or AD processing, because there are less heavy metals and plastic contaminants present. The calorific value of biomass derived from aerobically digested compost from an individual household is some 17,400 kJ/kg; significantly larger than the figure from the Tilburg plant of 4500 kJ/kg. However, the calorific value of the compost derived from a commercial anaerobic digester will not necessarily be as large, since there may be a significant proportion of indigestible matter in the feed.

- **The Combined AD-SMR System**

A comparable and comprehensive thermodynamic evaluation of SMR was previously undertaken by Rosen [36]. That has therefore not been duplicated here, although the results of that earlier study have been utilised in the present study. The overall energy and exergy efficiencies to produce hydrogen from garden and food waste was found to be 74.8% and 60.6% respectively. Outputs included compost from the AD plant and the H_2 from the SMR plant (see again Fig. 1). Likewise, inputs consisted of the organic element of the waste fed to the *Valorga* digester, all electricity used, external steam, and transport energy inputs. The overall energy balance and exergy budget for the AD processing plant are illustrated in Fig. 6 for 10,000 kJ/kg in compost calorific value. The left and right half of the energy balance (Fig. 6) represent the inputs and outputs; thereby depicting the energy losses. The left and right half of the exergy budget (again Fig. 6) reflect their inputs and outputs, including exergy consumption in respect to the latter. Sources of energy losses and exergy consumptions, as well as their differences, can therefore be clearly seen by scrutinising these pie charts.

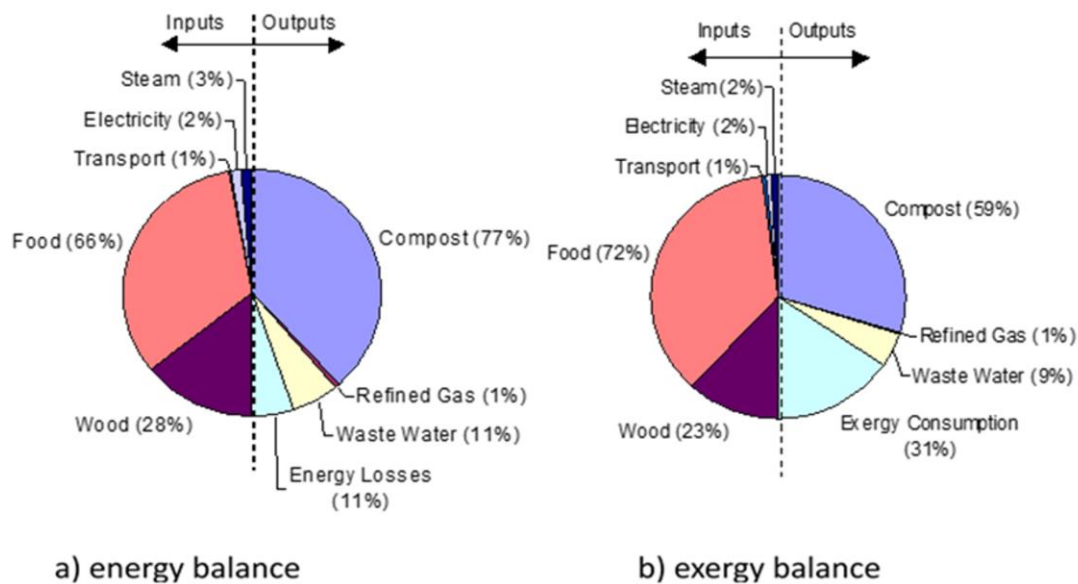


Fig. 6. The energy balance and exergy budget for the AD process (using a calorific value for compost of 10,000 kJ/kg).

The overall efficiencies of the combined processes lie in-between the figures for the overall efficiencies of the individual processes, but are closer to those of the AD plant. This is because the majority of the output from the combined process is the compost from the digester tanks and the calorific value of this has as much of an effect on the overall efficiencies for the combined AD-SMR system as it does for the AD process alone.

- **Comparison with Alternative Hydrogen Processes**

Rosen [43] investigated the energy and exergy efficiencies of various hydrogen production processes, using the SMR process and the same definition of efficiency. These processes can therefore be readily compared to the combined AD-SMR process analysed here. Rosen [43] described and compared the following processes:

(i) Hydrocarbon-based processes

- Steam methane reforming
- Coal gasification

(ii) Non-hydrocarbon based processes

- Current technology water electrolysis
- Advanced technology water electrolysis
- Thermochemical water decomposition

(iii) Integrated processes

- Steam methane reforming combined with current technology water electrolysis
- Steam methane reforming combined with advanced technology water electrolysis
- Steam methane reforming combined with thermochemical water decomposition

The overall energy and exergy efficiencies of these processes are summarised in Table 3 [43]. For each of the process chains the input energy and exergy are associated with the main feeds, hydrocarbons for the hydrocarbon based processes, high temperature heat for the non-hydrocarbon based processes and a mixture of both for the integrated processes. The output energy is associated with the waste cooling water, stack gas and hydrogen for the hydrocarbon based and integrated processes, as well as waste cooling water and hydrogen for the non-hydrocarbon based processes. The output exergy is mainly associated with the hydrogen produced for all of the processes, although the proportions vary from 86% for SMR to 19% for thermochemical water decomposition (ignoring exergy consumptions). This is reflected by the efficiencies given in Table 3.

Table 3 Overall energy and exergy efficiencies for alternative hydrogen production processes.
Source: Rosen [43].

Process	Energy Efficiency (%)	Exergy Efficiency (%)
Steam methane reforming (SMR)	86	78
Coal Gasification	59	49
Current technology water electrolysis	30	26
Advanced technology water electrolysis	49	41
Thermochemical water decomposition	21	19
SMR/Current technology water electrolysis	55	48
SMR/Advanced technology water electrolysis	70	62
SMR/thermochemical water decomposition	45	40

Nearly all of the inputs to the combined AD-SMR process are connected with the organic waste. The bulk of the energy outputs stem from the compost. The majority of the exergy outputs are associated with the compost and exergy consumptions. This is similar to the AD plant, but differs from all the alternative processes described by Rosen [43]; see again Table 3. This is because the processes described by latter [43] only yield hydrogen, whereas the combined AD-SMR system produces both H₂ and compost. The compost produced in the combined system dominates the efficiency of the plant, and the percentage of H₂ is small in comparison to other outputs.

3.4 Financial Appraisal

The present study employed *discounted cash flow* (DCF) accounting methods in order to evaluate the financial viability of the combined AD-SMR system. Financial appraisal uses the market rate of interest (net of inflation) as a lower bound on the discount rate, and therefore indicates the real return that would be earned on a private sector investment. This approach takes account of the ‘time value of money’ and discounting in order to obtain the appropriate investment appraisal criteria [44,45]. The *net present value* (NPV) of the sum of the capital cost, maintenance and operational costs, as well as (potentially) decommissioning, is calculated over the life of the project, along with the NPV of the hydrogen processing. Discounted cash flow (DCF) analysis has been used to determine the payback period of the combined AD-SMR plant via:

$$NPV = -I + R \left[\frac{1 - (1 + r)^{-N}}{r} \right] \quad (8)$$

where NPV is the net present value, I is the capital investment, R is the annual return on investment, N is the number of years (or plant life), and r is the discount rate. The DCF payback period is achieved when the NPV is zero. In the case of public sector investments a so-called *Test Discount Rate* (TDR) is often utilised. It is typically derived from a comparison with private sector discount rates [or *Weighted Average Cost of Capital* (WACC)]. In the UK, *HM Treasury* [46] recommends that the TDR for projects with durations of less than 30 years should be taken as 3.5%, then falling in line with the profile indicated in Table 4 below. A discount rate of 7% was selected in the current case as representing towards the upper end of the private sector WACC in the UK.

Table 4 The declining long-term UK ‘*Test Discount Rate*’. *Source:* HM Treasury [46].

Period of Years	0-30	31-75	76-125
Discount Rate	3.5%	3.0%	2.5%

Capital investment for the AD plant in Tilburg was £11 million (M) [47], and this figure was used for the present appraisal. The practical differences between the Tilburg plant and that studied here was considered negligible, because the investment cost of the pre-sorting unit in the Tilburg plant is comparable to that for gas refining plant used in the AD-SMR system. The capital investment for a SMR plant that produces 91 kg of H₂ a day was £391,050. The

potential revenue from the sale of hydrogen gas, given that the combined process could produce 33,171 kg of hydrogen annually, was £98,015 per year. This is based on £35 per 50 litre bottle, which is filled at 200 bar [6]. The return from the compost, based on a price of £10.66 per t, is £225,524 per year. Assuming a workforce of 12 at an average wage and benefits cost of £30,000 *per annum*, implies a labour cost of ~£360,000. Costs for running, maintenance, health and safety, decommissioning, etc. were assumed to be equal to the labour cost. The projected annual yield of organic waste per household, based on the *Bathnes* trials that charge for waste collections (see the composition depicted in Fig. 3). This implies that just over 1.4 million households would be needed to collect the 40,000 t of waste per year. In order for the plant to break-even each year a charge of £0.28 per household per year would need to be made. However, to attain a DCF payback period of less than 20 years, then an annual charge of at least £1.04 per household is needed. There is not presently a carbon credit scheme for the conversion of CH₄ into H₂ within the UK. Obviously, such a scheme would be desirable on climate change mitigation grounds, and could provide an incentive for the adoption of a combined AD-SMR facility.

3.4 Environmental Burdens of Hydrogen Processing

An indicative energy technology assessment would typically include an evaluation (even in just qualitative terms) of the likely environmental impact of the hydrogen generation process. Hydrocarbon production processes [43] vary in terms of their by-products, and hence each exhibits different environmental burdens. Coal-based processes give rise to serious problems due to high levels of sulphur content, possible hydrogen cyanide and heavy metals, which need removing from the raw gas, as well as the ash and slag that need disposal. Natural gas used in conventional SMR plants is the cleanest hydrocarbon-based fuel, producing only sulphur products that can be stripped from the raw gas (essentially CH₄). Steam methane reforming was considered by Kirk-Othmer [48] to be the most environmentally acceptable method of producing H₂, although conventional SMR with natural gas is not a sustainable over the longer-term due to the fact that it is a finite, fossil fuel, carbon emitter (albeit at a considerably lower level than with coal).

The AD process emits small amounts of sulphur in the biogas (CH₄) that needs to be removed. The quantity of sulphur and any other contaminants present in the biogas and compost are dependent on the composition of the organic waste used. The AD plant is beneficial to the environment in that it is an EfW option, which re-routes waste that would otherwise be sent to landfill sites. In addition, the near-pure methane that is produced has practically no contaminants, and therefore the by-products from the AD-SMR system would be minimal.

4. CONCLUDING REMARKS

4.1 Summary of the Findings from the Present Study

An indicative appraisal has been undertaken of a combined *anaerobic digestion* - *steam methane reforming* process (see Fig. 1) to produce H₂ from organic waste. The *anaerobic digestion* plant was based on the plant in Tilburg (The Netherlands), and was modelled from

the kerbside organic waste collections through to methane production. It is envisaged that a variety of local authorities would provide biogenic waste as a feedstock to a large, *Valorga*-type *anaerobic digestion* plant (again modelled on that in Tilburg plant) coupled to a suitably-sized SMR facility or several smaller ones in a cluster. However, in practice it is likely that the *anaerobic digestion* plant would be supplied by a variety of MSW feedstock types. The technical feasibility of this hydrogen production chain was assessed based on biogenic waste collected in a local authority area and its bioregion: that governed by the *Bathnes* Council (in the South West of England, UK). This was scaled-up to match that of a Tilburg-like *anaerobic digestion* plant. The overall efficiency of the combined *anaerobic digestion* - *steam methane reforming* system is high only if the plant delivers two co-products: compost, as well as H_2 . An important benefit of the H_2 produced from this process is that it is near-zero carbon and renewable. Widespread adoption of such facilities would reduce local waste disposal problems in the UK, and contribute to reducing the greenhouse gas emissions (since the reliance on fossil fuels would lessen). The results from the organic *municipal solid waste* collection trials could be used to identify areas that might provide ‘good quality’ sorted waste, and estimate the geographic area that could most benefit from biogenic municipal waste collection.

The majority of the energy that is lost in the combined *anaerobic digestion* - *steam methane reforming* plant (see again Fig 1) is due to waste water and mechanical inefficiencies. In contrast, the bulk of the exergy losses were due to internal processes, such as the fermentation process, the combustion process in the boiler, and reforming of the methane into H_2 . The products from the combined process are 3% by weight of H_2 and 97% by weight of compost. The overall energy efficiency is 74.6% and the overall exergy efficiency is 60.4%. Other H_2 process efficiencies vary from 21% to 86%, the higher efficiencies belonging to non-renewable processes. If the compost were considered as just ‘waste’ product, then the overall efficiencies fall to approximately 1% in terms of both the energy and exergy analysis, which are obviously low in comparison to other hydrogen production processes. This is because the high proportion of compost produced dominates the efficiency of the plant and the percentage of hydrogen is small in comparison to other outputs.

Discounted cash flow accounting indicated that in order to attain a payback period of less than 20 years, then an annual charge of at least £1.04 per household is needed. Due to *economies of scale* it may be beneficial to investigate the installation of a centralised, large-scale *steam methane reforming* plant, which could buy in synthetically produced methane from anaerobic digesters dispersed throughout the UK. Installing anaerobic digesters throughout the country would help with the waste disposal problem and would also provide the *steam methane reforming* plant with a sustainable, renewable feedstock. Such a scheme would contribute to reducing the current rate of global climate change since the reliance on fossil fuels would decrease and could be a key step in the direction of providing the UK with a more sustainable, renewable energy market.

4.2 Technological Bottlenecks and Recommendations for Further Research

A focus of the *Royal Society* (RoySoc) H_2 expert study [11] of options for producing low-carbon hydrogen at scale [11] was on a range of alternative technologies. These comprised

‘thermochemical routes’ (embracing *steam methane reforming*); biological routes [including *anaerobic digestion*]; ‘electrolytic routes’; and a suite of innovative technologies under the umbrella title of ‘*solar to fuels*’. In the present context, there are a number of technological bottlenecks associated with *anaerobic digestion* and *steam methane reforming* plants. They concluded that *anaerobic digestion* plants are feasible now at a laboratory or small scale [11]; notwithstanding the fact that the Tilburg facility demonstrates the practicality on a much larger scale [48]. The RoySoc experts argued that *anaerobic digestion* plants might have greatest impact if used to produce high value chemicals in conjunction with a biorefinery [11,18]. Achinas *et al.* [49] suggested that there were important technical, economical, and ecological barriers. Costs are particularly prohibitive when utilising multi-stage reactors. Optimising key elements (such as micro-organism species, pretreatment methods, purification technologies, and substrate properties) are the main challenge to cost-effective methane production according to Achinas *et al.* [49]. The US *Office of Energy Efficiency & Renewable Energy* [50] recently noted that gas-liquid mass transfer also provides a bottleneck, due to the low solubility of CH₄ and results in cost challenges to gas phase fermentation systems. In terms of the *steam methane reforming* technology, the RoySoc suggested that it was already a commercial route, but was not low carbon. They therefore recommended that it would have to be coupled with carbon capture technologies [11,13-16]. However, this H₂ expert group [11] did not consider the option of a combined *anaerobic digestion* - *steam methane reforming* facility of the type studied here that potentially delivers low carbon, renewable H₂.

Future *anaerobic digestion* research is required in order to fill the gap between engineering and biology/biotechnology identified above [11,49,50]. In the present context, further research would be useful in terms of verifying the quantities of hydrogen that could be practically produced via a combined *anaerobic digestion* - *steam methane reforming* facility from the total organic fraction of UK waste. This would need to highlight whether the distributed production of H₂ from the *municipal solid waste* would be beneficial overall to the UK (or elsewhere) in terms of the production of an affordable, sustainable energy market. The calorific value of compost derived from an anaerobic digester should be carefully determined to enable an accurate efficiency of the plant to be obtained. On a local scale, it would be valuable to optimise the environmental conditions inside an *anaerobic digestion* tank suitable for installation in *Bathnes*, or a local authority area of comparable size, and to establish the feasibility of installing such a plant on the basis of community collection trials (outlined in Section 3.2 above). Finally, the practical feasibility of a centralised *steam methane reforming* plant to produce methane from large anaerobic digesters dispersed across the UK or in similar industrialised countries.

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APPENDIX A. KEY ASSUMPTIONS AND OPERATIONAL PARAMETERS ASSOCIATED WITH THE ANAEROBIC DIGESTION SYSTEM

A.1 Organic Waste Collection

The organic waste input was assumed to be sorted at source. It amounted to a total waste input to the AD system of 40,000 t (see Section 3.2 above). The waste was assumed to be only collected over 250 days per year, because of weekends and ‘bank’ (i.e., public) holidays. This implying that 160 t of waste was collected per day within the *Bathnes* geographic area (of the South West of England). This was averaged over a period of one year to obtain a constant flow of 110 t per day. The proportions of different materials that make-up municipal solid waste in the *Bathnes* area is depicted in Fig. 4. The organic element of municipal solid waste was made up from the kitchen, garden and paper and card sections. It can be seen from Fig. 4 that the organic fraction of waste arisings is 55%, although only garden and food waste were assumed to be used in an anaerobic digester (because paper and card can be recycled). Thus, the proportion of food waste to garden waste presented in Fig. 4 can be seen to be about 17% wood and 83% food. The calorific values of wood and food waste was taken to be 14.5 GJ/t and 6.8 GJ/t respectively, were used for the energy input to the system and as a means for calculating the chemical exergy [51].

A2. Transport

The data for transport was obtained from conversations with the project supervisor of the *Bathnes Council* waste collection trials (Peter Francis, private communication). The ‘bin lorries’ (relatively large, heavy motor vehicles used for refuse collection in the UK) that were used for the trials were weighed to determine the amount of waste that was collected. These lorries or ‘dust carts’ have a six tonne (dry weight) and during the trials their weight increased up to 16 t when loaded (see also Section 3.2 above), hence they collect up to 10 t of waste. However, this is not the maximum capacity as research from other trials in the UK reported lorries collecting up to 16 t. If the lorries were to be used to collect waste for a commercial scale project, then collections would be carried out five days per week, accounting for bank holidays that equates to 250 days per year. Consequently, one lorry would be able to collect 4000 t of compostable waste per year, assuming that the lorries only collect one load every day. The *Valorga* digester in Tilburg typically operates at 80% capacity, which enables it to process 40,000 t of waste per year. Assuming that the lorries are available for use 250 days per year, this implies that 10 lorries would be required to collect the waste. A sample round from the trials collected waste from 180 households, taking approximately one hour to complete and resulted in approximately 2 t of organic waste. The lorries would therefore need to complete about 8 rounds per day of a similar size to collect the 16 t of waste needed. These round trips currently range from 1.5 miles (2.41 km) to about 20 miles (32.2 km). Taking an average of 10 miles (16.1 km) and 8 round trips per day, the lorries would travel about 80 miles (128.7 km) per day, thus 800 miles (1287.5 km) per day in total for all 10 vehicles. The distance travelled assumed that the *Valorga* (Tilburg-like) digester plant would be in a similar location relative to the collection rounds for the Bath recycling depot. The dust carts have a fuel consumption of 25 miles per gallon (mpg) (10.63 kilometres per litre (km/l)) during normal running, but they spend the majority of the time stopping and starting, which reduces the fuel consumption. Therefore a fuel consumption of 20 mpg (5.80 km/l) has been used. 800 miles (1287.5 km) at 20 mpg (5.80 km/l) indicates 40 gallons diesel (181 l) was used per day. The calorific value of diesel is 35 MJ/l, and hence 6.3 GJ per day was required for the transport of waste from households to the digester site. This was based on the lorries running for 250 days per year, therefore this has been averaged to obtain a daily value of 4.3 GJ.

A.3 Reception

The reception for the digester site (in Tilburg) contained of a conveyor belt was modelled to transport the waste from the reception to the crushing unit. The power requirement was assumed to be a third of that for the total conveyor belt power for the Tilburg facility, i.e., 5 kW. Assuming that the conveyor belts only run for 2000 hours per year, then the average power would be 1 kW. The plant in Tilburg has a unit that collects all MSW and sorts it into organic, non-organic and metal parts before it was sent to the crusher unit [34]. However, the present analysis assumed that the waste collected was sorted at source, and therefore there was no need for mechanical sorting.

A.4 Crushing

The pretreatment crushing unit (identified schematically in Fig. 1) was assumed to be of comparable size to the unit at the full-scale Tilburg plant [34]. The waste was moved to the mixer on a conveyor belt, requiring one third of the total conveyor belt power. Thus, 1 kW assumed for operational purposes over 2000 hours per year. The power requirement for the crushing unit itself was 150 kW; as with the Tilburg plant. Assuming that the crushing sheers operate for 2000 hours per year, then the average power consumed was at a rate of 34 kW.

A.5 The Mixer

The dilution section of the process was again assumed to be the same as that of the Tilburg plant. Waste was mixed with process water to an average of 30% total solids [34], and pumped into the *Valorga* digester tanks with a solids pump. The power rating of the mixer and solids pump was 91 kW. Assuming that the solids pump operates for 2000 hours per year, then the average power usage was at a rate of 21 kW.

A.6 Fermentation

The *Valorga*-type digester (see again Fig. 3) modelled in the present analysis was assumed to function in the same way as that of the full-scale Tilburg plant. Two tanks, each of 3300m³ in volume, produce approximately 75 m³ of biogas per tonne of organic bio-degradable matter, which equates to approximately 3.0 Mm³ biogas per year. The biogas contains approximately 56% of CH₄ and 100 ppm of H₂S [32,34]. 99% of the biogas produced from AD tanks consists of methane and CO₂, with the majority of the remaining elements being saturated water vapour and H₂S [32,52]. Thus, the biogas was modelled as containing 6.6% water vapour (saturated at 38°C) and 37.4% of CO₂. Both enthalpy and entropy values of each gas at 38°C [51] were used to calculate the energy and exergy characteristics in the biogas. Digested matter exiting the *Valorga*-type digester tanks was estimated to be approximately 50% of the total mass entering; in line with the Tilburg plant. The water content of the organic matter used as feed to the digesters was assumed to be partially released during fermentation, and hence the quantity of liquid exiting the tanks was greater than that entering. The water content of wood waste was taken to be 16%, and that for food waste as 60% [48]. In terms of the compost, its calorific value was used to calculate the energy value of the solids exiting the digester tanks, as well as the suspended solids in the process water. The composition of the compost was not known directly, and therefore the exergy of the compost and suspended solids was taken to be the same as the enthalpy of the compost. The enthalpy and entropy values of water were used to calculate the energy and exergy in the process water.

A.7 Low Pressure Gas Storage

The biogas collected was modelled commensurate with the output from the Tilburg plant. It was mainly stored in a low-pressure tank.

A.8 High Pressure Gas Storage

The proportion of biogas used to mix the tanks pneumatically was not known by direct measurement, but was assumed to be about 20% of the total biogas given off. This biogas was compressed and stored in a high-pressure gas storage container before being injected into the digester tanks. The power requirement of the compressors was the same as that of the Tilburg plant (72 kW), which was assumed to run continuously throughout the year.

A.9 Refining

The biogas produced from the plant in Tilburg was not refined on the site, and hence the analysis does not follow the procedure adopted in Holland to refine the biogas. This refining process has one principal aim, to remove as much CO₂ and H₂S from the biogas as possible. The carbon dioxide dilutes the calorific value of the biogas and H₂S is corrosive. Consequently, both contaminants needed to be removed before the gas could be used in any other process. There were several processes that could be used to remove each substance from the gas. CO₂ can be extracted by scrubbing (dissolving it in solvents, such as ethanolamines, in an aqueous solution under pressure). H₂S can be removed in a similar manner, or reacted with an ‘iron sponge’ (hydrated iron oxide (Fe₂O₃)): see the upper section the schematic process diagram illustrated in Fig. 1. This produces iron sulphide and water according to the following reaction:



However, it is more expensive to carry out these processes individually, and so a process that uses pressurised water to remove both substances from the biogas has been modelled. This technology - known as *Binax* - was developed by *Central Plants Inc.* to purify biogas, and it produces nearly pure methane [53]. In order to purify the biogas, it was compressed and injected into the base of a pressurised tower. The biogas flows up a CO₂-scrubbing tower (again depicted in the upper section the schematic process diagram illustrated in Fig. 1) and a counter-flow of water absorbs the contaminants, leaving near pure methane to be collected from the top. The water was depressurised and piped to a regenerator tower, where the CO₂ and H₂S were flashed from the water. The regenerated water was then re-circulated through the gas-scrubbing tower. The quality of the biogas produced from the *Binax* system contains 2% CO₂ and 4ppm H₂S [53]. Biogas was subsequently transported to the refining plant via fans, the power requirement being similar to the Tilburg plant, which run continuously throughout the year.

A.10 Dehydration

The digester material was modelled to exit the *Valorga*-type digester tanks under gravity in a manner akin to that employed for the Tilburg plant. It utilised a screw press that was electrically driven with a power requirement of 90 kW. Assuming that the screw press operates for 2000 hours per year, then the average power consumption would be 21 kW. The solids that result were assumed to have a calorific value analogous to that of compost, i.e., 4500 kJ/kg. The liquids exiting the press were assumed to contain 10% solids. This needed a power requirement for pumping to the centrifuge of about one fifth of the plant re-circulating pumping power, 4 kW. Assuming that the re-circulation pumps operate for 2000 hours per year the average power requirement was around 1 kW.

A.11 The Centrifuge

A centrifuge removed suspended solids from the process water and was modelled as being comparable to the unit at the Tilburg plant, i.e., it removes 5% of the suspended solids. The power requirement for this centrifuge was 38 kW. Should it operate for 2000 hours per year,

then the average power was taken to be 9 kW. The process water required for diluting the incoming organic waste to 30% total solids was calculated to be approximately 86% of the total liquid out of the *Valorga*-type digester. This was pumped into the process water storage tank, whilst the remaining liquid was supplied to the belt filter press. The pumping power requirements were assumed to be two fifths of that of the plant re-circulating pump, i.e., 8.8 kW. Again, if the re-circulating pumps operated over 2000 hours per year, this would result in an average power requirement of some 2 kW.

A.12 Process Water Storage

The process water storage tank heats the incoming liquid to approximately 60°C by steam injection, before it was pumped into the mixer. The heat transferred to the system was calculated from the mass flow rate of the steam flowing into the storage tank multiplied by the enthalpy of the steam at 100°C and 1 atm. The average heat transferred to the process water was found to be 306 kW, whereas the power requirement to pump this liquid to the mixer was assumed to be a fifth of the plant re-circulating pumping power, i.e., 4.4 kW. Again, assuming that the re-circulating pumps ran for 2000 hours per year, then their average power requirement was 1 kW.

A.13 Filtration

The remaining liquid from the centrifuge was pumped via a belt filter press, where a further 4% of the dry matter was removed. Waste water was then pumped to a sewerage plant and was considered lost from the process. The power requirement for the latter operation was assumed to be about fifth of the plant re-circulating pumping power, i.e., 4.4 kW. This resulted in an average power requirement of 1 kW, when the re-circulating pumps operated for 2000 hours per year. Similarly, the power requirement for the belt filter press was 10 kW and, for operating over 2000 hours per year that gave rise to an average power requirement of 2 kW.

A.14 Compost

The compost section of the process was presumed to operate in a manner akin to the Tilburg plant. The solid matter from the screw press, the centrifuge and the belt filter press was transported on a conveyor belt to an aerobic composting hall. These conveyor belts required about one third of the power of the overall plant conveyor belt, i.e., 5 kW. Once more, if the conveyor belts operate for 2000 hours per year, then the average power requirement was 1 kW. The energy content of the compost was assumed to be 4500 kJ/kg, which is the calorific value of the compost yielded by the Tilburg plant. The chemical composition of the compost was not directly known, and so the chemical exergy term was assumed to be the same as the equivalent energy term.