Optimisation of Rural Biomass Waste to Energy Systems

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Abstract

Optimisation of Rural Biomass Waste to Energy Systems

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Biomass waste to energy conversion systems were traditionally installed on rural farms to manage manure disposal and mitigate odour. These systems provide heating and electricity and are increasingly viewed as sources of revenue. Poorly operated or sized systems will not realise revenue. For farms that would like to install such systems, there is no tool available that optimises the systems prior to determination of their commercial viability. As such, there is a need to optimise these systems to determine the threshold herd size for commercially viability, and their maximum revenue. The associated optimisation problem is non-linear, non-convex and very difficult. Consequently, its solution is explored with a metaheuristic. The Tabu Search metaheuristic was adapted to solve this problem by: multi-period and diversification strategies that effectively search the solution space, handling of constraints using different strategies for searching feasible regions, with incursions into infeasible regions, and evaluation of a multi-objective function exploiting an approximation of the Pareto front. This dissertation is on research done to determine the threshold herd size for commercial viability of the biomass waste to energy conversion systems, and the maximum revenue from these systems. The threshold herd size was found by optimisation of the systems for different herd sizes. The threshold herd sizes were 80 dairy cows and 1200 swines for Quebec, and 100 dairy cows for Ontario. These considered co-digestion of manure and food waste, use of by-products, food waste tipping fees and an increase in the electricity tariff. The threshold herd size for Quebec also considered a favourable net metering contract. When digesting manure only, the threshold herd sizes were, 350 dairy cows for Quebec and 200 dairy cows for Ontario. The maximum revenue from the biomass waste to energy system was determined by optimising the system for a given herd size. Revenue was maximised by: minimising cost through proper sizing of the components, minimising consumption of propane and electricity from the grid, selling electricity to the utility, and capitalising on renewable energy incentives. The maximum revenue was determined for a herd size of 500 cows, and recommendations were made on its mode of operation.

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List of Acronyms

ADM1	Anaerobic Digester Model No. 1
BWECS	Biomass Waste to Energy Conversion System
C/N	Carbon-to-Nitrogen
CAD	Canadian Dollars
CDMA	Code Division Multiple Access
CHP	Combined Heat and Power
COD	Chemical Oxygen Demand
COD_p	particulate Chemical Oxygen Demand
COD_s	soluble Chemical Oxygen Demand
dq	direct-quadrature
FS	Fixed Solids
GISCOD	General Integrated Solid Waste Co-Digestion
HRT	Hydraulic Retention Time
HHV	Higher Heating Value
IRR	Internal Rate of Return
IWA	International Water Association
LHV	Lower Heating Value
mh	wet mass
ms	dry mass
MIMO	Multiple Input Multiple Output
MIND	Method for analysis of INDustrial energy systems
MSW	Municipal Solid Waste
Norg	Organic nitrogen
NPV	Net Present Value
PV	Photo Voltaics
Scat	Alkalinity
t_{mh}	tonnes of wet mass
t_{ms}	tonnes of dry mass
orthoP	orthophosphate
TAN	Total Ammonia Nitrogen
TC	Total Carbon
ThOD	Theoretical Oxygen demand
TIC	Total Inorganic Carbon
TKN	Total Kjeldahl Nitrogen
TOC	Total Organic Carbon
TP	Total Phosphorus
TS	Total Solids
TVA	Total Volatile Acids
TVS	Total Volatile Solids
USA	United States of America
USD	United States Dollars
VFA	Volatile Fatty Acids
VS	Volatile Solids

Nomenclature

C	Carbon
CH_3COOH	acetic acid
CH_4	Methane
Cl	Chlorine
CO_2	Carbon dioxide
H	Hydrogen
H_2	Hydrogen gas
H_2O	Water
H_2S	Hydrogen sulphide
HCO_3^-	Hydrogen carbonate
K	Potassium
K_2O	Potassium oxide
N	Nitrogen
NH_3	Ammonia
O	Oxygen
O_2	Oxygen gas
P	Phosphorus
P_2O_5	Phosphorus pentoxide
S	Sulphur

Chapter 1

Introduction

The first digester was built at a leper colony in Bombay, India in 1859 [1]. Since then the anaerobic digestion technology has advanced with many digesters built worldwide. The digesters are increasingly being used on rural farms and incorporate energy co-generation, forming biomass waste to energy conversion systems. Some dairy farms in Canada and the USA use these biomass waste to energy conversion systems to manage the disposal of manure and mitigate odour. These farms did not previously pay for manure disposal, but spread the manure on the land or stored it in lagoons for extended periods. This caused a bad odour and attracted flies, resulting in complaints from neighbours. Anaerobic digestion of the manure in a biomass waste to energy conversion system is an alternative method of manure disposal. The biogas produced by these systems is combusted to generate electricity and heating. The capital cost of a biomass waste to energy conversion system is very high. Gordondale Farms with 850 dairy cows paid USD 520,000 [2], Stencil Farm with 1000 cows paid USD 500,000 [2] and New Horizons Dairy with 2000 cows paid USD 1,526,000 [3] for their biomass waste to energy conversion systems. These costs are prohibitive to farmers with small herds and whose primary concern is to dispose of manure. In addition, there are problems faced by existing systems due to poor sizing and operation. The challenge is to maximise revenue of these systems to cover their high capital cost, besides providing another revenue source for the farms. Revenue is obtained from the sale of electricity to the grid and from food waste tipping fees. The farms' costs are also reduced by avoiding the use of electricity from the grid and the use of propane for heating. In New York State and Ontario province, electricity can be sold to the grid to generate revenue, or net metering arrangements can be made. Farms in Quebec province that have biomass waste to energy conversion systems do not feed electricity to the grid. The by-products of the biomass waste to energy conversion system can also be used as animal bedding after further processing. This is also a cost saving. The biomass waste to energy conversion systems will be described next.

1.1 Description of a Biomass Waste to Energy Conversion System

A diagram of the basic biomass waste to energy conversion system is shown in Figure 1.1. The system model consists of a digester, a lagoon, an internal combustion

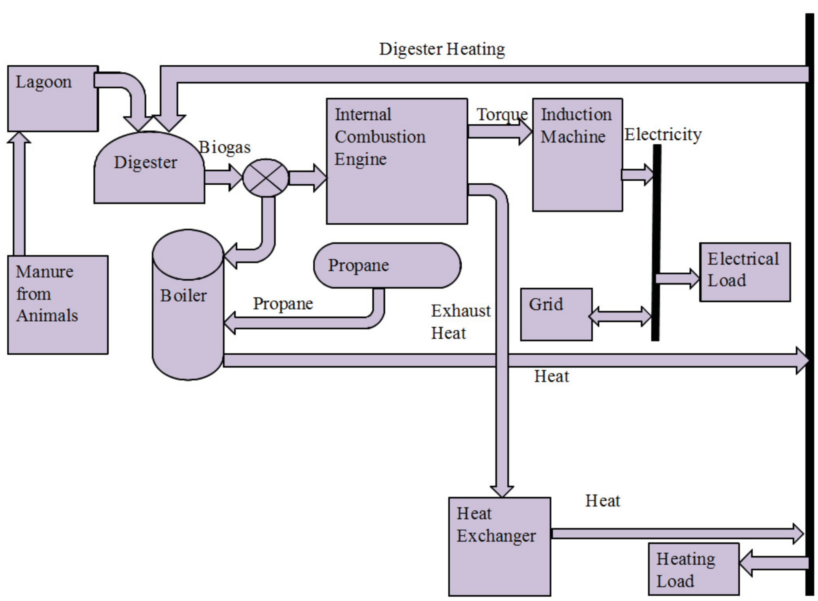


Figure 1.1: Biomass Waste to Energy Conversion System Model

engine, an induction generator, a boiler, a propane tank, a heat exchanger and the electricity grid. The source of biomass waste in this system is farm manure. Manure is stored in a lagoon. This allows for variation of flow into the digester. Biogas is produced as a result of the anaerobic digestion of the manure in the digester and combusted in an internal combustion engine to generate torque. The torque is applied to an induction generator to produce electricity. Some of the biogas generated is combusted in a boiler to produce heat. The exhaust heat from the internal combustion engine is captured by a heat exchanger. A propane tank is included in the system to provide a backup fuel supply. This is in the event that biogas generated is insufficient to run both the generator and the boiler, to meet the heating demand. The electricity grid connection is included since excess electricity can be sold to the grid or electricity can be obtained from the grid. The digester requires heating, which is obtained from the system.

The anaerobic digestion process in the digester occurs in the absence of oxygen. Biogas produced comprises of methane, carbon dioxide, nitrogen, water vapour and hydrogen sulphide [4]. There are three temperature ranges in which the bacteria for anaerobic digestion operate; psychrophilic (5°C-20°C) [5], mesophilic (25°C-43°C) [5] and thermophilic (50°C-70°C [4]). There are two types of digesters in use on farms reviewed: complete mix and plug flow digesters. In complete mix digesters, the manure is mixed within the digester [6]. In plug flow digesters, manure is introduced into one side of the digester, and when a new plug of manure is added, it pushes existing manure through the digester [6]. The HRT (Hydraulic Retention Time) of a digester is the time that biomass waste spends in the digester while undergoing anaerobic digestion. This is an important aspect of digester sizing which is dependent on the biomass waste flow rate and the volume of the digester. The farms reviewed in Section 1.2 have a typical HRT of 15-25 days.

1.2 Existing Biomass Waste to Energy Conversion Systems

Section 1.2 reviews existing biomass waste to energy conversion systems on farms and in cheese factories in North America. These systems have incurred high capital costs. In addition, due to poor sizing and operation, the systems produce excess biogas that has to be flared. As such the systems are not maximising revenue from the sale of electricity or avoidance of costs. This section highlights the manner in which the systems are operated and the need for their optimisation. Information on the commercial viability of biomass waste to energy conversion systems is not available. Cost savings and revenue from electricity generation and sale of digester effluent for some of the systems has been provided. This gives an indication of the potential commercial viability of the systems. Table 1.1 is a summary of farms with existing biomass waste to energy conversion systems in North America. Details of the biomass waste to energy conversion systems on these farms are discussed in this section.

Table 1.1: Existing Biomass Waste to Energy Conversion Systems in North America

Farm	**Herd Size (livestock)**	**Type of Digester**	**Installed Generation Capacity (kW)**	**Year of Installation**
Clover Hill Dairy	1250	plug flow	300	2007 [2]
Gordondale Farms	850	plug flow	140	2002 [2]
Double S. Dairy	1100	plug flow	200	2002 [2]
Stencil Farm	1300	plug flow	123	2002 [2]
Klaesi Brothers Farm	142	plug flow	74.6	2003 [7]
Ridgeline Dairy Farm	600	complete mix	130	2001 [8, 9]
Stanton Farm	2000	plug flow	300	2008 [10]
Blackburn Cheese Factory	-	fluidised bed	no generator set	2007 [11]
Port-Joli Cheese factory	-	fluidised bed	no generator set	2010 [11]
Saint-Hilaire Farm	10,000	plug flow	50	2007 [12]

The digester on Clover Hill Dairy farm in Wisconsin [2] is operated in the mesophilic temperature range with a design HRT of 20 days. Exhaust heat from the engine is used to heat the digester, milking parlour and lanes. Excess heat is generated.

There is no backup heat supply for the digester in the event that the engine is non-operational. The Clover Hill Dairy's biomass waste to energy conversion system includes a screw press that separates digester effluent into solids and liquids. The farm gets revenue of approximately USD 600 per week from selling the solid effluent as animal bedding [13]. The electricity generated by the system is not owned by the farm and hence revenue from electricity generation does not count towards the farm [2, 13].

Gordondale Farms in Wisconsin [2] generates 114m^3 of a mixture of manure, bedding and milking parlour waste daily. The digester is operated in the mesophilic temperature range and at a design HRT of 22 days. Electricity generated is sold to a utility company. Exhaust heat from the engine is used to heat the digester and milking parlour, and to heat water. The farm has no backup boiler for use, in the event that the engine-generator set is non-operational. The farms' approximate annual revenue from electricity sales is USD 28,800. The farm has also realised a reduction in the cost of heating the milking center and offices since heat from the heat exchanger is used for these areas. The Gordondale Farms' biomass waste to energy conversion system includes a screw press that separates the digester effluent into solids and liquids. The solids are used as bedding for the cows, which saves the farm bedding costs. The liquid effluent is used as fertiliser which saves the farm the cost of commercial fertilisers and lime. The electricity utility company owns and operates the electricity generation equipment and therefore revenue from the sale of electricity does not go to Gordondale Farms [14].

Double S. Dairy in Wisconsin [2] generates 125m^3 of a mixture of manure, wastewater and bedding daily. The digester is operated in the mesophilic temperature range at a design HRT of 20 days. Electricity generated is sold to a utility company. Information of revenue from the sale of electricity was not available. Exhaust heat captured from the engine is used to heat the digester, milking parlour, shop and a swimming pool. The digester cost USD 500,000 and was built in 2002. The farm also has a screw press that separates solid and liquid digester effluent. Use of the solid effluent as bedding saves the Double S. Dairy farm USD 30,000 annually in animal bedding costs [15].

Stencil Farm in Wisconsin [2] operates its digester in the mesophilic temperature range with a design HRT of 20 days. Electricity generated is used entirely on the farm. Exhaust heat from the system is used for heating the digester.

Klaesi Brothers Farm in Ontario [7] has a 500m^3 digester. 1520m^3 of manure is fed to the digester daily. The digester is operated at a HRT of 25-35 days and at a temperature of 35°C-42°C. Milk centre wash water is added to the manure. Electricity is generated during peak demand times and is used on site. The farm also has a net metering agreement with a utility company. The engine-generator set runs for a total of 12 hours a day since the net metering arrangement does not allow for sale of electricity in excess of 50kW demand . The engine produces approximately 88kW of exhaust heat that is used to heat the digester. In winter the exhaust heat is used to heat two farm houses and to heat water. The digester cost CAD 180,000 and the energy generation equipment cost CAD 110,000. Klaesi Brothers Farm receives a revenue of CAD 20,000 annually from the sale of electricity. The biomass waste to energy conversion system has a pay back period of 10 years [7].

The digester on Ridgeline Dairy Farm in New York [8, 9] is fed with 95m^3 of manure and food waste, daily. It is operated in the mesophilic temperature range at a HRT of 20 days. Electricity generated is used on site and also exported to the grid. Exhaust heat from the engine-generator set is used to heat water and to heat the digester. The total capital cost of the biomass waste to energy conversion system of Ridgeline Dairy Farm was USD 622,520 [9]. Ridgeline dairy farm gets revenue from food waste tipping fees and the sale of electricity. It also saves on heating costs of the barns and farm office [16]. The revenue, costs saving and commercial viability of the biomass waste to energy conversion system was not quantified.

Blackburn Cheese factory in Quebec treats its effluent by anaerobic digestion. The cheese factory has a 30m^3 digester that produces $28,000\text{m}^3$ of biogas annually. 1.1 million litres of washing water and 0.7 million litres of whey are treated annually [11]. The biogas generated is combusted in a boiler that heats water used in the cheese making process. 170,000kWh of energy is produced annually.

Port-Joli Cheese factory in Quebec also treats its effluent by anaerobic digestion. The cheese factory has a 16m^3 digester that treats 630,000 litres of wash water and 350,000 litres of whey annually [17]. The biogas generated is combusted in a boiler to heat water that is used in the cheese making process. $14,000\text{m}^3$ of biogas and 91,000kWh of energy are produced annually.

Manure from the swines on Saint-Hilaire Farm in Quebec is treated by anaerobic digestion in three digesters, each of volume 450m^3. The digesters operate in the temperature range 15°C-25°C [12]. Biogas is combusted in a boiler to generate 176kW of heat [12].

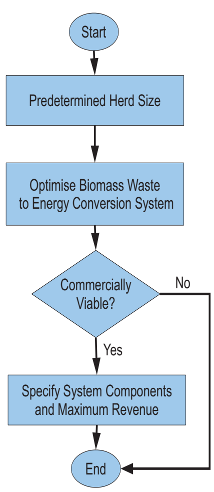
Biomass waste to energy conversion systems need to be optimised in order to maximise revenue. This is the rationale for the research carried out and forms the basis of the objectives of the research, which are given in Section 1.3.

1.3 Objectives of the Research

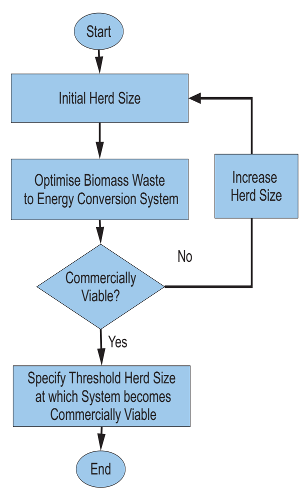
The objectives of the research undertaken are:

(i) determination of the maximum revenue that can be obtained for a given herd size from a biomass waste to energy conversion system (the process is illustrated in Figure 1.2(a)) and

(ii) specification of the threshold herd size at which a biomass waste to energy conversion system becomes commercially viable (the process is illustrated in Figure 1.2(b)).



(a) Determination of Maximum Revenue for a Given Herd Size



(b) Minimum Commercially Viable Herd Size

Figure 1.2: Process Flow

From the process flow diagram of Figure 1.2(b), a plot of herd size against NPV (Net Present Value) of the biomass waste to energy conversion systems is drawn (Figure 1.3). The plot is obtained by optimising the biomass waste to energy conversion systems for a range of herd sizes. In Figure 1.3 (which is shown only for illustrative purposes), there is a point where the NPV becomes negative. This is the threshold at which the biomass waste to energy conversion systems become commercially viable. The herd size at this point will be specified as the minimum for which biomass waste to energy conversion systems are commercially viable. Part of this research is to generate the most optimised curve as shown in Figure 1.3.

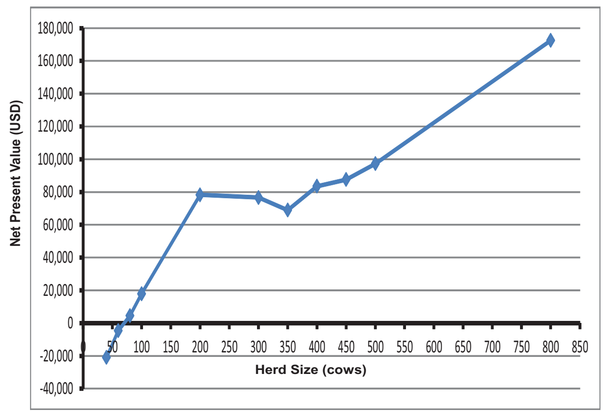


Figure 1.3: Illustration of Determination of Threshold Herd Size at which Biomass Waste to Energy Conversion Systems Become Commercially Viable

To determine the impact of the waste characteristics and the system parameters on the predictions of the optimisation tool, a sensitivity analysis should be carried out. The waste characteristics that may impact predictions are COD (Chemical Oxygen Demand) and biodegradability. The parameters of the system's components that may impact predictions are: HRT (Hydraulic Retention Time), digester temperature, the lower heating value of propane, the efficiencies of the heat exchanger and boiler, and the temperature of water in the heat exchanger. The overall system parameters that may impact the predictions are: the period over which the capital cost is paid, the lifetime of the engine-generator set, the life cycle of the biomass waste to energy conversion system, the interest rate, the power sizing component used for cost estimation, the factor used for installation costs, the allowance for the heating demand constraint, and the volume flow rate of manure produced per animal.

1.4 Motivation for Research Objectives

Biomass waste to energy conversion systems in North America have been described and the need to maximise revenue from these systems has been highlighted. The motivation for maximising revenue from biomass waste to energy conversion systems is the high capital cost of the systems. These costs are prohibitive to farmers with small herds and whose primary concern is to manage manure disposal. An optimally sized system that maximises revenue is however an attractive investment for farmers. Revenue is obtained from the sale of electricity and the sale of the by-products of the biomass waste to energy conversion processes. The farms also realise savings by not using electricity from the grid and not using propane for heating. An optimally sized system would also reduce capital costs.

Poor sizing of engine-generator sets on existing farms has resulted in production of excess biogas which has to be flared [2]. In addition, excess heat produced in the summer, from a system that is poorly sized has to be exhausted to the atmosphere. This is in contrast to the winter season where propane may be required to generate heat to supplement heat generated from combustion of biogas. This is the case for Green Valley Dairy [2], Lamb Farms [18], Sunnyside Farms [19] and Swiss Valley Farms [20] which flare excess biogas. Clover Hill Dairy [2] had to install additional generation capacity in order to use all the biogas generated. Wild Rose Dairy [2] has a 750kW engine-generator set and has excess heat year round, that is wasted. With an optimally sized system, the engine-generator set and boiler are able to meet the heating load throughout the year, with minimal use of the backup propane supply.

In addition to maximising the revenue from a given herd size, there is a need to determine the threshold herd size at which these systems become commercially viable. The motivation for determination of the threshold herd size at which biomass waste to energy conversion systems become commercially viable is two-fold. Firstly, it is to prevent the shut down of biomass waste to energy conversion systems due to low or no return on investment. Secondly, to encourage farmers to take up the technology in regions like Quebec in Canada, where there are very few installations, by providing a planning tool for farmers and policy makers. The planning tool will aid in designing programs to promote the installation of biomass waste to energy conversion systems on farms. In Quebec province there are no biomass waste to energy conversion systems on dairy farms. There are however biomass waste to energy conversion systems on swine farms [21, 22] and in cheese factories [11, 17]. There was a biomass waste to energy conversion system installed on a dairy farm in Quebec, [23, 24] that has since ceased operations. Overall, Quebec has fewer biomass waste to energy conversion systems compared to Ontario, Wisconsin and New York state. By providing a guideline on the threshold herd size for both swines and dairy cows, at which biomass waste to energy conversion systems become commercially viable, farms in Quebec will be encouraged to install these systems.

In attaining the objectives given in Section 1.3, original contributions have been made in this area of research. These contributions are discussed in the following section.

1.5 New Contributions of the Research

This section discusses new contributions from the research work undertaken. There are 7 contributions made:

(i) determination of the maximum revenue that can be obtained from a given herd size for a biomass waste to energy conversion system,

(ii) specification of the threshold herd size at which biomass waste to energy conversion systems become commercially viable,

(iii) use of the Tabu Search technique in optimisation of non-linear, non-convex, complex biomass waste to energy conversion systems,

(iv) development of a strategy for the evaluation of a multi-objective and multi-period function within the Tabu Search technique,

(v) development of a constraint handling strategy that balances the multi-period and multi-objective aspect of the optimisation problem,

(vi) development of a multi-period optimisation strategy that ensures a smooth transition from one period to another and

(vii) development of a diversification strategy suited to the multi-period problem, by incorporating all variables being optimised in the move to a new region.

A literature review of research on optimisation of biomass waste to energy conversion systems is done in the following section.

1.6 Literature Review

Previous research in the areas of the new contributions made is reviewed in this section.

1.6.1 Maximum Revenue from a given Herd Size

The rate at which biomass waste to energy conversion systems cease operation in the USA is relatively high [6, 25]. Since 1981, 23% of the biomass waste to energy conversion systems installed in the USA have been shut down [26]. The number of systems installed and shut down in the USA is illustrated in Figure 1.4. Although

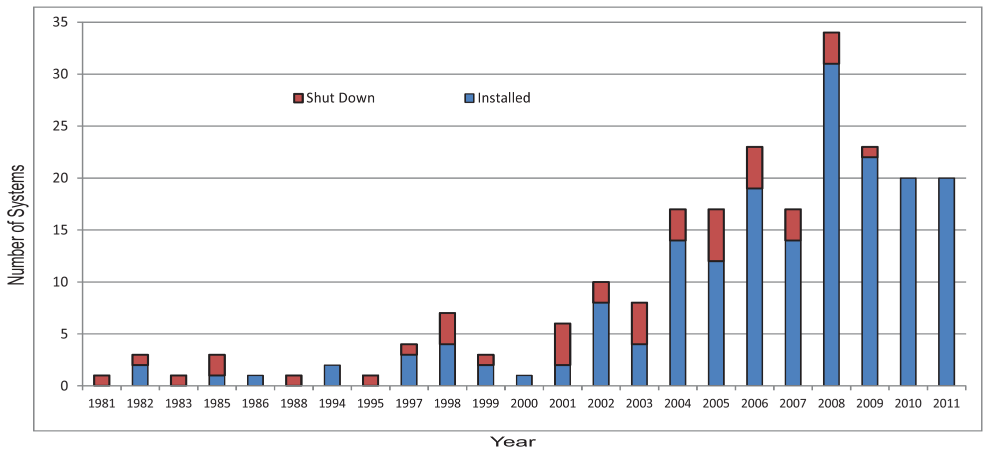


Figure 1.4: Biomass Waste to Energy Conversion Systems in the U.S.
Source: AgSTAR, United States Environmental Protection Agency, March 2012

the digester shut downs can be attributed to multiple factors like: failure due to poor design, poor system installation and poor management [6], farmers have also chosen to cease operations due to the high cost of operation and maintenance, compared to the return on the investment [25]. There was a biomass waste to energy conversion system installed on a dairy farm in Quebec, [23, 24] that has since ceased operations because expected revenue was not realised. The research done gives a guideline on the maximum revenue that can be obtained from biomass waste to energy conversion systems for a given herd size. This guideline can be used by farmers to sustain existing biomass waste to energy conversion systems.

1.6.2 Threshold Herd Size for Commercial Viability

Currently there is no guideline on the determination of the commercial viability of biomass waste to energy conversion systems. Estimates are given for example, commercial viability is estimated at 500 cows in [27], a value which is based on digestion of manure only. This estimate does not consider co-digestion, which would bring in additional revenue from tipping fees, in addition to increasing the biogas yield. This estimate does not consider the economic benefit of the by-products of the digestion, either. The geographical location of the farm is also ignored in the estimate. The geographical location of the farm is important as this is what will determine the electricity tariff and the heating load, based on the average temperatures of the region. The geographical location also determines the proximity of the farm to the co-subtrate used in the biomass waste to energy conversion system. The research done addresses these gaps, in determination of the threshold herd size at which biomass waste to energy conversion systems become commercially viable, for a given region.

1.6.3 Optimisation of Non-linear, Non-convex, Complex Biomass Waste to Energy Conversion Systems

Previous research done handled the optimisation of biomass energy conversion systems differently from the research undertaken. There are three major differences in the research reviewed and the research carried out. The first difference is that linear system models are used in some of the research reviewed, whereas the research undertaken here uses a non-linear system model. Secondly, the electrical energy source is not optimised in the research reviewed, in contrast to the research undertaken. Thirdly none of the research done on optimisation of biomass energy conversion systems used the Tabu Search heuristic.

Previous work done on the optimisation of energy conversion systems uses linear system models i.e., simplified models. HOMER is a software for the optimisation of on-grid and off-grid distributed power systems. Study [28] also used linear models to develop a convex optimisation algorithm for a co-generation facility. In [29] an efficient hybrid power system was developed for remote arctic villages using a linear optimisation technique. The difference between these studies and the research carried out here, is in the way the latter formulates the optimisation problem. The functions that model the energy conversion processes in the research carried out are non-linear, resulting in a non-linear optimisation problem.

There has also been research carried out where the system models to be optimised were non-linear. In these cases, the problems were simplified by optimising energy flow, energy usage or energy storage, rather than energy conversion processes. The following is a review of the simplified optimisation of the non-linear system models. In [30] a strength Pareto evolutionary algorithm was applied to the multi-objective optimisation of a stand-alone PV/wind/diesel system. Unlike the research carried out here, [30] did not model and optimise the energy conversion processes, but modeled and optimised the energy usage. This greatly simplified the system model and the optimisation problem. Similarly, in [31] the operating parameters of a coal fired power plant were optimised in order to maximise plant efficiency. The optimisation was split into stages to simplify the system model. In [32] and [33], the capacity and operation of a combined cooling, heating and power system were optimised using particle swarm optimisation and genetic algorithms, respectively. The optimisation problems were greatly simplified by only considering the system capacity and the ratio of electric to absorption cooling as variables. The authors did not take into consideration the coolant flow rate, which impacts the cost of running the system. This is different from what is being done in the optimisation problem of the research carried out. The optimisation problem of the research carried out includes a fuel sharing ratio. The fuel sharing ratio is treated as a variable of the optimisation. Study [34] used both genetic algorithms and sequential quadratic programming to optimise a multi-biomass tri-generation energy supply. The biomass supply chain, processing and storage were modeled in [34], and the optimisation was based on these models. This is different from the research carried out where the optimisation was based on the energy conversion processes in the system components. In [35] the energy production process for a biomass based energy production system was optimised. The objective function minimised the total operational costs. This is similar to the objective function of the research carried out, however the problem has been greatly simplified. The system model in [35] comprised of process sites. The optimisation was based on a material balance of the inputs and outputs of the sites. In the research carried out, the system model comprises of energy conversion process components, and the optimisation is based on the energy conversion processes. The energy conversion processes are modeled by complex non-linear differential equations. Study [36] used simulated annealing to minimise the capital and operational cost of a PV/wind hybrid energy conversion system. The optimisation variables were the sizes of the system components. The optimisation problem in [36] is also different from that of the research undertaken in that it is based on the system sizing, as opposed to the energy conversion processes.

When optimising an energy conversion system, both electricity and heat sources should be considered as was done in the research carried out. This was not the case in [37], where mixed integer linear programming was used to optimise the utilisation of waste heat from industries. The objective was to minimise the total energy cost. The total energy cost was expressed as the sum of the fuel cost and the waste heat distribution cost. Study [37] did not include optimisation of the electrical energy source.

1.6.4 Strategy for Evaluation of a Multi-objective and Multi- period Function within the Tabu Search

There are various methods used to evaluate multi-objective functions in an optimisation problem, some of which are: (i) the objectives can be combined into a normalised weighted function, (ii) one of the objectives can be evaluated at each iteration of the optimisation, or (iii) Pareto optimal solutions can be determined. In [38] a single-machine scheduling problem was solved using a multi-objective Tabu Search and a weighted objective function. In [39] a different objective was evaluated at each iteration of the optimisation. A multinomial probability mass function was used to select the objective to be evaluated at each iteration. Study [40] solved a mechanical component design problem using a multi-objective Tabu Search optimisation. The Pareto optimal method was used to evaluate the multi-objective function. The solution to proceed with the iteration was selected randomly from a set of Pareto solutions. The method used to evaluate the objective function in the research being carried out is the Pareto front method, where a set of Pareto incumbent solutions is kept. The selection of the solution to proceed with the iteration is done differently in the research carried out. Study [40] randomly selected a solution to proceed with the iteration, the research carried out selected the best solution by weighting and summing the components of the objective function. Selection of the best solution is done to allow the search to proceed with the maximised value instead of a randomly selected value. In addition, the weighting of the cost components of the objective function is aimed at ensuring that their sum is not dominated by the cost component with the largest value.

1.6.5 Constraint Handling Strategy

In the handling of constraints, it is good to allow infeasibility for non-convex constraints. When dealing with non-convex constraints, allowing feasible solutions only, results in the solution taking a longer path towards an optimum. This is because the solution path is limited to feasible regions only. This path can be shortened by allowing infeasible solutions during the optimisation. There are different ways of handling infeasibility. In [41], a ship routing and scheduling problem was solved using Tabu Search. The problem was divided into a main and a sub-problem. Tabu Search was used to solve the main problem optimising the shipping route. The sub-problem which optimised the quantity of cargo being shipped, was formulated as a linear programming problem. Infeasible solutions were generated in the sub-program. A fast heuristic was used to obtain feasible solutions for the sub-problem. In the research carried out, the optimisation problem is not split into a main and a sub-problem. The entire problem is solved using Tabu Search while allowing both infeasible and feasible solutions. In [42] infeasible solutions were handled by incorporating a random move sub-routine into a Tabu Search algorithm for a freight allocation problem. The optimisation problem encountered infeasible solutions, which were allowed. The method of constraint handling developed in the research carried out is different from that in [41] and [42]. The difference with the constraint handling in the research carried out is in the strategy developed to handle the infeasibility within the multi-period optimisation. A second objective function that minimises infeasibility is introduced. At each iteration the optimisation is carried out for the period with the most infeasible solution.

1.6.6 Multi-period Optimisation Strategy

The Tabu Search optimisation in the research carried out is a multi-period one. Different strategies are used for Tabu Search multi-period optimisation. In [43] a long term hydro scheduling problem was studied. The period for which the optimisation was to be carried out was selected at random. In [44] a Tabu Search was used to minimise the cost of turning on and off generating units in a hydro-thermal power system. The period for which the Tabu Search optimisation was to be carried out, was also randomly selected. A different strategy was used in [45], where an enhanced Tabu Search algorithm was used for solving an economic dispatch problem for power generating units. Selection of generating units for optimisation was done using a round robin method. A different generating unit was selected at each iteration. Another strategy for handling multi-period Tabu Search optimisation is to treat the period as a variable. This was done in [46]. Treating the period as a variable results in the neighbourhood consisting of Tabu moves from one period to the next. In a multi-period optimisation one has to worry about the difficulty of smoothing the transition from one period to the next during the optimisation. The drawback of the multi-period optimisation strategy of the studies cited is that the selection of the period to be optimised was being done at random. The result is that there is no smooth transition from one period to the next. The strategy developed in the research carried out is different from the strategies in the studies reviewed. In the former, selection of the period for which the optimisation is to be carried out, is done by balancing the use of the round robin method with selection of the period with the most infeasible solution.

1.6.7 Diversification Strategy

Diversification drives the Tabu Search into new regions. Diversification is applied if the incumbent solution does not improve after a given number of iterations. Three methods of diversification are: (i) performing random moves, (ii) performing a restart with the incumbent solution and (iii) generating a random solution as the current solution. In [47], random moves were made in order to diversify the Tabu Search in the optimal scheduling of a multiuser MIMO (Multiple Input Multiple Output) CDMA (Code Division Multiple Access) system. Diversification by performing a restart with the incumbent solution was done in [48], where a Tabu Search algorithm was applied to a heterogeneous fixed fleet vehicle routing problem. Scheduling of trucks in cross-docking systems was done in [49] using different meta-heuristics, that included the Tabu Search. In the Tabu Search heuristic of [49], diversification was applied by generating a random solution and using it as the current solution. The diversification strategy developed for the optimisation problem being solved ensured each variable being optimised contributed to the move to a new region. In this strategy, three consecutive restarts are performed with the incumbent solution, if the incumbent solution does not improve for max_iter_div iterations. If the incumbent solution improves after a restart is performed, the Tabu Search exits the diversification loop and proceeds with the optimisation. This is different from what is being done in

[48], and allows the solution to test three different regions during the diversification.

The original contributions from the Tabu Search optimisation and from attaining the objectives set out have been discussed. Four journal publications and three conference papers resulted from these contributions and from the research carried out. The following is a list of the journal publications and conference papers. **Journal Publications**

1. R. Namuli, C.B. Laflamme, P. Pillay, "A Computer Program for Modeling the Conversion of Organic Waste to Energy", *Energies*, vol. 4, pp 1973-2001, 2011 (published).

2. R. Namuli, B. Jaumard, A. Awasthi, P. Pillay, "Optimisation of Biomass Waste to Energy Conversion Systems for Rural Grid-Connected Applications", *Applied Energy* (in press).

3. R. Namuli, B. Jaumard, P. Pillay, "Adaptation of Tabu Search Technique for Optimisation of Biomass Waste to Energy Conversion Systems", *Journal of Heuristics* (submitted).

4. R. Namuli, P. Pillay , B. Jaumard, C.B. Laflamme, "Threshold Herd Size for Commercial Viability of Biomass Waste to Energy Conversion Systems on a Rural Farm", *Applied Energy* (submitted).

Conference Papers

1. R. Namuli, P. Pillay, "Maximisation of Revenue from Biomass Waste to Energy Conversion Systems on Rural Farms", *in Proceedings of the 2012 IEEE Power and Energy Society General Meeting, San Diego, California, USA*, 2012 (published).

2. R. Namuli, P. Pillay, "A Computer Program for the Analysis of Conversion of Organic Waste to Energy", *in Proceedings of the 2011 IEEE Power and Energy Society General Meeting, Detroit, Michigan*, 2011 (published).

3. R. Namuli, P. Pillay, "Modeling of Waste to Energy Systems for Rural Applications", *in Proceedings of the World Energy Congress, Montreal, Canada*, 2010 (published).

This chapter described biomass waste to energy conversion systems and discussed the motivation for the research undertaken. The rest of the dissertation details the research work carried out. Chapter 2 is on the mathematical modeling of the biomass waste to energy conversion system. Chapter 3 is on MATTEUS, a software used to calculate biogas generation and carry out energy and economic analyses. Chapter 4 is on the formulation of the optimisation problem and the adaptation of the Tabu Search. The determination of the maximum revenue that can be obtained from a given herd size is described in Chapter 5. Chapter 6 details the determination of the threshold herd size at which the biomass waste to energy conversion systems become commercially viable. The conclusion and future direction are given in Chapter 7.

Chapter 2

Mathematical Modeling of the Biomass Waste to Energy Conversion System

In the first chapter the system model of the biomass waste to energy conversion system was described (see Figure 1.1). This chapter explains the mathematical modeling of the system components. The input to the biomass waste to energy conversion system is volume flow rate of manure waste. This goes into the digester. The modeling of the digester is discussed in the next section. The output of the biomass waste to energy conversion system is heat and electricity.

2.1 Digester

The ADM1 (Anaerobic Digestion Model No. 1) [50] is used to model the digester. The ADM1 was formulated as a tool for modeling waste water treatment. The kinetic parameters of the ADM1 were modified to simulate the anaerobic digestion of dairy manure [51]. The manure from the lagoon undergoes anaerobic digestion, in the digester, to produce biogas. The anaerobic digestion process is modeled and the mass flow rate, the air-fuel ratio, the density and the LHV (Lower Heating Value) of biogas are calculated. These values are required by the internal combustion engine model to calculate torque output. The stages of the anaerobic digestion process are shown in Figure 2.1. The first stage of the anaerobic digestion process is hydrolysis, where bacteria break down organic matter to sugars, fatty acids and amino acids. This is followed by the acid digestion stages, acidogenesis and acetogenesis. During acid digestion the molecules from hydrolysis are absorbed by the acid forming bacte-

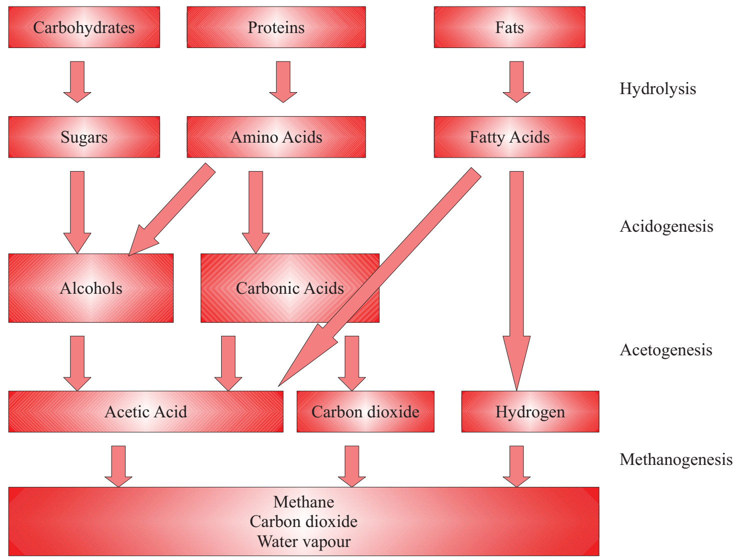


Figure 2.1: Anaerobic Digestion Process

ria, producing short chain fatty acids, carbon dioxide and hydrogen. The final stage of the anaerobic digestion process is gas digestion. During gas digestion methane forming bacteria attack the fatty acids to form methane, carbon dioxide and water vapour. The ADM1 model groups the anaerobic digestion processes into biochemical and physico-chemical processes. Biochemical processes are catalysed by intracellular or extracellular enzymes and act on a pool of organic material. Physico-chemical processes are not biologically mediated and involve association or dissociation, transfer between gas and liquid phases and precipitation. The ADM1 does not model precipitation. The ADM1 model is based on a completely stirred reactor with a single input and output waste stream and a constant liquid volume with a gas above it (Figure 2.2). The waste stream and the gas are categorised into components, designated by i. The waste stream components comprise of substrates and active biomass. There are 12 substrates and 12 active biomass components whose concentrations are defined by:

$$S_{\text{in},i} \quad \text{for } i = 1, 2, 3, ..., 12, \tag{2.1}$$

$$S_{\text{liq},i} \quad \text{for } i = 1, 2, 3, ..., 12, \tag{2.2}$$

$$X_{\text{in},i} \quad \text{for } i = 12, 13, 14, ..., 24, \tag{2.3}$$

$$X_{\text{liq},i} \quad \text{for } i = 12, 13, 14, ..., 24, \tag{2.4}$$

where S_{in} is the concentration of the substrate in the input waste stream, S_{liq} is the concentration of the substrate in the liquid phase of the waste stream, X_{in} is the concentration of the active biomass in the input waste stream and X_{liq} is the concentration of the active biomass in the liquid phase of the waste stream. The gas above the reactor has 3 components. The concentration of the substrates in the gas components and their partial pressures are defined by:

$$S_{\text{gas},i} \quad \text{for } i = 1, 2, 3, \tag{2.5}$$

$$p_{\text{gas},i} \quad \text{for } i = 1, 2, 3, \tag{2.6}$$

where S_{gas} is the concentration of the substrate in the gas component and p_{gas} is the partial pressure of the gas component. A mass balance of the components is carried out. The mass balance is the rate of mass change of the components [52]. The mass change occurs as a result of the biochemical and physico-chemical reactions. The structure used for modeling the biochemical reactions in the ADM1 is shown in Figure 2.3. The structure has two extracellular steps: disintegration and hydrolysis, and three intra-cellular steps: acidogenesis, acetogenesis and methanogenesis. The arrows in Figure 2.3 show the process flow, with hydrolysis, acidogenesis and acetogenesis

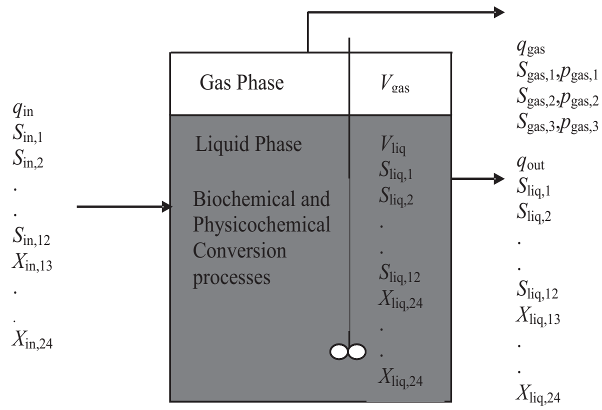


Figure 2.2: ADM1 Reactor

having a number of parallel reactions. There are 19 biochemical reactions modeled by ADM1, designated by j. Reactions $j = 1, 2, 3, 4$, are disintegration and hydrolysis reactions and $j = 5, 6, 7, ..., 19$, are acidogenesis, acetogenesis and methanogenesis reactions. The mass balance of the substrates in the liquid phase [50, 52] is calculated by:

$$\frac{dS_{\text{liq},i}}{dt} = \frac{q_{\text{in}}\, S_{\text{in},i} - q_{\text{out}}\, S_{\text{liq},i}}{V_{\text{liq}}} + \sum_{j=1}^{19} \rho_j\, v_{i,j} \qquad \text{kgCOD/m}^3\text{/day}, \tag{2.7}$$
$$\text{for } i = 1, 2, 3, ...12,$$

where S_{liq} is the concentration of the component in the digester, q_{in} is the volume flow rate of manure going into the digester, S_{in} is the concentration of the component going into the digester, q_{out} is the volume flow rate of the effluent leaving the digester, V_{liq} is the volume of the digester, ρ is the kinetic rate of the reaction and v is the stoichiometric coefficient of the reaction. kgCOD/m^3 is the chemical component base unit used to model the anaerobic digestion process. COD (Chemical Oxygen Demand) is the mass of oxygen required to completely oxidise a given organic compound. The calculation of the stoichiometric coefficients v of the different reactions is detailed in [50]. The kinetic rate ρ depends on the type of reaction. The kinetic rate of the disintegration and hydrolysis reactions [53] is calculated by:

$$\rho_j = k_j X_i \qquad \text{kgCOD/m}^3\text{/day}, \tag{2.8}$$

for $i = 13, 14, 15, 16$ and $j = 1, 2, 3, 4$,

where ρ is the kinetic rate of the reaction, k is the first order rate coefficient of the reaction and X is the concentration of the active biomass component. In [50], the substrate concentrations were obtained from experimental work and the rate coefficients were obtained from both experimental work and literature review [54, 55]. The kinetic rate of the acidogenesis, acetogenesis and methanogenesis reactions is

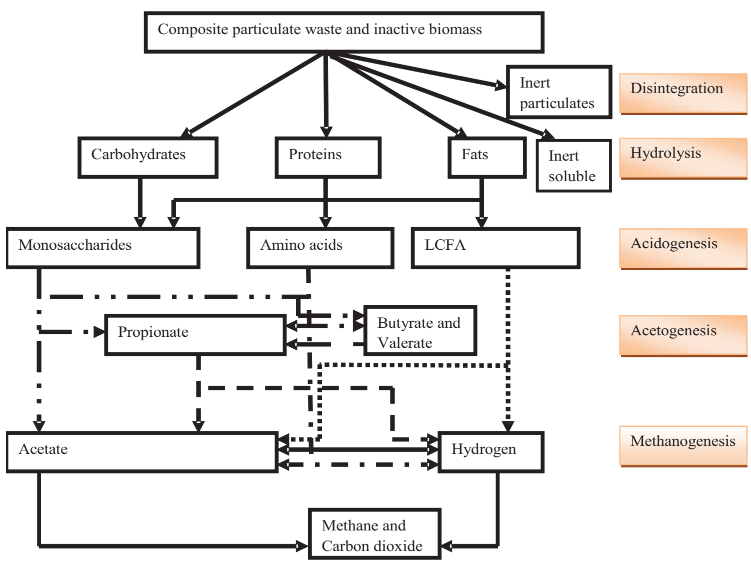


Figure 2.3: Modeling of Biochemical Reactions in ADM1

calculated by:

$$\rho_j = (k_{\mathrm{m},j} S_i/(K_i + S_i)) X I_1 I_2 I_3 \qquad \text{kgCOD/m}^3\text{/day}, \tag{2.9}$$

$$\text{for } i = 1, 2, 3, ...12, \text{ and } j = 5, 6, 7, ...12,$$

$$X = X_i \quad \text{for } i = 17, 18, 19, ...23 \qquad \text{kgCOD/m}^3, \tag{2.10}$$

where ρ is the kinetic rate of the reaction, k_m is the maximum specific rate of substrate utilisation, S is the concentration of the waste component, K is the concentration giving half the maximum rate of utilisation of the component, X is the concentration of active biomass in the component, I_1 is hydrogen inhibition, I_2 is free ammonia inhibition and I_3 is pH inhibition. In [50] the concentration of the active biomass and the substrate were obtained from both literature review and experimental work. The half-saturation coefficient and the maximum specific rate of substrate utilisation used in [50] were also obtained from literature review [54, 55] and experimental work. Hydrogen and free ammonia inhibitions are calculated by:

$$I = 1/(1 + S_\mathrm{I}/K_\mathrm{I}) \tag{2.11}$$

where I is inhibition, S_I is the concentration of the inhibitory component I and K_I is an inhibition constant. pH inhibition is calculated by:

$$I = \begin{cases} \exp(-3((\mathrm{pH}\text{-}\mathrm{pH_{UL}})/(\mathrm{pH_{UL}} - \mathrm{pH_{LL}}))^2) & \text{if } \mathrm{pH} < \mathrm{pH_{UL}} \\ (1 + 2 \times 10^{0.5(\mathrm{pH_{LL}} - \mathrm{pH_{UL}})})/(1 + 10^{(\mathrm{pH}\text{-}\mathrm{pH_{UL}})} + 10^{(\mathrm{pH_{LL}} - \mathrm{pH})}) & \text{if } \mathrm{pH} \geq \mathrm{pH_{UL}}, \end{cases} \tag{2.12}$$

where I is inhibition, $\mathrm{pH_{LL}}$ is the lower limit of pH and $\mathrm{pH_{UL}}$ is the upper limit of pH. In [50] inhibition constants and pH limits were determined through experimental work. The mass balance equation [52] for the gas phase is:

$$\frac{dS_{\mathrm{gas},i}}{dt} = -\frac{q_{\mathrm{gas}}\, S_{\mathrm{gas},i}}{V_{\mathrm{gas}}} + \rho_{\mathrm{T},i}\frac{V_{\mathrm{liq}}}{V_{\mathrm{gas}}} \qquad \text{for } \; i = 1, 2, 3, \qquad \mathrm{kgCOD/m^3/day}, \tag{2.13}$$

where S_{gas} is the concentration of the biogas component, q_{gas} is the volume flow rate of biogas from the digester, V_{gas} is the volume of the gas headspace in the digester, ρ_{T} is the kinetic rate of the liquid-gas transfer reaction of the biogas component and V_{liq} is the volume of the digester. The kinetic rates of the liquid-gas transfer reactions for hydrogen, methane and carbon dioxide are calculated by:

$$\rho_{\mathrm{T,H_2}} = k_{\mathrm{L}}a(S_{\mathrm{liq,H_2}} - 16K_{\mathrm{H,H_2}}p_{\mathrm{gas,H_2}}) \qquad \mathrm{kgCOD/m^3}, \tag{2.14}$$

$$\rho_{\mathrm{T,CH_4}} = k_{\mathrm{L}}a(S_{\mathrm{liq,CH_4}} - 64K_{\mathrm{H,CH_4}}p_{\mathrm{gas,CH_4}}) \qquad \mathrm{kgCOD/m^3}, \tag{2.15}$$

$$\rho_{\mathrm{T,CO_2}} = k_{\mathrm{L}}a(S_{\mathrm{liq,CO_2}} - K_{\mathrm{H,CO_2}}p_{\mathrm{gas,CO_2}}) \qquad \mathrm{kgCOD/m^3}, \tag{2.16}$$

where $\rho_{\mathrm{T,H_2}}, \rho_{\mathrm{T,CH_4}}$ and $\rho_{\mathrm{T,CO_2}}$ are the kinetic rates of the liquid-gas transfer reactions of hydrogen, methane and carbon dioxide respectively, k_{L} is the overall mass transfer coefficient, a is the specific transfer area, $S_{\mathrm{liq,H_2}}, S_{\mathrm{liq,CH_4}}$ and $S_{\mathrm{liq,CO_2}}$ are the concentrations of hydrogen, methane and carbon dioxide respectively, $K_{\mathrm{H,H_2}}, K_{\mathrm{H,CH_4}}$ and $K_{\mathrm{H,CO_2}}$ are the Henry's law coefficients of hydrogen, methane and carbon dioxide respectively and $p_{\mathrm{gas,H_2}}$, $p_{\mathrm{gas,CH_4}}$ and $p_{\mathrm{gas,CO_2}}$ are the partial pressures of hydrogen, methane and carbon dioxide respectively. The mass balance equation of the gas phase calculates the volume flow rate of biogas produced. The internal combustion engine model requires the mass flow rate of biogas, the air-fuel ratio of biogas and the LHV of biogas in order to calculate torque output. The volume flow rate of biogas, q_{gas} is required to solve the differential equation (2.13). This is calculated by:

$$q_{\mathrm{gas}} = k_{\mathrm{p}}(P_{\mathrm{gas}} - P_{\mathrm{atm}}) \qquad \mathrm{m^3/day}, \tag{2.17}$$

where q_{gas} is the volume flow rate of biogas, k_{p} is a pipe resistance coefficient, P_{gas} is the pressure of biogas and P_{atm} is atmospheric pressure. The mass flow rate of biogas is calculated from the density and the volume flow rate of biogas. The density of biogas is calculated by:

$$\rho_{\mathrm{gas}} = M_{\mathrm{gas}} P_{\mathrm{gas}} / R T_{\mathrm{biogas}} \qquad \mathrm{kg/m^3}, \tag{2.18}$$

where ρ_{gas} is the density of biogas, M_{gas} is the molar mass of biogas, P_{gas} is the pressure of biogas, R is the universal perfect gas constant and T_{biogas} is the temperature of biogas. The pressure of biogas is the sum of the partial pressures of hydrogen, methane, carbon dioxide and water vapour, which are calculated by:

$$p_{\mathrm{gas,H_2}} = S_{\mathrm{gas,H_2}} R T_{\mathrm{biogas}} \qquad \mathrm{bar}, \tag{2.19}$$

$$p_{\mathrm{gas,CH_4}} = S_{\mathrm{gas,CH_4}} R T_{\mathrm{biogas}} \qquad \mathrm{bar}, \tag{2.20}$$

$$p_{\mathrm{gas,CO_2}} = S_{\mathrm{gas,CO_2}} R T_{\mathrm{biogas}} \qquad \mathrm{bar}, \tag{2.21}$$

where $p_{\mathrm{gas,H_2}}$, $p_{\mathrm{gas,CH_4}}$ and $p_{\mathrm{gas,CO_2}}$ are the partial pressures of hydrogen, methane and carbon dioxide respectively, $S_{\mathrm{gas,H_2}}$, $S_{\mathrm{gas,CH_4}}$ and $S_{\mathrm{gas,CO_2}}$ are the concentrations of hydrogen, methane and carbon dioxide respectively, R is the universal perfect gas constant and T_{biogas} is the temperature of the biogas. The partial pressure of water vapour is calculated by:

$$p_{\text{gas},\text{H}_2\text{O}} = 0.0313 \exp(5290(T_{\text{biogas}} - 298)/298T_{\text{biogas}}) \qquad \text{bar}, \tag{2.22}$$

where $p_{\text{gas},\text{H}_2\text{O}}$ is the partial pressure of water vapour and T_{biogas} is the temperature of the biogas. The molar mass of biogas (M_{gas}) is required to calculated the density of biogas and is given by:

$$\begin{aligned} M_{\text{gas}} = (&M_{\text{CH}_4}\ p_{\text{gas},\text{CH}_4} + M_{\text{CO}_2}\ p_{\text{gas},\text{CO}_2} + \\ &M_{\text{H}_2}\ p_{\text{gas},\text{H}_2} + M_{\text{H}_2\text{O}}\ p_{\text{gas},\text{H}_2\text{O}})/P_{\text{gas}} \qquad \text{kg/mol}, \end{aligned} \tag{2.23}$$

where M_{gas} is the molar mass of biogas, M_{CH_4}, M_{CO_2}, M_{H_2} and $M_{\text{H}_2\text{O}}$ are the molar masses of methane, carbon dioxide, hydrogen and water vapour respectively, $p_{\text{gas},\text{CH}_4}$, $p_{\text{gas},\text{CO}_2}$, $p_{\text{gas},\text{H}_2}$ and $p_{\text{gas},\text{H}_2\text{O}}$ are the partial pressures of methane, carbon dioxide, hydrogen and water vapour respectively, and P_{gas} is the pressure of the biogas. The second input required for calculation of the torque output is the air-fuel ratio of biogas. This is calculated by:

$$AF = 2.38(4p_{\text{gas},\text{CH}_4} + p_{\text{gas},\text{H}_2})M_{\text{air}}/P_{\text{gas}}M_{\text{gas}}, \tag{2.24}$$

where AF is the air-fuel ratio of biogas, $p_{\text{gas},\text{CH}_4}$ is the partial pressure of methane, $p_{\text{gas},\text{H}_2}$ is the partial pressure of hydrogen, M_{air} is the molar mass of a standard composition of dry air, P_{gas} is the pressure of biogas and M_{gas} is the molar mass of biogas. The third input required for the calculation of the output torque, the LHV of the biogas is determined from the heat of combustion of the reactants in the digester:

$$LHV_{\mathrm{gas}} = (hrpo + \Delta H_p - \Delta H_{gas} - \Delta H_{air})/M_{\mathrm{gas}} \qquad \mathrm{kJ/kg}, \tag{2.25}$$

where LHV_{gas} is the Lower Heating Value of the biogas, $hrpo$ is the total heat of combustion of the gases at standard conditions, ΔH_p is the enthalpy change of the manure from standard temperature to the operating temperature of the digester, ΔH_{gas} is the enthalpy change of the biogas from standard temperature to the temperature of the biogas, ΔH_{air} is the enthalpy change of air from standard temperature to the operating temperature of the digester and M_{gas} is the molar mass of the biogas. The total heat of combustion of the gases at standard conditions, $hrpo$ is given by:

$$\begin{aligned} hrpo = ((&p_{\mathrm{gas,CH_4}} + p_{\mathrm{gas,CO_2}}) hfo_{\mathrm{CO_2}} + (2p_{\mathrm{gas,CH_4}} + p_{\mathrm{gas,H_2O}} + \\ &p_{\mathrm{gas,H_2}}) hfo_{\mathrm{H_2O}} - (p_{\mathrm{gas,CH_4}} hfo_{\mathrm{CH_4}} + p_{\mathrm{gas,CO_2}} hfo_{\mathrm{CO_2}} + \\ &p_{\mathrm{gas,H_2O}} hfo_{\mathrm{H_2O}}))/P_{\mathrm{gas}} \qquad \mathrm{kJ/mol}, \end{aligned} \tag{2.26}$$

where $hrpo$ is the total heat of combustion of the gases at standard conditions, $p_{\mathrm{gas,CH_4}}, p_{\mathrm{gas,CO_2}}, p_{\mathrm{gas,H_2O}}$ and $p_{\mathrm{gas,H_2}}$ are the partial pressures of methane, carbon dioxide, water vapour and hydrogen respectively, $hfo_{\mathrm{CO_2}}, hfo_{\mathrm{H_2O}}$ and $hfo_{\mathrm{CH_4}}$ are the heats of combustion of carbon dioxide, water vapour and methane respectively, and P_{gas} is the pressure of biogas.

Section 2.2 explains how the mass flow rate, the air-fuel ratio and the LHV of biogas are used to calculate torque in the internal combustion engine model.

2.2 Internal Combustion Engine

An engine-generator set comprises of an internal combustion engine coupled to an induction machine. The internal combustion engine produces a torque as a result of combustion of biogas. The torque is applied to the induction machine to generate electric power. The power rating of the induction machine has to be matched to that of the internal combustion engine. The internal combustion engine model is obtained from the ADVISOR software [56]. The internal combustion engine model used is based on the Advanced Vehicle Simulator fuel converter for the John Deere natural gas fuelled engine. The software has fuel use maps obtained from experimental work. The software uses the Newton-Raphson method and a two dimensional linear interpolation function, to calculate the torque output of the internal combustion engine:

$$T_{L,n+1} = T_{L,n} - \frac{f^{\text{ICE}}(T_{L,n})}{f^{\text{ICE}'}(T_{L,n})} \qquad \text{Nm}, \tag{2.27}$$

$$f^{\text{ICE}}(T_{L,n}) = \frac{m_{\text{gas}} LHV_{\text{gas}}}{\omega_{mech}} f^{\text{interp}}(fc_{\text{map\_trq}}, fc_{\text{map\_spd}}, fc_{\text{map\_bte}}, T_{L,n}, \omega_{mech}) \text{ Nm}, \tag{2.28}$$

where T_L is the torque output of the internal combustion engine, $f^{\text{ICE}'}$ is the derivative of the function (2.28), m_{gas} is the mass flow rate of biogas, LHV_{gas} is the LHV of biogas, ω_{mech} is the speed of the internal combustion engine, $fc_{\text{map\_trq}}$ is the torque range of the internal combustion engine, $fc_{\text{map\_spd}}$ is the speed range of the internal combustion engine and $fc_{\text{map\_bte}}$ is the fuel use map of the internal combustion engine in terms of brake thermal efficiency. ADVISOR sofware specifies the maximum torque for different engine speeds for a given engine rating. To match the power rating of the internal combustion engine to that of the induction machine, the maximum torque specified in the ADVISOR software is changed. It is changed to the torque required to produce the rated power of the induction machine. The ADVISOR software then uses interpolation to redefine the torque scale based on the new maximum torque specified. Torque output is then obtained from interpolation of mass flow rate, LHV, air-fuel ratio of biogas and engine speed, on the redefined torque scale. The torque output is used by the induction machine model to calculate the electricity output.

Exhaust gases are generated as a result of combustion of biogas in the internal combustion engine. The heat from the exhaust gases is captured by a heat exchanger and contributes to the total heat output of the biomass waste to energy conversion system. The mass flow rate and temperature of the exhaust gases are required to calculate the heat captured by the heat exchanger. The mass flow rate and the temperature of the exhaust gases are calculated by:

$$m_{\text{exh}} = m_{\text{gas}}(1 + AF) \qquad \text{kg/s,} \tag{2.29}$$

$$T_{\text{exh}} = (m_{\text{gas}} LHV_{\text{gas}} - T_L \omega_{mech})/m_{\text{exh}}\, cp_{\text{exh}} + T_{\text{amb}} \qquad \text{K,} \tag{2.30}$$

where m_{exh} is the mass flow rate of the exhaust gases, m_{gas} is the mass flow rate of the biogas, AF is the air-fuel ratio of the biogas. T_{exh} is the temperature of the exhaust gases, LHV_{gas} is the LHV of the biogas, T_L is the output torque, ω_{mech} is the speed of the internal combustion engine cp_{exh} is the specific heat capacity of the exhaust gases and T_{amb} is the ambient temperature.

2.3 Induction Machine

The induction machine was modeled in the dq (direct-quadrature) synchronous reference frame [57] and was based on the transient model of the induction machine shown in Figure 2.4. The dq currents i_{sd}, i_{sq}, i_{rd} and i_{rq} are used as state variables and the

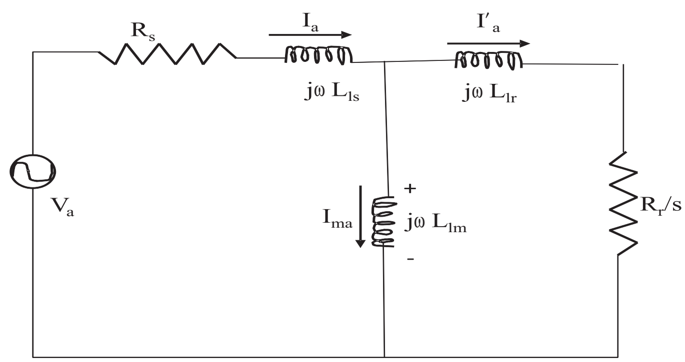


Figure 2.4: Induction Machine Equivalent Circuit Model

flux linkages are expressed in terms of these state variables. Power input is calculated by:

$$v_{sd} = R_s i_{sd} - \omega_d (L_s i_{sq} + L_m i_{rq}) + L_m \frac{di_{rd}}{dt} + L_s \frac{di_{sd}}{dt} \qquad \text{V}, \tag{2.31}$$

$$v_{sq} = R_s i_{sq} + \omega_d (L_s i_{sd} + L_m i_{rd}) + L_m \frac{di_{rq}}{dt} + L_s \frac{di_{sq}}{dt} \qquad \text{V}, \tag{2.32}$$

$$v_{rd} = R_r i_{rd} - \omega_{dA} (L_m i_{sq} + L_r i_{rq}) + L_m \frac{di_{sd}}{dt} + L_r \frac{di_{rd}}{dt} \qquad \text{V}, \tag{2.33}$$

$$v_{rq} = R_r i_{rq} + \omega_{dA} (L_m i_{sd} + L_r i_{rd}) + L_m \frac{di_{sq}}{dt} + L_r \frac{di_{rq}}{dt} \qquad \text{V}, \tag{2.34}$$

$$L_s = L_{ls} + L_m \qquad \text{H}, \tag{2.35}$$

$$L_r = L_{lr} + L_m \qquad \text{H}, \tag{2.36}$$

$$\omega_{dA} = \omega_d - \omega_m \qquad \text{rad/s}, \tag{2.37}$$

$$\omega_m = (P/2)\omega_{mech} \qquad \text{rad/s}, \tag{2.38}$$

$$T_{em} = (3/2)(P/2)L_m(i_{sq}i_{rd} - i_{sd}i_{rq}) \qquad \text{Nm}, \tag{2.39}$$

$$\frac{d\omega_{mech}}{dt} = (T_{em} - T_L)/J_{eq} \qquad \text{rad/s}^2, \tag{2.40}$$

$$P_{mech} = v_{sd}i_{sd} + v_{sq}i_{sq} \qquad \text{W}, \tag{2.41}$$

where v_{sd}, v_{sq}, v_{rd} and v_{rq} are dq voltages, i_{sd}, i_{sq}, i_{rd} and i_{rq} are dq currents, ω_d is the instantaneous speed of the dq winding, ω_{dA} is the instantaneous speed of the dq winding with respect to the rotor axis, ω_m is the rotor speed, ω_{mech} is the mechanical speed of the induction machine, P is the number of poles of the induction machine, T_{em} is the electromagnetic torque, T_L is the load torque, P_{mech} is the input power of the induction machine, R_s is the stator winding resistance, R_r is the rotor winding resistance, L_{ls} is the stator leakage inductance, L_{lr} is the rotor leakage inductance, L_m is stator magnetizing reactance and J_{eq} is the rotor inertia. The load torque T_L is the torque output of the internal combustion engine.

2.4 Heat Exchanger

The exhaust heat captured by the heat exchanger is calculated by [58]:

$$Q_{\text{HEX}} = \eta_{\text{HEX}}\, m_{\text{exh}}\, cp_{\text{exh}}(T_{\text{exh}} - T_{\text{water}}) \qquad \text{W}, \tag{2.42}$$

where Q_{HEX} is the heat from the heat exchanger, η_{HEX} is the efficiency of the heat exchanger, m_{exh} is the mass flow rate of the exhaust gases, cp_{exh} is the specific heat capacity of the exhaust gases, T_{exh} is the temperature of the exhaust gases and T_{water} is the temperature of the water in the heat exchanger.

2.5 Boiler

It is assumed that a dual fuel boiler is used. The heat output of the boiler is obtained by [59]:

$$Q_{\text{boiler}} = (m_{\text{propane}}\, LHV_{\text{propane}} + m_{\text{gas}}\, LHV_{\text{gas}})\, \eta_{\text{boiler}} \qquad \text{W}, \tag{2.43}$$

where Q_{boiler} is the heat output of the boiler, m_{propane} is the mass flow rate of propane, LHV_{propane} is the LHV of propane, m_{gas} is the mass flow rate of biogas, LHV_{gas} is the LHV of biogas and η_{boiler} is the efficiency of the boiler.

The boiler rating is calculated by:

$$b_{\text{r}} = \max_{d_{\text{h}}}(d_{\text{h}}^{m}) - Q_{\text{HEX}}^{m} + \delta_{\text{b}} \quad \text{for } m \in M \qquad \text{W}, \tag{2.44}$$

where b_{r} is the boiler rating, d_{h}^{m} is the heating demand, Q_{HEX}^{m} is the heat exchanger output, δ_{b} is an allowance for the boiler rating and M is a set of months comprising the optimisation.

This chapter described the mathematical modeling of the components of the biomass waste to energy conversion system. The models reviewed in this chapter are used in the Tabu Search optimisation. This will be revisited in Chapter 4. In the next chapter another model that can be used for prediction of biogas, electricity and heat generation from a biomass waste to energy conversion system will be discussed.

Chapter 3

Modeling of Biogas Generation using the Computer Program MATTEUS

This chapter is on MATTEUS, a computer program developed by Hydro-Québec for modeling the conversion of organic waste to energy. The input of MATTEUS is the mass flow rate of biomass waste, and the outputs are heat, electricity, process costs and the volume flow rate of biogas. Different waste treatment processes are included in MATTEUS. The specific waste treatment process analysed in this chapter is anaerobic digestion. The MATTEUS model uses waste characterisation parameters and mass flow rates at each stage of the waste treatment process. The waste characterisation parameters used in the MATTEUS model are: density, dry matter content and mass fractions of organic elements, matter and ashes. The contribution made is in the transformation of measurable waste characteristics, i.e., solids content, COD, volatile acids, nitrogen content, ammonia content, phosphorous content and orthophosphate content, into waste characterisation parameters used in the MATTEUS model. The MATTEUS model was also validated using empirical biogas measurements from biomass waste to energy conversion systems on farms in New York state [60].

This chapter is organised as follows: in Section 3.1 a review of models that predict conversion of biomass waste to energy and how they differ from MATTEUS is discussed, in Section 3.2 the modeling of MATTEUS done by Hydro-Québec is discussed and in Section 3.3 the contribution made on the transformation of measurable waste characterisation parameters into a form that can be used by MATTEUS is discussed, followed by the conclusion in Section 3.4.

3.1 Review of Research on Modeling of Anaerobic Digestion Processes

Before describing the MATTEUS model, a literature review of models that predict biogas generation from the anaerobic digestion of organic waste is done. Models that predict biogas generation can be classified by the modeling approach. These are: the mass balance approach, the fuzzy approach, the statistical and artificial neural network approach, and the knowledge based approach [61]. Each of these approaches is discussed next, and examples of the models done by researchers are given.

The mass balance approach uses equations to describe the interactions in the anaerobic digestion process. The models are basic [62]. Examples of models using the mass balance approach are those done by [63] and the MATTEUS model by Hydro-Québec [64]. The Contois equation was used to calculate the reaction kinetics in [63]. The MATTEUS model is described in the latter sections of this chapter. The drawback of the mass balance approach is that it is limited to continued stirred tank reactors and the model parameters are not easily determined [61].

In the fuzzy approach a discrete fuzzy model is developed to describe the anaerobic digestion process. The COD is known at each stage of the process and this is used as a tuning parameter. This approach is used in [65]. The fuzzy approach does not closely model the anaerobic digestion process and the predictions from these models are less accurate than those from the other models [61].

Statistical and artificial neural network models are based on activation functions that form a regression model or a network [61]. These models are used in [66] and [67]. As with the fuzzy approach, the statistical and artificial neural network approach does not closely model the anaerobic digestion processes. In addition the statistical and artificial neural network models require large amounts of data in order to predict biogas generation [61].

The knowledge based approach closely models the digestion pathways and applies mass balance, stoichiometric and kinetic equations at each stage of the anaerobic digestion process [61]. In [68] a knowledge based model describing the high rate anaerobic digestion of complex wastewater was developed. The acidogenesis and methanogenesis processes were modeled separately without the alkalinity recycle. This model greatly simplified the dynamic parameter estimation. A multi-model anaerobic digestion estimator consisting of sub-models and a knowledge based system, was developed by [69]. The knowledge based system used biogas and pH measurements for process diagnosis. The sub-models used monod, zero order and first order rate equations, together with COD and VFAs measurements to estimate process outputs. The multi-model is a simple model that allows for easy state variable and kinetic parameter estimations, and can be easily integrated in an adaptive model-based control system. This makes it suitable for online control of an anaerobic digestion process [69]. The ADM1 model [50] is also a knowledge based model. The ADM1 model uses several kinetic parameters and closely models the anaerobic digestion process as a series of biochemical and physico-chemical reactions. These have been discussed in Section 2.1. The kinetic parameters of ADM1 have been modified to simulate dairy manure anaerobic digesters [51] and anaerobic co-digestion of olive mill waste [70]. Another knowledge based model developed is the general integrated solid waste co-digestion model [71] for analysis of co-digestion of any combination of solid waste streams. The model calculates particulate waste fractions of carbohydrates, proteins, fats and inerts. These particulate waste fractions are used with the ADM1 model for prediction of biogas generation from co-digestion of waste.

The ADM1 model was selected for use in the optimisation because it closely models the anaerobic digestion processes and when calibrated for the waste being treated, it gives accurate predictions of biogas generation. This is important to the optimisation as the waste characteristics defer with geographical regions and the biogas yield will also differ with geographical regions. Although the predictions of biogas generation using the mass balance approach have certain limitations, the basic approach used is favourable for fast computation in commercial software. The performance of the MATTEUS software which is based on the mass balance approach will therefore be reviewed in the following sections.

MATTEUS uses mass fractions of C, H, O, N and S to calculate biogas generation. These mass fractions are obtained from proximate and ultimate analysis. Ultimate analysis gives the percentage of C, H, O, N and S in biomass. Proximate analysis gives the percentage of volatile matter, moisture, fixed carbon and ash in biomass. The following is a discussion of the differences in the use of proximate and ultimate analysis data by MATTEUS and by other models that predict biogas generation.

In [72] proximate analysis and thermal analysis were used to determine the chemical characteristics of MSW (Municipal Solid Waste). The percentages of volatile matter, moisture, fixed carbon and ash content were also determined using the proximate analysis method. The individual stoichiometric equations of each phase of the anaerobic digestion process were given, however an overall mass balance analysis of the process was not done. Stoichiometric equations are representations of balanced chemical reactions. The volume of biogas generated per tonne of MSW was estimated from the chemical composition of the MSW, and not from a mass balance analysis. MATTEUS calculates biogas generation differently using a mass balance approach. MATTEUS characterises the input waste using proximate and ultimate analysis, which gives the percentage of C, H, O, S, P, K and ashes in the input waste.

The software then writes a mass balance equation of the anaerobic digestion reaction using the percentages of C, H, O, S, P, K and ashes in the input waste. The mass flow rate of biogas generated is obtained from the gas product of the mass balance equation.

The potential application of agricultural and animal waste to energy production in Greece was investigated in [73]. The study cited the criteria for selection of the waste treatment method as: the moisture content of the input waste, the C/N (Carbon-to-Nitrogen) ratio, physical and chemical characteristics of the input waste. The study did not use the criteria cited to predict biogas generation from the waste. All these criteria are used in MATTEUS to carry out a mass balance analysis, and to calculate biogas generated. MATTEUS is therefore an improvement of [73].

The anaerobic digestion technology for industrial wastewater treatment was studied in [74]. The operating conditions for the anaerobic digestion process were identified as: organic loading rate, temperature and pH. Temperature and organic loading rate are also key operating conditions in the MATTEUS model. In [74] the optimal pH range for methane producing bacteria was given as 6.8-7.2, and an acidic pH was given for acid forming bacteria. The determination of pH is important to the anaerobic digestion process analysis, in order to monitor the accumulation of VFA (Volatile Fatty Acids). The determination of pH during the anaerobic digestion process is a section that can be added to MATTEUS. This will enable the specification of the operating conditions of the digester, under which the biogas predictions are made.

India's biogas generation potential was assessed in [75]. The study obtained data on the volume of waste generated and grouped the waste into: MSW, crop residue, agricultural waste, animal manure, wastewater and industrial waste. India's biogas generation potential was determined from estimated biogas yields of these different types of waste. The chemical characteristics of each type of waste were not taken into consideration. MATTEUS improves on such an assessment. It uses the chemical characteristics of the waste and the operating conditions of the anaerobic digestion process, to write a mass balance equation and calculate the biogas yield.

An overview of the biogas production potential in Zimbabwe was presented in [76]. The different types of waste were grouped into: MSW, sewage sludge, animal manure and crop residue. Data from literature reviewed [77–81] was extrapolated to estimate biogas generation potential. MATTEUS would improve on the prediction of the biogas generation potential, since it carries out a mass balance analysis using the characteristics of the input waste. Similarly, in [82] methods for evaluation of renewable energy sources were outlined. The authors identified biogas yield as being dependent on the physical and chemical composition of the waste. The waste characteristics given in [82] were obtained from literature [83]. Biogas yield was calculated as a product of: input waste, waste availability factor, percentage of dry matter, percentage of organic content and rate of biogas generation (obtained from empirical measurements [83]). Although the calculation of biogas generated was not the same as that of MATTEUS, waste characterisation in [82] was better than that in [75] and [76]. In [82], dry matter content, organic matter content, percentage of total nitrogen, percentage of P_2O_5, percentage of K_2O and C/N ratio were specified. MATTEUS would improve on such an assessment since it uses the additional characteristics, density of input waste, and mass fractions of C, H, O, S, P, K and ashes in the input waste, to carry out a mass balance analysis, and calculate the biogas yield.

The waste treatment processes in MATTEUS are laid out in modules. A similar approach was used in [84], where an investment decision tool for biogas production from agricultural waste was presented. In [84] the anaerobic digestion process was modeled as a four module process. These processes included pre-treatment of waste, anaerobic digestion, gas treatment and solids treatment. These waste treatment processes are similar to those of MATTEUS. The gas treatment involved biogas cleaning and utilisation in an internal combustion engine, or flaring of the biogas. MATTEUS offers additional options for utilisation of the biogas, i.e., a boiler, a gas turbine and a gas absorption refrigeration system. Both [84] and MATTEUS use mechanical dehydration for the solids treatment. In [84], liquid effluent is treated by evaporation or reverse osmosis, or is used for irrigation. MATTEUS offers more options for liquid effluent treatment which include: ultraviolet radiation, ultraviolet peroxidation, ozonisation, biofiltration and active carbon filtering. Disinfection of liquid effluent may be required if manure is co-digested with food waste, and the resulting liquid effluent is to be spread on land.

MATTEUS carries out an economic analysis of the waste treatment processes. Similar work has been done in this area and comparisons of the depth of analysis can be made. In [84] an investment decision tool for biogas production from agricultural waste was presented. There is a difference in the economic analysis carried out in [84] and that carried out in MATTEUS. In [84] a financial evaluation was carried out to check the viability of the process. The financial evaluation included a calculation of the IRR (Internal Rate of Return), the NPV and the payback period. MATTEUS' analysis is different in that it calculates the avoided costs of waste disposal and revenue from the sale of the by-products of the waste treatment.

In [85] a technical and economic evaluation of a biogas based water pumping system was done to assess its viability. The potential reduction in CO_2 emissions as a result of using biogas was predicted. This aspect of the analysis is similar to that of MATTEUS. The study carried out an economic assessment based on NPV, benefit to cost ratio and IRR. The economic analysis done by MATTEUS can be broadened to include the calculation of the NPVs of the waste treatment systems. This will give an indication of the commercial viability of the waste treatment systems.

The review of the biogas prediction models and analysis is followed by a description of the MATTEUS program.

3.2 Description of MATTEUS

The different waste treatment stages of the anaerobic digestion process modeled in MATTEUS are: conditioning of input waste, secondary treatment, drying of sludge, conditioning of digestate, treatment of digestate, storage of liquid and solid effluents, disposal of liquid and solid effluents, purification, utilisation and storage of biogas. MATTEUS characterises and analyses input waste, waste flow streams and by-products of waste processing. Physical properties and volume flow rates of the waste streams are calculated. An economic analysis of the waste treatment methods is also done. The various waste treatment stages of MATTEUS are laid out in modules. The process flow from inputs to production of energy and disposal of final products is shown in Figure 3.1. The type of waste to be treated is characterised by parameters given in Table 3.1. MATTEUS has a database of the waste characterisation parameters in Table 3.1, obtained from a literature review of ultimate and proximate analysis of waste [86–106]. Users can choose to use the parameters from the database or to enter their own parameters. Provision has been made in the MATTEUS software for entry of the pH of the input waste. The calculation of the pH of the waste at the various treatment stages is to be developed in the future upgraded version of the software [64]. The calculation of the precipitation of phosphorus should

Table 3.1: Waste Characterisation Parameters

Parameter	**Description**
density (t_{mh}/m^3)	density
dry matter content (t_{ms}/t_{mh})	
C (t/t_{ms})	mass fraction of organic carbon in input waste
H (t/t_{ms})	mass fraction of organic hydrogen in input waste
O (t/t_{ms})	mass fraction of organic oxygen in input waste
N (t/t_{ms})	mass fraction of organic nitrogen in ammonia
S (t/t_{ms})	mass fraction of organic sulphur in input waste
ashes (t/t_{ms})	mass fraction of inorganic matter in input waste
$P_2O_5(t/t_{ms})$	mass fraction of phosphorus in input waste (included in the ashes)
$K_2O(t/t_{ms})$	mass fraction of potassium in input waste (included in the ashes)
VS (t/t_{VS})	mass fraction of volatile solids in input waste
soluble inorganic matter (t/t_{mi})	mass fraction of soluble inorganic matter in input waste
P soluble (t/t_P)	mass fraction of soluble phosphorus in input waste
K soluble (t/t_K)	mass fraction of soluble potassium in input waste
distance (km)	distance to waste treatment site
cost of waste disposal (USD/t_{ms})	avoided cost of waste disposal

also be considered in future versions of the software. The user is required to define: mass flow rates of input waste, HRT, equipment costs, operational and maintenance costs, transportation, process energy required, utilisation rates, site conditions, global warming factors and capital costs. Section 3.2.1 describes how MATTEUS models the anaerobic digestion process.

3.2.1 Mathematical Modeling of the Anaerobic Digestion Process in MATTEUS

This section describes the mathematical modeling of the anaerobic digestion process, by MATTEUS. Mass flow rates are calculated for each waste treatment stage. A sequential analysis of the mass flow rates and physical properties of the treated waste, through the various stages is done. The following sections describe the determination of the physical properties of the waste and operating conditions of the digester. The mass balance analysis carried out by MATTEUS is also explained.

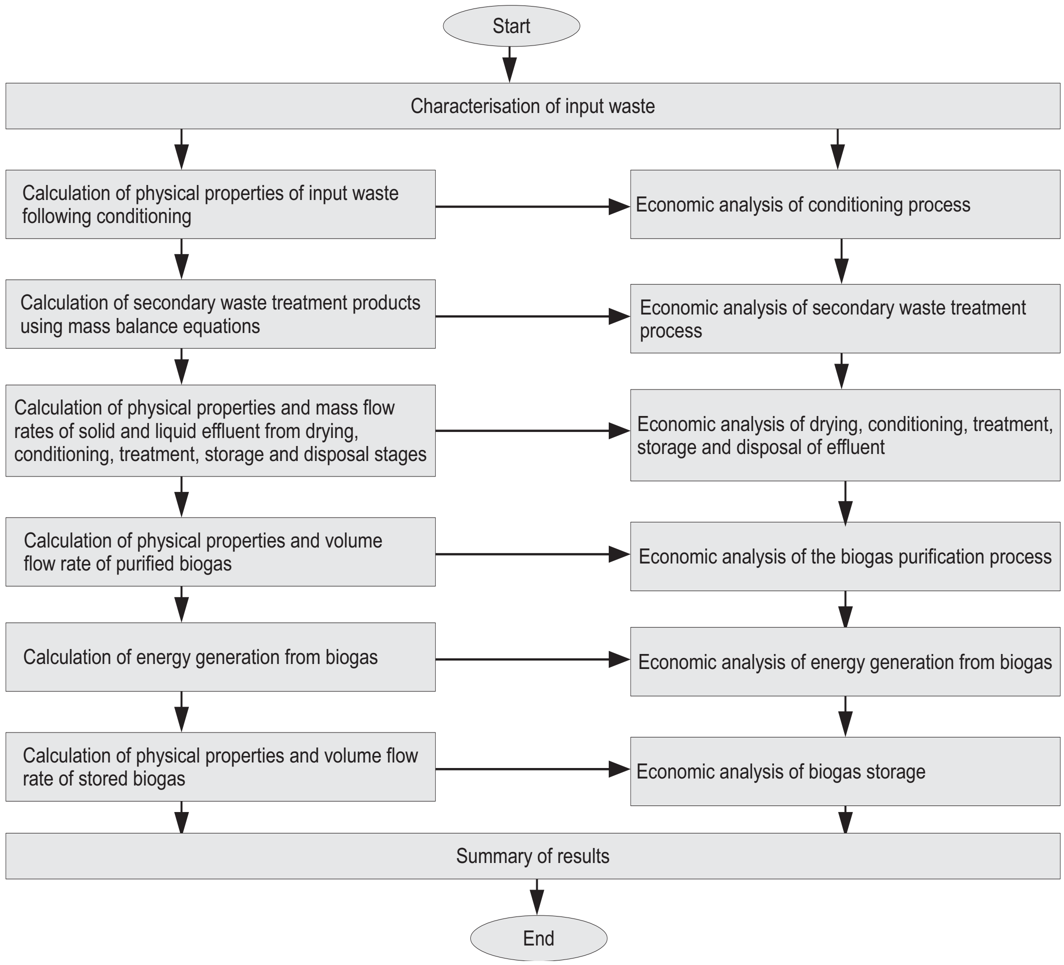


Figure 3.1: The MATTEUS Process Flow Chart

Dry Matter Content

The dry matter content of input waste is one of the properties used to characterise waste flow. It is obtained from the ratio of the mass of dry matter to wet matter.

Mass Balance Analysis of the Anaerobic Digestion Process

This section describes the formulation of the mass balance equation of the anaerobic digestion process. The anaerobic digestion process forms both biogas and biomass.

The process of formation of biogas and biomass is expressed by the stoichiometric equation [53]:

$$
\begin{aligned}
& C_aH_bO_cN_dS_e + \\
& ((4(a - f\acute{a}) - (b - f\acute{b}) - 2(c - f\acute{c}) + 3(d - f\acute{d}) + 2(e - f\acute{e}))/4)H_2O \rightarrow \\
& ((4(a - f\acute{a}) - (b - f\acute{b}) - 2(c - f\acute{c}) - 3(d - f\acute{d}) - 2(e - f\acute{e}))/8)CH_4 \\
& + ((4(a - f\acute{a}) - (b - f\acute{b}) + 2(c - f\acute{c}) + 3(d - f\acute{d}) + 2(e - f\acute{e}))/8)CO_2 \\
& + (d - f\acute{d})NH_3 + (e - f\acute{e})H_2S + fC_{\acute{a}}H_{\acute{b}}O_{\acute{c}}N_{\acute{d}}S_{\acute{e}},
\end{aligned}
\tag{3.1}
$$

where a, b, c, d, e are molar quantities of the elements that constitute one mole of organic molecule, á, $\acute{b}$, ć, $\acute{d}$, é are molar quantities of the elements that constitute one mole of the new biomass and f is the stoichiometric coefficient of formation of the new biomass. The molar quantities a, b, c, d and e are obtained from the molecular formula of the initial biomass ($C_aH_bO_cN_dS_e$). The molar quantities á, $\acute{b}$, ć, $\acute{d}$ and é are obtained from the molecular formula of the new biomass ($C_{\acute{a}}H_{\acute{b}}O_{\acute{c}}N_{\acute{d}}S_{\acute{e}}$), formed from the anaerobic digestion process. The stoichiometric coefficient f is determined by balancing the stoichiometric equation, for the formation of biogas and new biomass (3.1).

In order to determine the mass of biogas and new biomass (digester effluent) generated, the stoichiometric equation (3.1) is expressed as a mass basis of volatile solids [64]:

$$
\begin{aligned}
&C_\alpha H_\beta O_\gamma N_\delta S_\varepsilon + \\
&\frac{18.01}{4}\left[\frac{4(\alpha-\Phi\acute{\alpha})}{12.01}-\frac{\beta-\Phi\acute{\beta}}{1.01}-\frac{2(\gamma-\Phi\acute{\gamma})}{15.99}+\frac{3(\delta-\Phi\acute{\delta})}{14.01}+\frac{2(\varepsilon-\Phi\acute{\varepsilon})}{32.06}\right]H_2O \rightarrow \\
&\frac{16.05}{8}\left[\frac{4(\alpha-\Phi\acute{\alpha})}{12.01}+\frac{\beta-\Phi\acute{\beta}}{1.01}-\frac{2(\gamma-\Phi\acute{\gamma})}{15.99}-\frac{3(\delta-\Phi\acute{\delta})}{14.01}-\frac{2(\varepsilon-\Phi\acute{\varepsilon})}{32.06}\right]CH_4 \\
&+\frac{43.99}{8}\left[\frac{4(\alpha-\Phi\acute{\alpha})}{12.01}-\frac{\beta-\Phi\acute{\beta}}{1.01}+\frac{2(\gamma-\Phi\acute{\gamma})}{15.99}+\frac{3(\delta-\Phi\acute{\delta})}{14.01}+\frac{2(\varepsilon-\Phi\acute{\varepsilon})}{32.06}\right]CO_2 \\
&+(17.04(\delta-\Phi\acute{\delta})/14.01)NH_3+(34.08(\varepsilon-\Phi\acute{\varepsilon})/32.06)H_2S+\Phi C_{\acute{\alpha}}H_{\acute{\beta}}O_{\acute{\gamma}}N_{\acute{\delta}}S_{\acute{\varepsilon}}, \qquad (3.2)
\end{aligned}
$$

where $\alpha, \beta, \gamma, \delta$ and ε are coefficients of the initial biomass of composition $C_\alpha H_\beta O_\gamma N_\delta S_\varepsilon$, $\acute{\alpha}, \acute{\beta}, \acute{\gamma}, \acute{\delta}, \acute{\varepsilon}$ are coefficients of the new biomass, and Φ is the ratio of the mass of the new biomass to the mass of the initial biomass (on a dry basis of volatile solids and without ashes). MATTEUS calculates the coefficients of the composition of the initial biomass $C_\alpha H_\beta O_\gamma N_\delta S_\varepsilon$ from the mass fractions of elements of the input waste entered by the user, or obtained from the database. These are defined in Table 3.1.

The nitrogen contained in the initial organic matter, which is not found in the new biomass is converted into ammonia. The sulphur contained in the initial organic matter is converted to H_2S. CH_4, CO_2 and H_2S produced constitute the biogas. NH_3 is also produced. Water can be produced in the reaction or consumed depending on the composition of the organic matter. The phosphorous present in the resulting effluent is mineral based and therefore precipitates. Consideration should be given to the calculation of the mass of phosphorous precipitated in the effluent, in future versions of MATTEUS.

In order to calculate the mass flow rate of biogas and new biomass (digester effluent) in (3.2), the terms $(\alpha - \Phi\acute{\alpha})$, $(\beta - \Phi\acute{\beta})$, $(\gamma - \Phi\acute{\gamma})$, $(\delta - \Phi\acute{\delta})$ and $(\varepsilon - \Phi\acute{\varepsilon})$ have to be determined. The typical rate of production of new biomass by the anaerobic digestion process is 0.03 - 0.04kg per kgCOD eliminated [107]. The following is an explanation of how these terms are calculated.

Calculation of the terms is done separately for dissolved and non-dissolved volatile solids. This starts with the calculation of the mass flow rate of volatile solids eliminated using [64]:

$$m_{\mathrm{VS,el}} = \sum_{i=1}^{n^{\mathrm{comp}}} m_{\mathrm{comp},i}\, \eta_{\mathrm{VS}} \qquad \mathrm{t/h}, \tag{3.3}$$

where $m_{\mathrm{VS,el}}$ is the mass flow rate of the total volatile solids eliminated, n^{comp} is the number of elements, $m_{\mathrm{comp},i}$ is the mass flow rate of C, H, O, N or S in the initial volatile solid and η_{VS} is the rate of elimination of total volatile solids. The mass flow rate of the new biomass is calculated by [64]:

$$m_{\mathrm{VS,newbiomass}} = \Phi\, m_{\mathrm{VS,el}} \qquad \mathrm{t/h}, \tag{3.4}$$

where $m_{\mathrm{VS,newbiomass}}$ is the mass flow rate of the total volatile solids in the new biomass, Φ is the ratio of the mass of the new biomass to the mass of the initial biomass (on a dry basis of volatile solids and without ashes) and $m_{\mathrm{VS,el}}$ is the mass flow rate of the total volatile solids eliminated. MATTEUS uses a default value of $\Phi = 0.04$ $\mathrm{t_{ms}/t_{CODeliminated}}$ [107]. The mass flow rate of each component of the new biomass is then calculated by [64]:

$$m_{\mathrm{comp\_newbiomass}} = m_{\mathrm{VS,newbiomass}}\, \hat{\omega}_{\mathrm{comp\_newbiomass}} \qquad \mathrm{t/h}, \tag{3.5}$$

where $m_{\text{comp\_newbiomass}}$ is the mass flow rate of C, H, O, N or S in the new biomass, $m_{\text{VS,newbiomass}}$ is the mass flow rate of the total volatile solids in the new biomass and $\hat{\omega}_{\text{comp\_newbiomass}}$ is the mass fraction of C, H, O, N or S in the new biomass. The ash content in the initial biomass is not included in the calculation of the mass flow rate of C, H, O, N or S in the new biomass. The mass fractions of C, H, O, N and S in the new biomass are given in Table 3.2 and are obtained from experimental analysis done by [88, 92].

Table 3.2: Properties of New Biomass

Property	**Mass Fraction Value**
density (t_{mh}/m^3)	1.02 - 1.07
dry matter content (t_{ms}/t_{mh})	0.090
C (t/t_{ms})	0.500
H (t/t_{ms})	0.090
O (t/t_{ms})	0.220
N (t/t_{ms})	0.120
S (t/t_{ms})	0.010
ashes (t/t_{ms})	0.060
P_2O_5(t/t_{ms})	0.202
K_2O(t/t_{ms})	0.010
VS (t/t_{VS})	0.370
P soluble (t/t_P)	0.370
K soluble (t/t_K)	1.000
other soluble inorganic matter (t/t_{mi})	0.370

Source: Buchanan, 2004 [88] and Samson, 1990 [92]

The terms in (3.2) are therefore calculated by [64]:

$$x_{\text{term}} - \Phi \acute{x}_{\text{term}} = m_{\text{comp}}\, \eta_{\text{VS}} - m_{\text{comp\_newbiomass}} \qquad \text{t/h}, \tag{3.6}$$

$$\text{for } x_{\text{term}} \in X_{\text{term}} \quad \text{and} \quad X_{\text{term}} = \{\alpha, \beta, \gamma, \delta, \varepsilon\},$$

$$\acute{x}_{\text{term}} \in \acute{X}_{\text{term}} \quad \text{and} \quad \acute{X}_{\text{term}} = \{\acute{\alpha}, \acute{\beta}, \acute{\gamma}, \acute{\delta}, \acute{\varepsilon}\},$$

where Φ is the ratio of the mass of the new biomass to the mass of the initial biomass (on a dry basis of volatile solids and without ashes), m_{comp} is the mass flow rate of

C, H, O, N or S in the initial volatile solid, η_{VS} is the rate of elimination of total volatile solids, $m_{\mathrm{comp\_newbiomass}}$ is the mass flow rate of C, H, O, N or S in the new biomass, $\alpha, \beta, \gamma, \delta, \varepsilon$ are coefficients of the initial biomass of composition $\mathrm{C}_\alpha\mathrm{H}_\beta\mathrm{O}_\gamma\mathrm{N}_\delta\mathrm{S}_\varepsilon$ and $\acute{\alpha}, \acute{\beta}, \acute{\gamma}, \acute{\delta}, \acute{\varepsilon}$ are coefficients of the new biomass.

Heating Values of Input Waste

The LHV and HHV (Higher Heating Value) of the input organic matter are required to calculate energy released from the reactions in the digester. These are calculated by [108]:

if $IM > OM$ then use

$$HHV_{\mathrm{ref}} = 34.91\widehat{\omega}_{\mathrm{C}} + 117.83\widehat{\omega}_{\mathrm{H}} - 10.34\widehat{\omega}_{\mathrm{O}} - 1.51\widehat{\omega}_{\mathrm{N}} + 10.05\widehat{\omega}_{\mathrm{S}} \quad \mathrm{GJ/t}, \tag{3.7}$$

$$LHV_{\mathrm{ref}} = HHV_{\mathrm{ref}} - 22.36\widehat{\omega}_{\mathrm{H}} \quad \mathrm{GJ/t}, \tag{3.8}$$

otherwise

$$HHV_{\mathrm{ref}} = 34.91\omega_{\mathrm{C}} + 117.83\omega_{\mathrm{H}} - 10.34\omega_{\mathrm{O}} - 1.51\omega_{\mathrm{N}} + 10.05\omega_{\mathrm{S}} - 2.11\omega_{\mathrm{ashes}} \quad \mathrm{GJ/t}, \tag{3.9}$$

$$LHV_{\mathrm{ref}} = HHV_{\mathrm{ref}} - 22.36\omega_{\mathrm{H}} \quad \mathrm{GJ/t}, \tag{3.10}$$

where IM is inorganic matter, OM is organic matter, HHV_{ref} and LHV_{ref} are the Higher Heating and Lower Heating Values of C, H, O, N and S respectively, from MATTEUS' database, $\widehat{\omega}_{\mathrm{C}}$, $\widehat{\omega}_{\mathrm{H}}$, $\widehat{\omega}_{\mathrm{O}}$, $\widehat{\omega}_{\mathrm{N}}$ and $\widehat{\omega}_{\mathrm{S}}$ are mass fractions on a dry basis of C, H, O, N and S respectively, contained in the volatile solids of the input waste and ω_{C}, ω_{H}, ω_{O}, ω_{N}, ω_{S} and ω_{ashes} are mass fractions on a dry basis of C, H, O, N, S and ashes respectively, in the input waste.

The mass fractions of dry weight are used instead of the mass fractions of wet weight. This is because the coefficients in (3.7), (3.8), (3.9) and (3.10) are obtained from experimental analysis of the mass fractions of C, H, O, N and S in different types of dry waste. The equations are formed by extrapolating data from the experiments. If the user provides the mass fractions of C, H, O, N and S, the LHV and HHV are corrected using [108]:

$$LHV_{\text{new}} = LHV_{\text{ref}}(1 - \omega_{\text{ashes\_new}})/(1 - \omega_{\text{ashes}}) \qquad \text{GJ/t}, \tag{3.11}$$

$$HHV_{\text{new}} = HHV_{\text{ref}}(1 - \omega_{\text{ashes\_new}})/(1 - \omega_{\text{ashes}}) \qquad \text{GJ/t}, \tag{3.12}$$

where LHV_{new} and HHV_{new} are the Lower Heating and the Higher Heating Values of the components entered by the user, $\omega_{\text{ashes\_new}}$ is the mass fraction of ashes entered by the user and ω_{ashes} is the mass fraction of ashes from MATTEUS' database.

Density of Input Waste

The density of input waste is the bulk density of the sludge. Figure 3.2 is a profile of the variation of bulk density of sludge with water content. Figure 3.2 is plotted from data on the dry matter content and density of livestock manure, compost and MSW [109–113] (see Table 3.3). The following equations were formulated by the authors of MATTEUS [64] from Figure 3.2, and used to calculate the bulk density:

$$\rho_{\text{b}} = 1.0 \quad \text{for} \;\; \phi_{\text{b}} \leq 0.15 \qquad \text{t/m}^3, \tag{3.13}$$

$$\rho_{\text{b}} = 1.0 - \exp(-0.3/(\phi_{\text{b}} - 0.1)) \quad \text{for} \;\; \phi_{\text{b}} > 0.15 \qquad \text{t/m}^3, \tag{3.14}$$

where ρ_{b} is the bulk density of the waste and ϕ_{b} is the dry matter content of the waste.

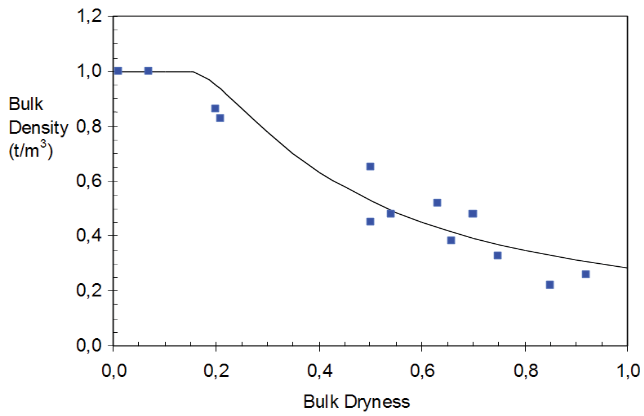


Figure 3.2: Variation of Bulk Density of Livestock Manure, Compost and MSW with Bulk Dryness

Volume Flow Rate of Waste and Biogas

In general MATTEUS uses mass flow rates to calculate waste flow through the treatment stages. However, some waste treatment stages like transport, secondary treatment and storage require volume flow rate for the calculations. The volume flow rate of the waste is calculated from the mass flow rate of the wet waste and the bulk density of the waste, ρ_{b} ((3.13) or (3.14)).

The volume flow rate of each of the biogas components is calculated using the perfect gas law. The sum of the volume flow rates of the biogas components gives the volume flow rate of the biogas.

Total Throughput of the Mass Flow Rate, LHV and HHV of C, H, O, N and S

The total throughput of the mass flow rate, LHV and HHV of C, H, O, N and S is required for formulation of the mass balance equation. Each stage of the waste

Table 3.3: Dry Matter Content and Bulk Density of Different Types of Waste

Type of Waste	**Dry Matter Content** (t_{ms}/t_{mh})	**Bulk Density** (t_{mh}/m^3)
cow manure	0.21	0.83
pig manure (liquid)	0.01	1.00
pig manure (liquid)	0.07	1.00
layer manure	0.54	0.48
layer manure	0.63	0.52
chicken manure	0.75	0.33
manure	0.85	0.22
turkey manure	0.66	0.38
compost from paper sludge	0.50	0.45
compost from cow manure	0.50	0.65
compost from cow manure	0.70	0.48
granules of municipal sludge	0.93	0.26

Source: Bary, 2005 [109], Alberta Government, 2006 [110], Arrouge, 1997 [111], Rosenow, 1998 [112] and Browne, 1995 [113]

treatment process generates partial mass flow rates and partial heating values of C, H, O, N and S. The total throughputs are obtained by summing the partial values.

Temperature and Pressure of the Waste Treatment Processes

In addition to the anaerobic digestion process, MATTEUS also analyses other waste treatment processes namely: ozonisation, mechanical dehydration, aerobic digestion, osmosis, ultra-violet radiation and bio-filtration. The various stages of the waste treatment processes require values of temperature and pressure. When there is rapid energy transfer, the temperature and pressure of a given waste treatment stage impact the temperature and pressure of the stage that follows it. The temperature and pressure of the latter are calculated by [64]:

$$x_{\mathrm{TP}} = \left(\sum_{i=1}^{n^{\mathrm{comp}}} m_{\mathrm{comp},i} \; x_{\mathrm{TP\_comp},i} \right) / m_{\mathrm{waste}} \qquad {}^\circ\mathrm{C} \text{ or atm}, \tag{3.15}$$

where x_{TP} is the temperature or pressure of the waste, n^{comp} are the number of elements, m_{comp} is the mass flow rate of C, H, O, N or S, $x_{\mathrm{TP\_comp}}$ is the temperature or pressure of C, H, O, N or S and m_{waste} is the mass flow rate of the waste, at the previous treatment stage. If the temperature and pressure of a given stage do not impact the temperature and pressure of the stage that follows it, default values are used.

Organic Loading Rate

Organic loading rate is the ratio of the biodegradable organic matter added to the digester daily, to the volume of the digester. It is expressed by [114]:

$$\mathrm{OLR} = \frac{\text{organic matter biodegradability in input waste added daily}}{\text{volume of digester}} \quad \mathrm{kgVS/m^3/d}, \tag{3.16}$$

where OLR is the organic loading rate. In MATTEUS the organic loading rate is expressed in terms of $\mathrm{kgCOD/m^3/day}$, i.e., the mass of oxygen required to entirely oxidise the compounds contained in the waste. The organic loading rate in MATTEUS is calculated using [53]:

$$m_{\mathrm{COD}}/m_{\mathrm{ms}} = 31.99(\alpha/12.01 + \beta/4.04 - \gamma/31.98 + \varepsilon/32.06) \quad \mathrm{kgCOD/m^3/d}, \tag{3.17}$$

where m_{COD} is the mass of oxygen required for oxidisation, m_{ms} is the mass of dry matter, and α, β, γ, δ and ε are coefficients of biomass of composition $C_\alpha H_\beta O_\gamma N_\delta S_\varepsilon$. The factors in (3.17) are calculated by writing a balanced stoichiometric equation of the anaerobic digestion process as discussed previously under the formulation of the mass balance equation (3.2). It is assumed that the nitrogen component of the waste reacts with hydrogen to form NH_3, but does not react with oxygen to form nitrogen oxides. The formation of NH_3 is included in the mass balance analysis (3.2).

Digester Operating Temperature

MATTEUS specifies three options for the operating temperature of the digester. These are: 55°C for thermophilic, 35°C for mesophilic and 20°C for psychrophilic temperature. The user selects one of these temperatures as the operating temperature of the digester. The operating temperature of the digester is assumed to be constant. The calculation of the heat losses in the digester and the heat of reaction of the anaerobic digestion process, are to be included in future versions of the MATTEUS software [64]. The calculation of the digester's heating requirement, will ensure that the digester's temperature is constant, as required for the anaerobic digestion process.

Dilution of Digester Effluent

Digester effluent may be diluted to reduce dry matter content or toxicity. MATTEUS calculates toxicity of nitrogen in the effluent, and dry matter content of the effluent. The calculated values are compared to the limits set by MATTEUS, and water is added to achieve set limits. This impacts the economic analysis since it involves addition of water to the effluent. The mass of water to be added is calculated by [64]:

$$m_{\text{water}} = m_{\text{waste}}(\phi - \phi')/\phi' \qquad \text{t/h}, \tag{3.18}$$

where m_{water} is the mass flow rate of the water added, m_{waste} is the mass flow rate of wet waste, ϕ is the dry matter content of the digester effluent before the addition of water and ϕ' is the desired dry matter content of the digester effluent. The toxic limits used by MATTEUS are: 3000mg/l for nitrogen in ammonia, 12000mg/l for potassium and 8000mg/l for sodium [115]. The limits of toxicity are set to ensure that high levels of nitrogen, sodium and potassium in the digester do not inhibit the anaerobic digestion process [115]. The MATTEUS software controls the toxic limit of nitrogen.

Heat of Reaction of Effluent

The anaerobic digestion process generates or absorbs heat, depending on the nature of the organic material. The net heat generated is calculated by ($HHV_{\mathrm{ref,before}} - LHV_{\mathrm{ref,after}}$), using (3.7) [64].

Rate of Elimination of Volatile Solids

The digester's performance is characterised by the rate of elimination of total volatile solids. The total volatile solids include dissolved and non-dissolved volatile solids. The rate of elimination of dissolved volatile solids is higher than the rate of elimination of non-dissolved volatile solids. The two values are given in MATTEUS and are used to calculate the rate of elimination of total volatile solids as [64]:

$$\eta_{\mathrm{VS}} = (\eta_{\mathrm{DVS}} m_{\mathrm{DVS}} + \eta_{\mathrm{NDVS}} m_{\mathrm{NDVS}})/m_{\mathrm{VS}}, \tag{3.19}$$

where η_{VS} is the rate of elimination of total volatile solids, η_{DVS} is the rate of elimination of dissolved volatile solids, m_{DVS} is the mass of dissolved volatile solids, η_{NDVS} is the rate of elimination of non-dissolved volatile solids, m_{NDVS} is the mass of non-dissolved volatile solids and m_{VS} is the mass of total volatile solids. MATTEUS uses a rate of elimination of dissolved and non-dissolved volatile solids of 95% and 40% respectively, at 37°C for a HRT of 25 days. The rate of elimination of total volatile solids in paper is typically 60% [116], whereas that of MSW is 57% [117]. The typical rate of elimination of total volatile solids in dairy manure is 30% [118]. MATTEUS prompts the user to fit the values of the rate of elimination of dissolved and non-dissolved volatile solids, to the typical values of the rate of elimination of total volatile solids.

Carbon-to-Nitrogen Ratio

The input waste should have a C/N (Carbon-to-Nitrogen) ratio of 20-40 to allow a balanced growth of micro-organisms during the anaerobic digestion process. The C/N ratio is the ratio of the total carbon available to the anaerobic digestion process, to the total nitrogen in the dissolved and non-dissolved matter. Organic carbon that is non-biodegradable such as lignin is not included in the total carbon because it is biologically inert. MATTEUS calculates the C/N ratio of the input waste and generates an error message, if it exceeds 40. The error message is an indication to the user that the high C/N ratio will affect the biogas yield from the anaerobic digestion process.

The description of the modeling of the anaerobic digestion process in MATTEUS is followed by the description of the calculation of heat and electricity generation in MATTEUS.

3.2.2 Heat Generation

The stoichiometric ratio of air and the temperatures of exhaust gases are used to estimate heat generation from combustion of biogas. MATTEUS defines the exhaust temperature of boilers of different capacities using data given in Table 3.4. Table 3.4 also shows the stoichiometric ratios of air used for the range of the boiler capacities.

Table 3.4: Exhaust Temperatures for Biogas Boilers of Different Capacities

Parameter	**Value**			
Energy of evaporation	<3MW	3-6MW	6-19MW	>19MW
Stoichiometric ratio of air	1.2-1.3	1.2-1.3	1.15-1.3	1.1-1.2
Exhaust gas temperature	220°C	200°C	170°C	170°C

Source: Japan Energy Conservation Handbook 2005/2006 [119]

3.2.3 Electricity Generation

The efficiency of energy conversion is used to calculate the electricity generated for a given rating of a spark ignition engine-generator set. MATTEUS calculates the efficiency of energy conversion using [120]:

$$\eta_{\mathrm{e}} = 0.08(\log P_{\mathrm{e}} - \log 20)/(\log 1000 - \log 20) + 0.28 \text{ for } 20 \leq P_{\mathrm{e}} \leq 5000\text{kW}, \quad (3.20)$$

where η_{e} is the efficiency of energy conversion and P_{e} is the electrical power output. If exhaust heat is recovered, total CHP (Combined Heat and Power) efficiency in relation to LHV is given in Table 3.5 [121] for different spark ignition engine ratings. The total CHP efficiency is used to estimate electricity and heat production.

Following the description of the modeling of biogas generation and energy production, MATTEUS' economic analysis of these processes is discussed.

Table 3.5: CHP Efficiencies of Spark Ignition Engine Generator Sets

Parameter	**Value**				
Reference Capacity (kW)	100	300	1000	3000	5000
Total CHP efficiency (%)	78	77	71	69	73

Source: Golstein et al., 2003 [121]

3.2.4 Economic Analysis

This section explains MATTEUS' economic analysis of the anaerobic digestion process.

Scaling of Capital Costs

MATTEUS uses reference capital costs, which are capital costs of equipment of known capacities. There is a relationship between the cost of equipment and its capacity [122]. This cost is plotted against the equipment capacity on a logarithmic scale in [122], and the equation of the best fit curve obtained is:

$$C_1 = C_{\text{ref}}(Q_1/Q_{\text{ref}})^{x_{\text{rate}}} \qquad \text{USD,} \tag{3.21}$$

where C_1 is the required capital cost, C_{ref} is the reference capital cost, Q_1 is the required equipment capacity, Q_{ref} is the reference equipment capacity and x_{rate} is a power sizing component. MATTEUS uses a default power sizing component of 0.6. The value of the power sizing component is generally in the interval $0 \leq x_{\text{rate}} \leq 1$ [122]. Where equipment is to be purchased and installed, the total reference capacity cost is used and is given by [64]:

$$C_{\text{total\_ref}} = C_{\text{ref\_1}}(1 + C_{\text{installation}} + C_{\text{eng\_admin}}) \qquad \text{USD,} \tag{3.22}$$

where $C_{\text{total\_ref}}$ is the total reference capacity cost, $C_{\text{ref\_1}}$ is the reference investment cost, $C_{\text{installation}}$ is the installation cost and $C_{\text{eng\_admin}}$ is the cost of engineering and administration. The digester capacity is calculated by [64]:

$$Q_{\text{digester}} = 24V_{\text{waste}}\text{HRT} \qquad \text{m}^3, \tag{3.23}$$

where Q_{digester} is the capacity of the digester, V_{waste} is the volume flow rate of input waste in m^3/day and HRT is the hydraulic retention time in days.

Operation and Maintenance Costs

MATTEUS calculates the annual operation and maintenance costs as 5% of equipment costs. If the unit operation and maintenance cost, of a given reference capacity is known, the unit operation and maintenance cost of another equipment capacity can be calculated by [122]:

$$c_{1,\text{O\&M}} = (c_{\text{ref,O\&M}}\, Q_{\text{ref}}(Q_1/Q_{\text{ref}})^{x_{\text{rate}}})/Q_1 \qquad \text{USD}, \tag{3.24}$$

where $c_{1,\text{O\&M}}$ is the required unit operational and maintenance cost, $c_{\text{ref,O\&M}}$ is the reference unit operation and maintenance cost, Q_{ref} is the reference capacity, Q_1 is the required capacity and x_{rate} is the power sizing component. Energy costs are not scaled as they remain the same as those of the reference capacity for a given location.

3.3 Comparison of MATTEUS' Predictions with Results from Case Studies

The MATTEUS model, for organic waste analysis has been described in the previous sections. This section describes the contribution made in the transformation of measurable waste characteristics namely: solids content, COD, volatile acids, nitrogen content, ammonia content, phosphorous content and orthophosphate content, into waste characterisation parameters used in the MATTEUS model. The section also describes the validation of the MATTEUS model that was done, using empirical biogas measurements. Two case studies were analysed, A.A. Dairy farm [123] and Noblehurst Dairy farm [124]. Ultimate and proximate analysis data of the case studies was unavailable, hence ultimate analysis data was derived using a transformation matrix [125]. The transformation matrix is a model developed by [125] that calculates concentrations of the components of input waste from measurable waste characteristics namely: solids content, COD, volatile acids, nitrogen content, ammonia content, phosphorous content and orthophosphate content. The concentrations of the input waste components are what is used to model the anaerobic digestion process in models like ADM1 and GISCOD discussed in Section 2.1. Proximate analysis data available in MATTEUS' database was used.

3.3.1 Transformation Matrix

Since MATTEUS uses ultimate analysis to characterise the biomass waste, this data had to be determined in order to predict biogas generated. The transformation matrix [125] was used to calculate ultimate analysis data. The ADM1 model uses mass fractions of composite organic matter, but these cannot be used directly in MATTEUS.

This is because the mass fractions are derived for modeling of anaerobic digestion in the wastewater treatment process [50]. The transformation matrix is therefore used to calculate the mass fractions of the components in the organic waste under consideration. The transformation matrix calculates the composition of carbohydrates, proteins and fats in input waste, and subsequently concentrations of input waste components. The concentrations of input waste components are used by the ADM1 model [50], to predict biogas generation. The contribution made is in obtaining the mass fractions of elements in these waste components for use in MATTEUS. The mass fractions of the elements were derived from the concentrations of waste components used in the ADM1 model, as calculated by the transformation matrix. The following is a description of how this was done.

The transformation matrix is an interface between measurable waste characteristics and the ADM1 model's input waste components. The inputs to the transformation matrix are: COD, VFA, total organic carbon, organic nitrogen, total ammonia in nitrogen, orthophosphate, total inorganic carbon, alkalinity, fixed solids and input waste volume flow rate. The transformation matrix was developed on the basis that waste components can be expressed as mass fractions of the elements C, H, O, N and P. The waste components also have an associated charge. The mass fractions and associated charge of the input waste characteristics are used to calculate their stoichiometric coefficients. The stoichiometric coefficients of the ADM1 components are then calculated from a mass and charge balance analysis. These are used to calculate the concentrations of the ADM1's input waste components. The input waste characteristics are converted to concentrations of ammonia, bicarbonate, orthophosphate, cations, VFA, sugars, fats, proteins, carbohydrates and organic inerts. The process flow for the derivation of the concentrations of the ADM1's input waste components, using the transformation matrix is illustrated in Figure 3.3. In

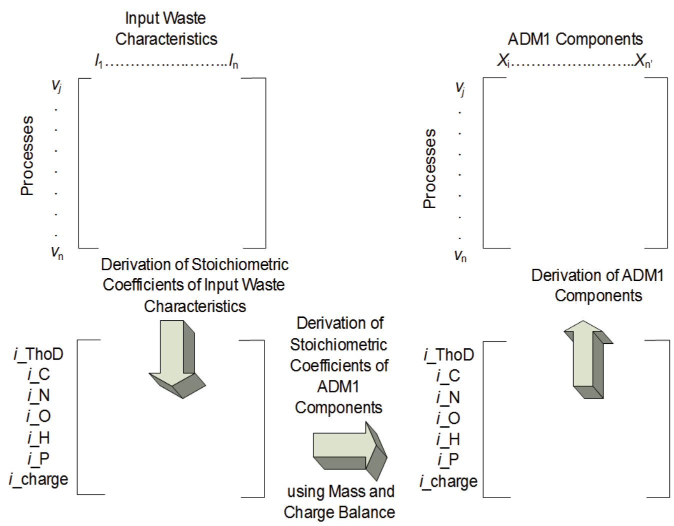


Figure 3.3: Illustration of the Transformation Matrix

Figure 3.3, v is the stoichiometric coefficient of conversion process j, I is an input waste characteristic and X is an ADM1 component. The stoichiometric coefficients of the ThOD (Theoretical Oxygen Demand), the elements and charge are denoted by i_ThOD, i_C, i_N, i_O, i_H, i_P and i_charge respectively. The stoichiometric coefficients of the input waste characteristics are calculated from their mass and charge balances. The following section details the determination of mass fractions of elements to be used in the MATTEUS model.

3.3.2 Estimating Ultimate Analysis Data

The mass fractions of C, N, H, O and P in the input waste are calculated from the concentrations of the ADM1 model's input waste components. As shown in Figure 2.3, the ADM1 models the input waste as a composite material. The composite material disintegrates into inert particulate matter, soluble inert matter and soluble organic matter [50]. The soluble organic matter is hydrolysed into carbohydrates, proteins and fats. The transformation matrix is used to calculate the mass fractions of waste components in carbohydrates, proteins, fats, inert particulate matter and soluble inert matter. The mass fractions of each of the components in the input waste are then derived from the mass fractions of these components in the carbohydrates, proteins and fats. The derived mass fractions are used by MATTEUS for waste characterisation. This procedure is explained using manure characteristics from two farms, A.A. Dairy [123, 126] and the Noblehurst Dairy [124]. Table 3.6 gives the measurable manure characteristics from the two farms. The waste characteristics used by the transformation matrix (Table 3.7) are obtained from the measurable waste characteristics. The acronyms used in Table 3.7 are defined in the list of

Table 3.6: Characteristics of Manure from Case Studies on Farms

Parameter	**A.A. Dairy**	**Noblehurst Dairy**
TS	11.15%	10.40%
COD	153496mg/L	77800mg/L
soluble COD	24239mg/L	23508mg/L
TVA (Total Volatile Acids)	3687mg/L	3042mg/L
organic Nitrogen	2500mg/L	2109mg/L
Ammonia Nitrogen	2159mg/L	1925mg/L
Total Phosphorus	813mg/L	498mg/L
Orthophosphate	457mg/L	240mg/L
TVS (Total Volatile Solids)	9.44%	7.72%
FS (Fixed Solids)	17,106mg/L	-
Reduction in TVS	29.7%	17.2%

acronyms. The values reported by the case studies were for total COD and yet the

Table 3.7: Composition Matrix of Inputs to the Transformation Matrix

Measured Characteristic	COD_p ($gCOD/m^3$)	CODs-VFA ($gCOD/m^3$)	VFA ($gCOD/m^3$)	TOC (gC/m^3)	Norg (gN/m^3)	TAN (gN/m^3)	TP-orthoP (gP/m^3)	orthoP (gP/m^3)	TIC ($molHCO_3^-/m^3$)	SCat (equ/m^3)	FS (g/m^3)
A.A. Dairy	129257.00	20782.71	3456.29	53324.40	2500.00	2159.00	356.00	457.00	1684.00	60.00	17106.00
Noblehurst	77800.14	20465.66	3042.34	42420.00	2108.70	1924.56	258.39	239.58	7260.00	60.00	26532.00

transformation matrix uses particulate COD to calculate the ADM1 inputs. The value of particulate COD is obtained by subtracting soluble COD from total COD. COD_s - VFA is the difference between soluble COD and volatile fatty acids. The transformation matrix uses the acetic acid component of the VFA to calculate the concentrations of the input waste components of the ADM1 model [125]:

$$\mathrm{VFA} = (\mathrm{ACETIC}/1000)(64/60)\rho_\mathrm{b} \qquad \mathrm{gCOD/m^3}, \tag{3.25}$$

where VFA is volatile fatty acids concentration in $\mathrm{gCOD/m^3}$, is acetic acid concentration in mg/kg and ρ_b is the density of input waste in $\mathrm{kg/m^3}$. The conversion to $\mathrm{gCOD/m^3}$ is calculated from the number of moles of oxygen required to fully oxidise one mole of the acetic acid [125]. This is illustrated in (3.26), in which two moles of oxygen are required to fully oxidise one mole of acetic acid. One mole of oxygen has a molecular mass of 32g, hence one mole of acetic acid is 64gCOD. The molecular mass of acetic acid is calculated from its molecular formula and obtained as 60g, hence the factor (64/60) in (3.25).

$$\mathrm{CH_3COOH + 2O_2 \rightarrow 2CO_2 + 2H_2O} \tag{3.26}$$

TOC (Total Organic Carbon) and TIC (Total Inorganic Carbon) in the input waste were not reported in the case studies reviewed and are calculated by [71, 123, 127]:

$$\mathrm{TOC} = 0.555^*\mathrm{TVS} \qquad \mathrm{gC/m^3}, \tag{3.27}$$

$$\mathrm{TC} = 0.486^*\mathrm{TS} \qquad \mathrm{gC/m^3}, \tag{3.28}$$

$$\mathrm{TIC} = \mathrm{TC} - \mathrm{TOC} \qquad \mathrm{gC/m^3}, \tag{3.29}$$

where TOC is total organic carbon, TVS are total volatile solids, TC is total carbon, TS are total solids and TIC is total inorganic carbon. TP-orthoP is the difference between total phosphorus and orthophosphate. Alkalinity was not measured for both case studies and is obtained from [71], for dilute manure. Values of dilute manure were selected for this calculation because the manure from the case study farms is mixed with milking parlor wash water. The outputs of the transformation matrix are concentrations of the waste components X_{ch} (carbohydrates), X_{pr} (proteins) and X_{li} (fats) (Table 3.8). To obtain mass fractions of the elements in X_{ch}, X_{pr} and X_{li}, the

Table 3.8: Outputs of Transformation Matrix

Component	**ThOD (per unit mass)**	**A.A. Dairy ($kgCOD/m^3$)**	**Noblehurst Dairy ($kgCOD/m^3$)**
X_{ch}	1.0627	91.695	46.657
X_{pr}	1.5160	10.583	4.286
X_{li}	2.8900	1.593	0.574

total mass of the elements in these waste components is expressed as a fraction of the total solids. As shown in Table 3.8 the concentrations of X_{ch}, X_{pr} and X_{li} are expressed in COD units. The concentrations are converted to mass units by [128]:

$$X_{\text{comp,kg/cubicm}} = X_{\text{comp,kgCODcubicm}} / \text{ThOD}_{X_{\text{comp}}} \qquad \text{kg/m}^3, \qquad (3.30)$$

where $X_{\text{comp,kg/cubicm}}$ is the mass in a cubic metre of the waste component, $X_{\text{comp,kgCODcubicm}}$ is the COD value of the waste component and $\text{ThOD}_{X_{\text{comp}}}$ is the Theoretical Oxygen Demand of the waste component. The mass fractions of the elements in the waste components are obtained from the interface of the transformation matrix and the ADM1 model [128] (Table 3.9). The percentage composition of carbohydrates, proteins and fats in the input waste is assumed to be the same as that of the ADM1 model, i.e., 30% carbohydrates, 30% proteins and 30% fats in the input waste [50]. The mass fractions defined in the ADM1 waste components, are used to

Table 3.9: Mass Fractions of Elements in ADM1 Components

Element	X_{ch}	X_{pr}	X_{li}
αC(g/g of component)	0.40	0.47	0.76
αN(g/g of component)	-	0.15	-
αO(g/g of component)	0.53	0.28	0.11
αH(g/g of component)	0.06	0.10	0.12
αP(g/g of component)	0.01	-	0.01

calculate the mass fractions of the elements in the input waste on a dry weight basis:

$$\hat{\omega}_{\mathrm{C}} = (\alpha \mathrm{C}_{Xch} + \alpha \mathrm{C}_{Xpr} + \alpha \mathrm{C}_{Xli})/\mathrm{TS}, \tag{3.31}$$

$$\hat{\omega}_{\mathrm{N}} = \alpha \mathrm{N}_{Xpr}/\mathrm{TS}, \tag{3.32}$$

$$\hat{\omega}_{\mathrm{O}} = (\alpha \mathrm{O}_{Xch} + \alpha \mathrm{O}_{Xpr} + \alpha \mathrm{O}_{Xli})/\mathrm{TS}, \tag{3.33}$$

$$\hat{\omega}_{\mathrm{H}} = (\alpha \mathrm{H}_{Xch} + \alpha \mathrm{H}_{Xpr} + \alpha \mathrm{H}_{Xli})/\mathrm{TS}, \tag{3.34}$$

$$\hat{\omega}_{\mathrm{P}} = (\alpha \mathrm{P}_{Xch} + \alpha \mathrm{P}_{Xli})/\mathrm{TS}, \tag{3.35}$$

where $\hat{\omega}_{\mathrm{C}}, \hat{\omega}_{\mathrm{N}}, \hat{\omega}_{\mathrm{O}}, \hat{\omega}_{\mathrm{H}}$ and $\hat{\omega}_{\mathrm{P}}$ are mass fractions of C, N, O, H, P, on a dry weight basis in the input waste, $\alpha \mathrm{C}_{Xch}, \alpha \mathrm{C}_{Xpr}, \alpha \mathrm{C}_{Xli}$ are mass fractions of C in carbohydrates, proteins and fats respectively, $\alpha \mathrm{N}_{Xpr}$ is the mass fraction of N in proteins, $\alpha \mathrm{O}_{Xch}, \alpha \mathrm{O}_{Xpr}, \alpha \mathrm{O}_{Xli}$ are mass fractions of O in carbohydrates, proteins and fats respectively, $\alpha \mathrm{H}_{Xch}, \alpha \mathrm{H}_{Xpr}, \alpha \mathrm{H}_{Xli}$ are mass fractions of H in carbohydrates, proteins and fats respectively, $\alpha \mathrm{P}_{Xch}, \alpha \mathrm{P}_{Xli}$ are mass fractions of P in carbohydrates and fats respectively and TS are total solids. The mass fractions of elements in the input waste obtained from the calculations, for the case study farms are given in Table 3.10.

Table 3.10: Mass Fractions of Elements in Input Manure

Element	Mass Fractions A.A. Dairy Farm	Mass Fractions Noblehurst Dairy Farm
$\hat{\omega}_{\mathrm{C}}$	0.3392	0.3167
$\hat{\omega}_{\mathrm{N}}$	0.0093	0.0071
$\hat{\omega}_{\mathrm{O}}$	0.4239	0.4006
$\hat{\omega}_{\mathrm{H}}$	0.0527	0.0489
$\hat{\omega}_{\mathrm{P}}$	0.0077	0.0073

3.3.3 Proximate and Ultimate Analysis Data from MATTEUS' Database

Not all the proximate and ultimate analysis values could be calculated, therefore some values were obtained from MATTEUS' database (Table 3.11).

Table 3.11: Proximate and Ultimate Analysis Data from MATTEUS' Database

Parameter	Value
mass fraction of S in input waste	0.001
mass fraction of ashes in input waste	0.150
mass fraction of K_2O in input waste	0.031
mass fraction of soluble VS in input waste	0.500
mass fraction of soluble inorganic matter in input waste	0.500
mass fraction of soluble P in input waste	0.500
mass fraction of soluble K in input waste	1.000
mass fraction of soluble N in input waste	0.500
density of input waste	990kg/m^3

3.3.4 Operating Conditions of the Digesters in the Case Studies

The operating conditions of the digesters in the case studies [123, 124] are entered in MATTEUS (Table 3.12). The specification of the reduction in TVS is important in the

Table 3.12: Operating Conditions of Digesters

	Temperature	HRT	Reduction of TVS
A.A.Dairy Farm	35°C	34 days	29.7%
Noblehurst Dairy	38°C	37 days	17.2%

prediction of biogas generation. Percentage reduction in TVS is dependent on HRT and the temperature of the digester. MATTEUS' database specifies a value of 60% at 37°C for a HRT of 25 days. The percentage reduction in TVS is for a specific HRT and at a specific temperature. The rate of reduction of TVS is different for different digesters. The A.A. Dairy farm data indicated a 29.7% [123] reduction in TVS and the Noblehurst Dairy farm data indicated an average of 17.2% [124] reduction in TVS. These were at HRTs of 34 days [123] and 37 days [124] respectively. These values cannot be used in MATTEUS which specifies a percentage reduction in TVS for a different temperature and different HRT. In addition, MATTEUS uses a rate of elimination of dissolved and non-dissolved volatile solids at its specified temperature and HRT. MATTEUS specifies ranges for rates of reduction of dissolved and non-dissolved volatile solids. If values outside the specified range are entered in order to match the empirical reduction in TVS, the prediction of biogas generated is not close to the empirical value of biogas generated for both case studies. MATTEUS recommended a range of 50-60% reduction in TVS [64]. It was decided to use the closest value calculated that is within the allowed range of dissolved and non-dissolved volatile solids. This value is 50% for both the A.A. Dairy farm and the Noblehurst Dairy farm case studies. This is an area of improvement for MATTEUS, in that two options should be provided for specification of reduction in TVS. The value for reduction in TVS could be obtained from the MATTEUS database, or the MATTEUS model could use TVS values entered by users. The dry matter content of the input waste is calculated by:

$$\omega_{\mathrm{ms}} = \mathrm{TS}/m_{\mathrm{mh}}, \tag{3.36}$$

where ω_{ms} is the dry matter content, TS is total solids expressed in mg/L and m_{mh} is the mass flow rate of input waste. The values of mass flow rate of input waste and dry matter content calculated for the farms in the case studies are given in Table 3.13.

Table 3.13: Parameters used in MATTEUS

Parameter	**A.A. Dairy Farm**	**Noblehurst Dairy Farm**
dry matter content	0.114	0.104
mass flow rate of input waste (kg/day)	34,303.5	67,537.8

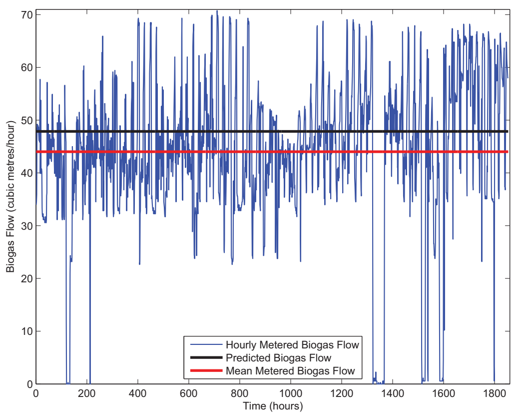
3.3.5 Results and Discussion

The results obtained from MATTEUS are summarised in Table 3.14. MATTEUS predicted generation of 47.87m^3 of biogas per hour of 47.5% methane content for the A.A. Dairy farm. Biogas generation for the Noblehurst Dairy farm was predicted at 84.53m^3/h and 47.2% methane content. These predictions are compared with empirical data of metered biogas from the farms. Data for both farms is obtained from [60]. The metered biogas flow for the A.A. Dairy farm was obtained for April 2007 to May 2007 and is shown in Figure 3.4(a). This period was selected because all three months had above 90% reliable data. Figure 3.4(a) and Table 3.14 show that the mean metered biogas flow rate is 8.8% below that predicted by MATTEUS. The metered biogas flow for the Noblehurst Dairy farm was obtained for December 2005 to Jan 2006 and is shown in Figure 3.4(b). This period was selected because it had above 96% reliable data. Figure 3.4(b) and Table 3.14 show that the mean metered biogas flow rate is 7.9% below that predicted by MATTEUS. The error in prediction of methane content of biogas is 19.6% for the A.A. Dairy farm and 22.6% for the Noblehurst Dairy farm.

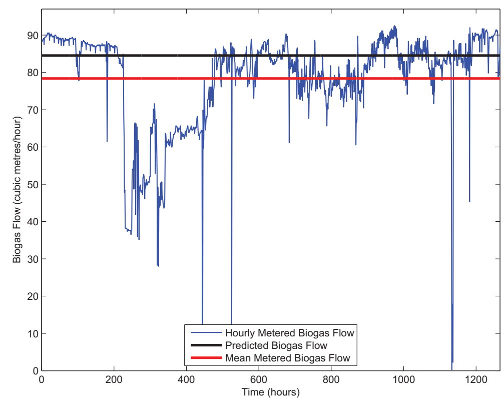
The value of the percentage reduction in TVS recommended by MATTEUS was

Table 3.14: Comparison of Biogas Yield Predicted by MATTEUS with Actual Yields

	MATTEUS' Prediction	**Mean Biogas from Empirical Measurements**	**Error**
A.A. Dairy biogas yield (m^3/h)	47.87	44.01	8.8%
Noblehurst Dairy biogas yield (m^3/h)	84.53	78.37	7.9%
A.A. Dairy %CH_4 Content	47.5%	59.1%	19.6%
Noblehurst Dairy %CH_4 Content	47.2%	61.0%	22.6%



(a) A.A. Dairy Farm



(b) Noblehurst Dairy Farm

Figure 3.4: Metered Biogas Flow

used and not the values from the case studies. This was done because MATTEUS derives the percentage reduction of TVS from the percentage reduction of non-dissolved and dissolved volatile solids. The specification of the percentage reduction in TVS, by the user is not provided for. The 20.3% error in the TVS estimation for A.A. Diary farm gave an 8.8% error in the biogas yield estimation done by the MATTEUS software. Similarly the 32.8% error in the TVS estimation for Noblehurst Dairy gave a 7.9% error in the biogas yield estimation done by the MATTEUS software. The biogas yield calculated by MATTEUS is dependent on the mass fractions of C, H, O, N and S in the input waste, and the percentage reduction in TVS. The error in the prediction of biogas volume flow rate and methane content can be accounted for by the use of the basic mass balance approach to model the anaerobic digestion process in MATTEUS. Further improvements should be considered in future versions of the MATTEUS sofware with regard to the formulation of the mass balance equation for prediction of biogas, and the specification of the TVS reduction.

Another source of errors was in the conversion of the volume flow rate of input waste to tonnes/hour for use in MATTEUS. The values of input waste from the case studies were in cubic feet per cow day [123], to one decimal place and mg/kg [124], rounded off to the nearest whole number. These values were converted to tonnes/hour for use in MATTEUS, which involved conversion factors given to a number of decimal places. These conversions led to losses in accuracy, and additional discrepancies in actual values of biogas and methane content, from values predicted by MATTEUS. Conversions to a higher number of decimal places were experimented with in the calculations, before obtaining the reported results. However in future work, other sources of empirical data should be used to experiment with the number of decimal places used in the calculations. This would establish a standard for conversion of data from the units of measurement to the units used in MATTEUS.

The density of manure was not reported by the case studies and was obtained from MATTEUS' database, creating another source of error. In future work, empirical measurements of biogas used to validate results from MATTEUS should include the density of input waste.

The percentage error in the methane content predicted for the Noblehurst Dairy farm case study [124] is particularly high. This is because the measured value includes the volume of CO_2. The percentage volume of CO_2 in biogas was not isolated during measurements [124]. Typically biogas contains 40-75% CH_4 and 25-60% CO_2 among other gases [129]. CO_2 constitutes a significant volume of biogas, thus the large percentage error. The prediction of methane content in biogas by MATTEUS, can further be benchmarked with empirical data from other case studies.

3.4 Conclusion

In this chapter, the modeling of the anaerobic digestion process to predict biogas generation has been reviewed. The MATTEUS model for analysis of waste treatment processes has been described, with particular reference to anaerobic digestion. Chapter 2 described the ADM1, another model for calculation of biogas generated from the anaerobic digestion of organic waste. The difference between the ADM1 model and MATTEUS is in the way the anaerobic digestion process is modeled. MATTEUS writes a single stoichiometric equation (a representation of a balanced chemical reaction) of the anaerobic digestion process, and calculates the mass of biogas generated from this equation. The ADM1 model is different in that it structures the anaerobic digestion process into parallel biochemical reactions. The ADM1 then writes and solves mass balance equations for each of these reactions. The rate of the reactions is included in the mass balance equations of the ADM1 model. The ADM1 models the anaerobic digestion process more practically, and will be responsive to small changes in the input waste's volume flow rate and characteristics, compared to MATTEUS. The Tabu Search heuristic used to solve the research problem applies small changes to the volume flow rate of input waste, in trying to find an optimal solution. The ADM1 model was therefore selected for use in the biomass waste to energy conversion system model of the optimisation problem being solved. In the next chapter on the

Tabu Search optimisation, the functions used to model the digester refer to equations used in the ADM1 model.

Chapter 4

Tabu Search Optimisation

The Tabu Search heuristic has been used to optimise the BWECS (biomass waste to energy conversion systems), in solving the research problem. Developments were made to the basic Tabu Search to adapt it to the optimisation problem. This chapter explains the contribution made in development of the adaptations to the basic Tabu Search. The chapter is organised as follows: the principle of Tabu Search is explained in Section 4.1, followed by the statement of the optimisation problem in Section 4.2, the description of the optimisation of BWECS is given in Section 4.3, the Tabu Search algorithm is described in Section 4.4 and the experiments and results are discussed in Section 4.5.

4.1 Principle of Tabu Search

Before describing the principle of Tabu Search, the terms used to describe the Tabu Search are defined. A heuristic is an iterative rule used to find an optimum solution, that terminates as soon as no immediately accessible solutions can improve the incumbent solution [130]. A metaheuristic is a master strategy that modifies other heuristics, to produce solutions beyond those that are generated when searching a local optimum [130]. As such, Tabu Search is a meta-heuristic [131], that guides a local heuristic search procedure to explore the solution space beyond a local optimum [130].

In Tabu Search, the optimisation problem is formulated as [131]:

$$\text{minimise } \ f(u) : u \in U, \tag{4.1}$$

where $f(u)$ is the objective function, and u is selected from a set of constraints U. A move n leads from one solution to the next. The move is defined as [131]:

$$n : U(n) \to U. \tag{4.2}$$

The moves $n \in \mathcal{N}$ that can be applied to u form a set denoted by $\mathcal{N}(u)$, and termed the neighbourhood of u [131]. A characteristic of the Tabu Search is to constrain the search by restricting moves [131]. This leads to creation of an element of memory, that is managed using a Tabu list. Moves that result in a good solution, are used to update the current solution and are stored in the Tabu list. The reverse moves are also stored in the Tabu list. Use of memory in the form of a Tabu list prevents cycling, which occurs if a solution is stuck in a local optimum. In the basic Tabu Search, moves that are in the Tabu list are not allowed during the optimisation, during a given number of iterations [131]. The Tabu list is updated by removing older entries and adding new entries with every move. The length of the Tabu list or the number of iterations for which a move is Tabu, is dependent on the optimisation strategy. The basic Tabu Search algorithm is described in Algorithm 1.

Algorithm 1 Basic Tabu Search

```
Select an initial solution u ∈ U
Set u^incumbent ← u
Set iter ← 0
Initialise the Tabu list: T^list ← ∅
while stopping condition is not reached do
    Find the best admissible solution u ∈ N(u) with respect to f(u)
    if f(u) < f(u^incumbent) then
        Update the incumbent solution u^incumbent ← u
        Update the Tabu list
    end if
end while
```

where u is the current solution, U is the constraints set, $u^{\text{incumbent}}$ is the incumbent solution, iter is the iteration counter, T is the Tabu list, $\mathcal{N}(u)$ is the neighbourhood of solution u and $f(u)$ is the objective function.

The following is an explanation of the choice of Tabu Search over other metaheuristics for solving the optimisation problem. The successful implementation of a metaheuristic is dependent on how well it is modified for the problem being solved [132]. The BWECS is a complex model constituting of components that model the energy conversion processes. As discussed in Chapter 2, the digester model, the internal combustion engine model and the induction machine models use complex non-linear differential equations. Each of the models of the BWECS is a difficult non-linear optimisation problem, that is treated as a black box. As such a metaheuristic is selected for solving the optimisation problem. The reasons for the choice of Tabu are: (i) it uses a deterministic approach for optimisation, (ii) it moves aggressively to a local optimum and (iii) it can easily be tailored to the optimisation problem. The following is an explanation of these reasons.

Tabu Search uses a deterministic approach to search the solution space, which shortens the computational time. The other metaheuristics like genetic algorithms and simulated annealing perform a random search of the solution space. This results in long computational times, making simulated annealing and genetic algorithms less suited to complex problems like the optimisation of BWECS. Three metaheuristics namely: Tabu Search, simulated annealing and genetic algorithms were compared in solving facility location problems, under time-limited, solution-limited, and unrestricted conditions, [133]. Tabu Search showed good performance in most of the facility location problems experimented with, compared to the simulated annealing and genetic algorithm.

Again compared to simulated annealing, Tabu Search moves aggressively to a local optimum. Simulated annealing works on the premise that a slow decent will lead to a local optimum that is closer to a global optimum. With Tabu Search the best available move is made at each iteration, and the search does not spend time in regions whose solution are less attractive [131]. In [134], a Tabu Search algorithm that diversifies the search by using 3 different neighborhoods was developed for solving a flowshop scheduling problem. The Tabu Search was compared with an ant colony algorithm that was used to solve the same problem. The Tabu Search performed better than the ant colony algorithm.

The third reason for selection of Tabu Search, is that Tabu Search can easily be tailored to take into account the nature of the optimisation problem. This is done by proper selection of variables, handling of constraints and parameter tuning. The success of Tabu Search is as a result of tuning its parameters to the problem being solved [132]. A multiple Tabu Search algorithm was developed by [135] to solve a dynamic economic generator dispatch problem. The multiple Tabu Search algorithm used additional strategies for initialisation, carried out adaptive and multiple searches, crossover and restarts. The performance of the Tabu Search was compared with that of simulated annealing, a genetic algorithm and particle swarm optimisation, in solving the problem. A higher quality solution was obtained, with better computational efficiency using the multiple Tabu Search algorithm.

Tabu Search was identified as suited to solving the optimisation of BWECS. Aspects of the basic Tabu Search however had to be adapted to the optimisation of BWECS. The developments made to the Tabu Search are the subject of the rest of this chapter. In order to validate the Tabu Search algorithm developed, future work should be done on adapting another metaheuristic to optimise BWECS.

4.2 Statement of the Optimisation of BWECS

4.2.1 Outline of the Problem

The optimisation problem consists in dimensioning the BWECS for a given manure input in a given time period $m \in M$. M is a set of the number of months in the multi-period dimensioning problem. The BWECS under study is shown in Figure 4.1, for a farm with n_{herd} livestock (cows and swines in the experimental results).

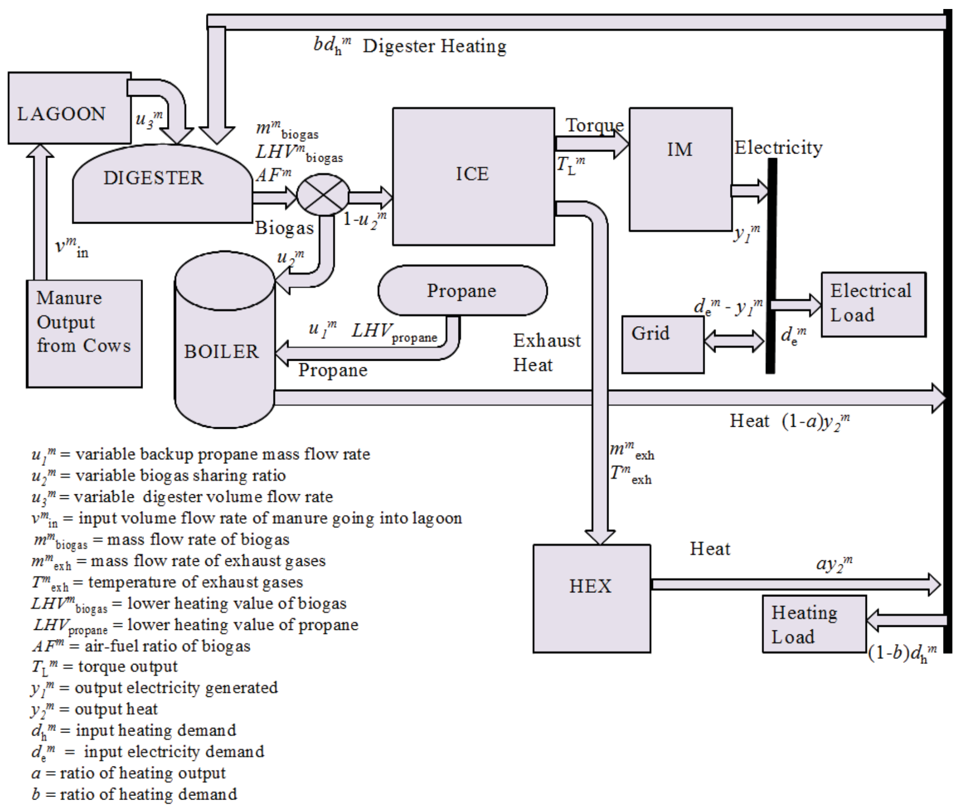


Figure 4.1: Biomass Waste to Energy Conversion System Model

Dimensioning is carried out with an adapted monthly setup, for: the backup propane flow rate, u_1^m, the split of biogas between the internal combustion engine (ICE) and the boiler, u_2^m and the volume flow rate of manure from the lagoon, u_3^m.

This is subject to the constraint of operating the BWECS such that the electricity and heating demands of the farm and the digester are met, while maximising revenue from the system. Manure from the livestock at a volume flow rate v_{in}^m goes into a lagoon, where it is stored. The manure from the lagoon is fed to a digester at a volume flow rate, u_3^m. In the digester, the manure undergoes anaerobic digestion to produce biogas at a mass flow rate, m_{biogas}^m, air-fuel ratio, AF^m and lower heating value, LHV_{biogas}^m. The biogas produced is to be shared between an internal combustion engine and a boiler, at a ratio determined by the variable u_2^m. The mass flow rate of biogas going into the internal combustion engine is $(1 - u_2^m)m_{\text{biogas}}$ and that going into the boiler is $m_{\text{biogas}}\, u_2^m$. The biogas is combusted in the internal combustion engine generating a torque T_{L}^m. The torque T_{L}^m is applied to an induction machine (IM) to generate electricity, output y_1^m. The electricity is used by the farm to meet the electricity load d_{e}^m. If excess electricity is produced by the BWECS it is sent to the electricity grid. The electricity sent to the grid is designated by $d_{\text{e}}^m - y_1^m$. If the electricity generated by the BWECS is insufficient to meet the demand of the farm, electricity is obtained from the grid and is designated by $y_1^m - d_{\text{e}}^m$. Combustion of biogas in the internal combustion engine produces exhaust gases at a mass flow rate and temperature denoted by m_{exh}^m and T_{exh}^m respectively. Heat from the exhaust gases is captured by the heat exchanger (HEX) and forms the heat output ay_2^m. The biogas that goes into the boiler is combusted to generate heat, denoted by $(1 - a)y_2^m$. The total heat output y_2^m has to meet the heating demand of both the digester bd_{h}^m and the farm $(1 - b)d_{\text{h}}^m$. The heating demand of the digester is calculated taking into consideration the heat losses from the walls, floor and roof of the digester, and the heat required to raise the temperature of the influent manure to the digester's operating temperature. The equations used are given in Section 5.1.1. When the boiler does not generate enough heat to meet the total heating load, propane will also be combusted in the boiler. The propane is supplied as a backup fuel from a propane tank, at a mass flow rate u_1^m and lower heating value LHV_{propane}.

The optimisation of the BWECS described is done with the objective of maximising revenue. The optimisation problem is expressed as a cost minimisation problem by:

$$\min f^{\text{cost}}(u_1^m, u_2^m, u_3^m) \quad \text{for a given manure input } v_{\text{in}}, \tag{4.3}$$

$$\text{subject to: } C_{\text{BWECS}}(u_1^m, u_2^m, u_3^m) \leq 0 \quad \text{for } m \in M, \tag{4.4}$$

$$\text{such that}: u_1^m \in \{0, 0.0001,\ 0.0002,\ 0.0003, ..., 0.0036\} \quad \text{for } m \in M, \tag{4.5}$$

$$u_2^m \in \{0,\ 0.01,\ 0.02,\ 0.03, ..., 0.99\} \quad \text{for } m \in M, \tag{4.6}$$

$$u_3^m \in \{1,\ 2,\ 3, ..., 59\} \quad \text{for } m \in M, \tag{4.7}$$

$$u = (u_1^1, u_2^1, u_3^1, u_1^2, u_2^2, u_3^2, ..., u_1^{|m|}, u_2^{|m|}, u_3^{|m|}) \quad \text{for } m \in M, \tag{4.8}$$

where u_1^m, u_2^m and u_3^m are the variables: backup propane mass flow rate, biogas sharing ratio and volume flow rate of manure going into the digester respectively. C_{BWECS} denotes a set of global constraints, some of which are linear and others non-linear. The set of global constraints will be described in Section 4.3.2. Using the variables, u_1^m, u_2^m and u_3^m, the outputs y_1^m and y_2^m can be obtained as described in Algorithm 2. u denotes the solution of the optimisation problem as described in the Tabu Search (see Algorithm 2). The outputs y_1^m and y_2^m will be used in Section 4.3.1 to describe the components of the objective function.

Algorithm 2 Optimisation of a BWECS

Initialization

Inputs: $n_{\text{herd}},\ d_{\text{e}}^m,\ d_{\text{h}}^m,\ v_{\text{in}}^m$ for $m \in M$

Initialize parameters: $V_{\text{lagoon}}^0,\ a,\ b,\ \eta_{\text{HEX}},\ \eta_{\text{boiler}},\ T_{\text{water}},\ LHV_{\text{propane}}$

for $m \in M$ **do**

  Build an initial solution (u_1^m, u_2^m, u_3^m) for $m \in M$

  Calculate the outputs of the BWECS model components

$$(V_{\text{lagoon}}^m, u_3^m) = \text{LAGOON}(v_{\text{in}}^m, V_{\text{lagoon}}^{m-1}, n_{\text{herd}})$$

$$(AF^m, LHV_{\text{biogas}}^m, m_{\text{biogas}}^m) = \text{DIGESTER}(u_3^m, bd_{\text{h}}^m)$$

$$(T_L^m, m_{\text{exh}}^m, T_{\text{exh}}^m, cp_{\text{exh}}^m) = \text{ICE}(m_{\text{biogas}}^m, (1-u_2^m),\ AF^m,\ LHV_{\text{biogas}}^m)$$

$$y_1^m = \text{IM}(T_{\text{L}}^m)$$

$$ay_2^m = \eta_{\text{HEX}}\, m_{\text{exh}}^m\, cp_{\text{exh}}^m (T_{\text{exh}}^m - T_{\text{water}})$$

$$(1-a)y_2^m = (LHV_{\text{propane}}\, u_1^m + m_{\text{biogas}}^m\, LHV_{\text{biogas}}^m\, u_2^m)\, \eta_{\text{boiler}}$$

end for

Evaluate the objective function f^{cost}

Tabu Search Optimisation

iter ← 0

while iter ≤ max_iter **do**

  Perform Tabu Search which includes evaluation of each of the BWECS model components

  Evaluate iterative solutions and update the incumbent solutions accordingly (see Section 4.3.1 on formation of Pareto incumbent solutions from the objective function)

end while

4.2.2 Optimisation Process Flow

Algorithm 2 describes the process flow of the optimisation. The inputs of the BWECS are: herd size n_{herd}, electricity demand d_{e}^m, heating demand d_{h}^m and volume flow rate of manure from the livestock v_{in}^m. These inputs are specified for each time period, $m \in M$. The parameters of the optimisation are initialised, i.e., V_{lagoon}^o, volume of manure in the lagoon, a, ratio of heating output, b, ratio of heating demand, η_{HEX}, efficiency of the heat exchanger, η_{boiler}, efficiency of the boiler, T_{water}, water temperature and LHV_{propane}, lower heating value of propane. An initial solution (u_1^m, u_2^m, u_3^m) is built for each of the time periods $m \in M$. This is done by calculating the outputs of the manure storage and the energy conversion processes in each component of the BWECS, using the functions: LAGOON, DIGESTER, ICE, IM, and the linear equations of the heat exchanger and the boiler (see Chapter 2). The function LAGOON is linear and calculates the storage of manure from the livestock, for each of the time periods $m \in M$. The functions DIGESTER, ICE and IM include complex non-linear differential equations and are represented as component models in the BWECS optimisation problem. These component models have been described in Chapter 2. Each of the component models of the functions DIGESTER, ICE and IM model a difficult non-linear optimisation problem. A variable that determines the output of the energy conversion processes in each of these component models is selected to define the solution (u_1^m, u_2^m, u_3^m), as shown in Algorithm 2. As such the non-linear optimisation problems of the component models are solved by optimisation of the BWECS, with the solution (u_1^m, u_2^m, u_3^m). The inputs and outputs of the component models and equations are defined in Table 4.1. The electricity and heat outputs, y_1^m and y_2^m respectively, are obtained and used in computation of the objective function. Once an initial solution has been found and the objective function computed, the Tabu Search optimisation is carried out to determine the near optimal solutions. The Tabu Search algorithm is described in Section 4.4.

Table 4.1: Inputs and Outputs of the Model Components

Input/Output	**Description**
n_{herd}	herd size
d_{e}^{m}	electrical demand of the farm
d_{h}^{m}	heat demand
v_{in}^{m}	volume flow rate of the manure from the livestock
V_{lagoon}^{m}	volume of the manure in the lagoon
m_{biogas}^{m}	mass flow rate of the biogas from the digester
m_{exh}^{m}	mass flow rate of the exhaust gases
T_{exh}^{m}	temperature of the exhaust gases
cp_{exh}	specific heat capacity of the exhaust gases
AF^{m}	air-fuel ratio of the biogas
LHV_{biogas}^{m}	Lower Heating Value of the biogas
T_{L}^{m}	output torque of the internal combustion engine
y_{1}^{m}	electricity output
y_{2}^{m}	heat output

4.3 Description of the Optimisation of BWECS

The optimisation problem involves evaluation of the biogas production and electricity and heat production from the volume flow rate of manure, v_{in}^{m} for $m \in M$. Starting with v_{in}^{m}, the inputs and outputs of the BWECS components are calculated in turn using the functions, LAGOON, DIGESTER, ICE, IM and the linear equations of the boiler and the heat exchanger. The functions of the respective BWECS components are indicated in Figure 4.1, together with the inputs and outputs. This section describes the objective function and the constraints of the optimisation, followed by an outline of the process flow of the optimisation problem.

4.3.1 Objective Function

The formulation of the optimisation problem maximises revenue from a BWECS subject to meeting the heating demand of the farm and the digester. The objective function has four components; the cost of capital, C_{capital}^{m}, the cost of propane,

C^m_{propane}, the cost of incentives, $C^m_{\text{incentives}}$ and the cost of grid electricity, $C^m_{\text{grid\_electricity}}$ for $m \in M$. The following is a description of the components of the objective function.

Cost of Capital

The cost of capital C^m_{capital} is calculated from the capital expenditure on the digester, lagoon, boiler and engine-generator set. The capital expenditure on these items is dependent on their sizes, which in turn depends on the herd size. The size of the digester and the lagoon are dependent on the volume flow rate of manure from the livestock, v^m_{in}. The cost of the boiler and engine-generator set are dependent on the ratings of the respective equipment. This capital expenditure is amortized monthly to obtain the cost of capital C^m_{capital}. The cost of capital is calculated using the non-linear function (4.9), details of which can be found in Chapter 5.

$$\begin{aligned} C^m_{\text{capital}} = \text{CAPITAL}(\, &\text{HRT},\, c_{\text{digester}},\, c_{\text{lagoon}},\, P_{\text{rated}},\, c_{\text{engine}},\, c_{\text{boiler}},\, C_{\text{cap\_incentive}}, \\ &i_{\text{rate}},\, n_{\text{period}},\, v^m_{\text{in}},\, V_{\text{lagoon\_storage}},\, d^m_{\text{h}},\, ay^m_2), \quad \text{for } m \in M, \end{aligned} \tag{4.9}$$

where CAPITAL is the function for calculation of the cost of capital, v^m_{in} is the volume flow rate of manure from the livestock, HRT is the hydraulic retention time, c_{digester} is the cost of the digester, $V_{\text{lagoon\_storage}}$ is the storage capacity of the lagoon, c_{lagoon} is the unit cost of the lagoon, P_{rated} is the power rating of the induction machine, c_{engine} is the cost of the engine-generator set, d^m_{h} is the heating load, a is the ratio of heat output from the heat exchanger, y^m_2 is the heat output, c_{boiler} is the cost of the boiler, $C_{\text{cap\_incentive}}$ is the capacity incentive, i_{rate} is the interest rate and n_{period} is the number of periods over which the interest is charged.

Cost of Propane

The monthly cost of propane, C^m_{propane} is a linear function of the backup propane mass flow rate, u^m_1 and is given by (4.10). For the details of the function see Chapter 5.

$$C^m_{\text{propane}} = \text{PROPANE}(c_{\text{propane}}, u^m_1) \quad \text{for } m \in M, \tag{4.10}$$

where PROPANE is the function for calculating the cost of propane, c_{propane} is the unit cost of propane and u^m_1 is the backup propane mass flow rate.

Cost of Incentives

A performance incentive is given for generation of renewable energy. This incentive is included in the objective function and is calculated by a linear function (4.11), details of which can be found in Chapter 5.

$$C^m_{\text{incentives}} = \text{INCENTIVES}(c_{\text{incentives}}, y^m_1) \quad \text{for } m \in M, \tag{4.11}$$

where $C^m_{\text{incentives}}$ is the cost of incentives, INCENTIVES is the function for calculating the cost of incentives, y^m_1 is the electricity output and $c_{\text{incentives}}$ is the unit cost of incentives.

Cost of Grid Electricity

The cost of grid electricity, $C^m_{\text{grid\_electricity}}$ is a non-linear function of the electricity output, y^m_1 (4.12), the details of which can be found in Chapter 5.

$$C^m_{\text{grid\_electricity}} = \text{GRID\_ELECTRICITY}(c_{\text{tariff}}, d^m_{\text{e}}, y^m_1) \quad \text{for } m \in M, \tag{4.12}$$

The four cost components of the objective function form a multi-objective optimisation problem. With the Tabu Search method used, sampling of the neighbourhood results in many solutions. Each of these solutions is to be evaluated using the multi-objective function. The incumbent solution is to be selected as the one with the minimum overall cost. In determination of a solution that will minimise the overall objective, an easy way is to compute the overall cost as:

$$z = \sum_{m=1}^{M} (C^m_{\text{capital}} + C^m_{\text{propane}} - C^m_{\text{incentives}} + C^m_{\text{grid\_electricity}}) \quad \text{for } m \in M. \tag{4.13}$$

The drawback of (4.13) is the different ranges of the values of the cost components. This means that the overall objective will largely be minimising the cost components with the highest value. This can be overcome by the use of weights, but it is difficult to find the proper weights. A better method is to express the objective function as a cost vector of the components, resulting in a cost vector for each of the solutions. Let

$$\vec{f}_k^{\text{ cost}} = \left[\sum_{m=1}^{M} C^m_{\text{capital}}, \quad \sum_{m=1}^{M} C^m_{\text{propane}}, \quad - \sum_{m=1}^{M} C^m_{\text{incentives}}, \quad \sum_{m=1}^{M} C^m_{\text{grid\_electricity}} \right], \tag{4.14}$$

for $k \in K$ and $m \in M$,

be the set of solutions. The individual cost components of the solution vectors are compared for dominance. The vectors with the non-dominant cost components form a Pareto incumbent front. The solutions on the Pareto incumbent front are selected as the incumbent solutions. There are several incumbent solutions, all of which are retained, as shown in Figure 4.2 for the comparison of the cost of propane and the cost of grid electricity.

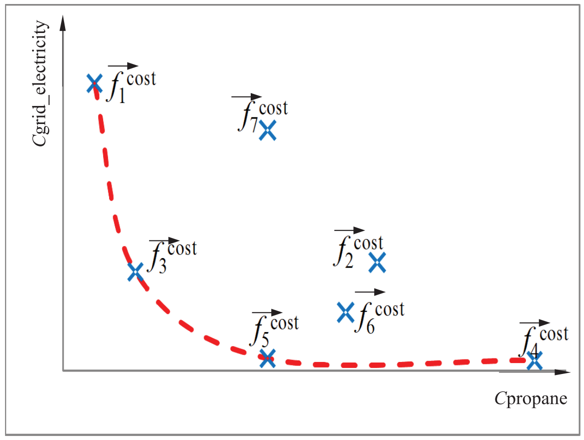


Figure 4.2: Illustration of Pareto Incumbent Front

4.3.2 Global Constraints

This section describes the global constraints, C_{BWECS}, and how they are derived from the optimisation problem. The initial solution described in Algorithm 2 satisfies the global constraints. In the Tabu Search optimisation that follows, the solution (u_1^m, u_2^m, u_3^m) has to be checked for satisfaction of the global constraints. These constraints are defined as:

$$0 \;\leq\; (v_{\text{in}}^m n_{\text{days}}^m + V_{\text{lagoon\_manure}}^{m-1} - n_{\text{days}}^m u_3^m) \;\leq\; V_{\text{lagoon\_storage}}\, v_{\text{in}}^m, \tag{4.15}$$

$$(V_{\text{D}} - \text{HRT} u_3^m) \;\geq\; 0, \tag{4.16}$$

$$(P_{\text{rated}}/\omega_{\text{mech}} - \text{ICE}(LHV_{\text{biogas}}^m,\, \omega_{\text{mech}},\, (1 - u_2^m) m_{\text{biogas}}^m)) \;\geq\; 0, \tag{4.17}$$

$$d_{\text{h}}^m \;\leq\; (\eta_{\text{HEX}}\, m_{\text{exh}}^m\, cp_{\text{exh}}(T_{\text{exh}}^m - T_{\text{water}}) +$$

$$(LHV_{\text{propane}}\, u_1^m + m_{\text{biogas}}^m\, LHV_{\text{biogas}}^m\, u_2^m)\, \eta_{\text{boiler}}) \;\leq\; (d_{\text{h}}^m + \delta_{\text{h}}), \tag{4.18}$$

$$(b_{\text{r}} - d_{\text{h}}^m + \eta_{\text{HEX}}\, m_{\text{exh}}^m\, cp_{\text{exh}}(T_{\text{exh}}^m - T_{\text{water}})) \;\leq\; 0, \tag{4.19}$$

for $m \in M$,

where v_{in}^m is the volume flow rate of manure from the livestock, n_{days}^m are the number of days, $V_{\text{lagoon\_manure}}^{m-1}$ is the volume of manure in the lagoon, u_3^m is the volume flow rate of manure from the lagoon, $V_{\text{lagoon\_storage}}$ is the storage capacity of the lagoon, V_{D} is the volume of the digester, HRT is the hydraulic retention time of the digester, P_{rated} is the power rating of the induction machine, ω_{mech} is the speed of the internal combustion engine, ICE is the function for evaluation of the torque output of the internal combustion engine, LHV_{biogas}^m is the lower heating value of biogas, u_2^m is the biogas sharing ratio, m_{biogas}^m is the mass flow rate of biogas, d_{h}^m is the heating demand, η_{HEX} is the efficiency of the heat exchanger, m_{exh}^m is the mass flow rate of the exhaust gases, cp_{exh} is the specific heat capacity of the exhaust gases, T_{exh}^m is the temperature of the exhaust gases, T_{water} is the temperature of water, u_1^m is the mass flow rate of backup propane, LHV_{propane}^m is the lower heating value of propane, η_{boiler} is the efficiency of the boiler, δ_{h} is an allowance for the heating constraint and b_{r} is the boiler rating. The manure from the livestock is stored in a lagoon with a storage capacity of $V_{\text{lagoon\_storage}}$ days. The volume flow rate of manure from the lagoon into the digester, u_3^m is varied to minimise the cost of the system. Constraint (6.15) is set to ensure that the net volume of manure in the lagoon is not negative. In a given month m, the volume of manure that goes into the lagoon $n_{\text{day}}^m u_3^m$, should not be greater than the sum of the volume of the manure that was in the lagoon the previous month $V_{\text{lagoon\_manure}}^{m-1}$, and the volume of manure from the livestock in month m. Constraint (6.15) also ensures that the volume of manure in the lagoon is not greater than the storage capacity of the lagoon.

Constraint (6.17) is set to ensure that the volume of manure in the digester, HRTu_3^m, is not greater than the volume of the digester V_{D}. The digester is modeled using non-linear differential equations. The digester model is treated as a black box for purposes of optimisation. The differential equations in the black box, DIGESTER, used to calculate the mass flow rate, m^m_{biogas}, the air-fuel ratio, AF^m and the lower heating value of biogas, LHV^m_{biogas} can be found in [50]. The output torque of the internal combustion engine is determined by applying the Newton-Raphson method to a two dimensional linear interpolation function. The linear interpolation function is multiplied by the available torque. The available torque is calculated from the mass flow rate of biogas to the internal combustion engine, the lower heating value of biogas, and the speed of the internal combustion engine. The internal combustion engine model is also treated as a black box of these functions (ICE). The details of the modeling of the internal combustion engine can be found in [56]. The internal combustion engine is coupled to an induction machine of rating, P_{rated}, that generates electric power. The induction machine is modeled using non-linear differential equations detailed in [57]. The induction machine is also treated as a black box, IM, with the input as torque and the output as electricity, y^m_1. The electricity generated is a function of the torque, which in turn is a function of the mass flow rate of biogas to the internal combustion engine. Constraint (6.18) is therefore set to limit the mass flow rate of biogas to not more than what is required to generate rated power, P_{rated} in the induction machine.

Sometimes the biogas generated by the digester may be insufficient for sharing between the internal combustion engine and the boiler. Priority is then given to the combustion of biogas in the internal combustion engine, and propane is combusted in the boiler. This is done to generate electricity that can be sold to the utility. The revenue from the sale of electricity to the utility will be greater than the cost savings from the avoided use of propane for heating. A propane tank that supplies propane at a mass flow rate, u^m_1 is therefore included in the BWECS. The heat produced by the boiler is calculated from the mass flow rate of biogas to the boiler, $m^{m}_{\text{biogas}}\, u_2$, the mass flow rate of propane, u^{m}_{1}, the lower heating value of propane and the lower heating value of biogas. Exhaust heat is also produced as a result of the combustion process in the internal combustion engine. This exhaust heat is captured by the heat exchanger. Constraint (6.19) is set to ensure that the heat output of the BWECS meets the heating demand of the farm and the digester. Constraint (6.20) is set to ensure that the heat to be generated by the boiler is not greater than the boiler rating, b_{r}. The contribution of the heat captured by the heat exchanger is subtracted from the heat output of the boiler in formulation of Constraint (6.20). The boiler rating is calculated by a non-linear equation given in Chapter 5.

Infeasible solutions arise if the constraints are not met. The measure of infeasibility of the solution is calculated as:

$$f^{\text{infeas}} = \sum_{m=1}^{M} (S^{m}_{\text{lagoon\_volume}} + S^{m}_{\text{digester\_size}} + S^{m}_{\text{mbiogas}} + S^{m}_{\text{heating\_demand}} + S^{m}_{\text{boiler\_rating}}), \quad (4.20)$$

for $m \in M$,

where f^{infeas} is the total measure of infeasibility, $S^{m}_{\text{lagoon\_volume}}$, $S^{m}_{\text{digester\_size}}$, S^{m}_{mbiogas}, $S^{m}_{\text{heating\_demand}}$ and $S^{m}_{\text{boiler\_rating}}$ are the measures of infeasibility of the volume of manure in the lagoon, the digester size, the mass flow rate of biogas to the engine-generator set, the total heat output and the boiler rating, respectively. The measures of infeasibility are derived from the respective Constraints (6.15), (6.17), (6.18), (6.19) and (6.20).

Using the measure of infeasibility of the volume of manure in the lagoon as an example:

$$n_{\text{days}}^{m} u_{3}^{m} + S_{\text{lagoon\_volume}}^{m} = V_{\text{lagoon\_manure}}^{m-1} - V_{\text{lagoon\_storage}} v_{\text{in}}^{m} + v_{\text{in}}^{m} n_{\text{days}}^{m}, \tag{4.21}$$

for $m \in M$,

the solution is feasible for $S_{\text{lagoon\_volume}}^{m} \geq 0$,

where n_{days}^{m} are the number of days, u_{3}^{m} is the volume flow rate of manure from the lagoon, $S_{\text{lagoon\_volume}}^{m}$, is the measure of infeasibility of the volume of manure in the lagoon, $V_{\text{lagoon\_manure}}^{m-1}$ is the volume of manure in the lagoon, $V_{\text{lagoon\_storage}}$ is the storage capacity of the lagoon and v_{in}^{m} is the volume flow rate of manure from the livestock. The other measures of infeasibility are defined similarly. The handling of infeasibility is discussed in Section 4.4.2.

4.4 Description of the Tabu Search Algorithm

This section describes the adaptations of the Tabu Search algorithm developed for optimisation of a BWECS. The Tabu Search is described in Algorithm 3. The notation and the parameters of the Tabu Search are given in Tables 4.2 and 4.3 respectively.

4.4.1 Basic Tabu Search Algorithm

As described in Section 4.1, the basic Tabu Search defines a neighbourhood of moves that can be applied to the solution, keeps a list of the forbidden moves (Tabu list) and incorporates a stopping condition. These aspects of the basic Tabu Search included in the optimisation of the BWECS are discussed in this section.

Definition of the Neighbourhood

The neighbourhood of u_i^m is defined as:

$$\mathcal{N}(u_i^m)^{new} = \left\{ \begin{array}{ll} v : v = u_i^m + \delta_i & i = 1, 2, 3 \\ \quad v = u_i^m - \delta_i & m \in M \\ & u \in U^{\text{MODEL}} \cup U^{\text{GLOBAL}} \end{array} \right\}$$

$$LB_v \leq v \leq UB_v : v \in \mathcal{N}(u_i^m),$$

where u_i^m is the optimisation variable, U^{MODEL} is the set of constraints to be satisfied by the BWECS black box models, U^{GLOBAL} is the set of global constraints to be satisfied by the optimisation, LB_v is the lower bound of the neighbourhood and UB_v is the upper bound of the neighbourhood. The move from u_i^m to $u_i^m \pm \delta_i$ is selected within the specific limits and step sizes for the different variables, specified in Section 4.2.1.

Tabu List

A Tabu list is formulated from moves that result in the current solution. Each entry of the Tabu list is a vector of the move from u_i^m to $u_i^m \pm \delta_i$, and its associated month. Reverse moves are also included in the Tabu list. The Tabu list includes a random number $n^{\text{TL\_length}}$, selected within a given interval, that decides for how many iterations a Tabu condition persists.

Stopping Condition

The stopping condition of the Tabu Search algorithm is set to termination of the optimisation, if no improvement in the incumbent solution has been observed after max_iter iterations, following the application of diversification.

Table 4.2: Tabu Search Notation

Notation	Description
$u_i^{m,\,\text{init}}$	initial solution
u_i^m	current solution
S^{best}	set of the Pareto incumbent solutions
S^{current}	set of the Pareto current solutions
$\mathcal{N}(u_i^m)$	neighbourhood of variable u_i^m
LB_v	lower bound of neighbourhood
UB_v	upper bound of neighbourhood
T^{list}	Tabu list
U^{MODEL}	set of constraints to be satisfied by the BWECS black box models
U^{GLOBAL}	set of global constraints to be satisfied by the optimisation

4.4.2 Adaptations of the Tabu Search

Four aspects of the Tabu Search have been developed for adaptation to the problem being solved. These are: use of the Pareto optimal front method to evaluate the multi-period and multi-objective function, constraints handling, the multi-period optimisation strategy and the diversification strategy. This section describes the adaptations developed.

Pareto Incumbent Solutions

During the Tabu Search optimisation a different variable is optimised for each time period, $m \in M$, for as long as the current solution is improving. This implies that only the cost components of the period for which the optimisation is carried out are modified, each time the objective function is evaluated. In order not to lose the benefit of the modified cost components, they are summed separately for all the periods to form the cost vector (4.15). The cost vectors are then checked for non-dominance and the

Algorithm 3 Tabu Search

Initialization

Build a feasible initial solution $u_i^{m,\text{init}}$

Set $u_i^m \leftarrow u_i^{m,\text{init}}, \quad S^{\text{best}} \leftarrow \{u_i^{m,\text{init}}, \quad m \in M, \quad i = 1, 2, 3\}$

Initialize the Tabu list: $T^{\text{list}} \leftarrow \emptyset$

Set the bounds

Evaluate $\vec{f}^{\text{cost}}_{\min}, \quad \vec{f}^{\text{infeas}}_{\min}$

Tabu Search

iter $\leftarrow 0$

while iter $\leq$ max_iter **do**

  while iter $\leq$ max_iter_div **do**

    Phase 1: Minimize Cost

    iter_opt $\leftarrow 0$

    while iter_opt $\leq$ max_iter_opt /*Attempt at finding a solution with a smaller cost regardless of the infeasibility*/ **do**

      Perform a round robin search on the months : For a given month $m \in M$, select one variable with index $i(m) : i(m) = i(m-1) + 1 \pmod 3$

      Update the neighbourhood of the selected variable

      Evaluate all solutions $u_i^{m'}$ in $\mathcal{N}(u_i^m)$ with respect to $\vec{f}^{\text{cost}}_{\min}, \quad \vec{f}^{\text{infeas}}_{\min}$ (only for storage with solution)

      $S^{\text{current}} \leftarrow \underset{u'}{\text{argmin}} \vec{f}^{\text{cost}}_{\min}(u')$

      for $u = (u_1^1, u_2^1, u_3^1, u_1^2, u_2^2, u_3^2, ..., u_1^{|m|}, u_2^{|m|}, u_3^{|m|})$ and $m \in M$

    end while

    iter_feas $\leftarrow 0$

    Phase 2: Minimize Infeasibility

    while iter_feas $\leq$ max_iter_feas /* Reducing infeasibility*/ **do**

      Select the month $m \in M$ for which the search is to be carried out :

      $m \leftarrow \underset{m'}{\text{argmax}} \vec{f}^{\text{infeas}}_{\min}(u')$ for $u = (u_1^1, u_2^1, u_3^1, u_1^2, u_2^2, u_3^2, ..., u_1^{|m|}, u_2^{|m|}, u_3^{|m|})$

      Update the neighbourhood of the selected variable

      Evaluate all solutions $u_i^{m'}$ in $\mathcal{N}(u_i^m)$ with respect to $\vec{f}^{\text{infeas}}_{\min}, \quad \vec{f}^{\text{cost}}_{\min}$ (only for storage of solution)

      $S^{\text{current}} \leftarrow \underset{u'}{\text{argmin}} \vec{f}^{\text{infeas}}_{\min}(u')$

      for $u = (u_1^1, u_2^1, u_3^1, u_1^2, u_2^2, u_3^2, ..., u_1^{|m|}, u_2^{|m|}, u_3^{|m|})$ and $m \in M$

    end while

  end while

  Apply diversification

end while

Table 4.3: Parameters of the Tabu Search

Parameter	Description	Value
$V_{\text{lagoon\_storage}}$	storage capacity of the lagoon (days)	35
HRT	hydraulic retention time (days)	20
n_{herd}	number of livestock	500cows, 8000swines
n^{m}_{day}	number of days in a month	varies
P_{rated}	rating of the induction machine (hp)	150
LHV_{propane}	lower heating value of propane (kJ/kg)	46,300 [136]
T_{water}	water temperature (°C)	35
η_{HEX}	heat exchanger efficiency (%)	70
η_{rated}	boiler efficiency (%)	70
c_{lagoon}	unit cost of lagoon (USD/m^3)	2.47 [6]
c_{propane}	unit cost of propane (USD/m^3)	1.98[25]
$c_{\text{incentives}}$	unit cost of incentives (USD/kWh)	0.07 [137]
$n^{\text{rand\_div}}$	consecutive random moves (diversification Strategy D1)	5
$n^{\text{nonimprov\_div}}$	consecutive non-improving moves to apply diversification	5
$n^{\text{restart\_div}}$	restarts with incumbent solution (diversification Strategy D2)	3
max_iter_div	number of iterations for application of diversification	100
δ_{h}	allowance for heat demand constraint (kW)	10
max_iter	number of iterations for the stopping condition	150
max_iter_opt	number of iterations for the minimisation of cost	50
max_iter_feas	number of iterations for the minimisation of infeasibility	25
max_iter_div	number of iterations for the application of diversification	100 (cows data) 50 (swines data)
S^{infeas}	threshold of infeasibility	varies
S^{infeas}_0	initial threshold of infeasibility	varies

non-dominated solutions form a Pareto incumbent front, as described in Section 4.3.1. Summing the cost components separately over all the periods, M, incorporates the multi-period nature of the optimisation into the evaluation of the objective function. This is different from the references cited in the literature review (see Chapter 1), in that although the optimisation is carried out for one period, the Pareto incumbent front is formed by summing the cost components over all the periods. The Pareto front method of evaluating multi-objective functions has therefore been modified to incorporate the multi-period nature of the optimisation problem.

Method of Handling Constraints

There are two sets of constraints in the optimisation problem of the BWECS. U^{MODEL} is the set of constraints to be satisfied by the models of the BWECS and U^{GLOBAL} is the set of global constraints to be satisfied by the solution of the optimisation problem, i.e., $C_{\text{BWECS}}(u_1^m, u_2^m, u_3^m)$ (4.4). The global constraints are defined in Section 4.3.2. The set of constraints to be satisfied by the models of the BWECS, U^{MODEL} is not defined because the BWECS models are treated as black boxes in the optimisation problem. The method of handling constraints discussed applies to the set of global constraints, U^{GLOBAL}. Infeasible solutions result if the global constraints are not satisfied. Infeasible solutions are allowed in the Tabu Search optimisation in order to allow the search to move to low cost regions during the minimisation of cost. To ensure that the search goes back to a feasible region, a second objective function is introduced. The second objective function minimises infeasibility (4.20). The Tabu Search optimisation alternates between minimising cost (Phase 1) and minimising infeasibility (Phase 2). Thresholds are set for the extent to which infeasibility is allowed. These thresholds are progressively reduced during the course of the optimisation.

Multi-period Optimisation Strategy

A multi-period optimisation strategy is developed to ensure a smooth transition from one period to the next during optimisation. Different strategies are used for the phase for minimisation of cost (Phase 1) and minimisation of infeasibility (Phase 2). The period is measured in months. The variables are optimised for each month. During the phase for minimisation of cost, optimisation is done based on a round robin strategy of the months, starting with the month of January. If a solution is encountered that is worse than the current solution, another variable is selected for optimisation, in the same month. If all three variables do not result in an improved solution, the current solution is not updated. This is repeated for the twelve months period. If the current solution does not improve over this 12 months period, it is updated with the least non-improving solution. The optimisation strategy during the phase for minimisation of infeasibility is such that the month with the most infeasible solution is selected for optimisation. This is in contrast to the phase of minimisation of cost, where the round robin method is used. Once a feasible solution is encountered during the phase of minimisation of infeasibility, the strategy reverts to minimisation of cost.

Diversification

If the incumbent solution does not improve for max_iter_div iterations, diversification is applied. Diversification is applied by performing three consecutive restarts with the incumbent solution. For each restart performed, a different variable is selected for optimisation. Diversification is only applied if after the max_iter_div iteration, the current solution does not improve for $n^{\text{nonimprov\_div}}$ consecutive iterations. The Tabu list is emptied on performing each of the restarts.

Experiments were carried out to test the Tabu Search aspects developed. The following section describes the experiments and discusses the results.

4.5 Experiments and Results

This section begins with a description of the data instances and definitions of the experiments.

4.5.1 Data Instances

Two data instances are used in the experiments. One of the data instance is obtained from a dairy farm of herd size 500 cows ([60]) and the other is obtained from a swine farm of herd size 8000 swines [138].

4.5.2 Descriptions of the Strategies of the Tabu Search Experiments

The experiments carried out are grouped into strategies. Many strategies were tested and the most successful ones were reported. The strategies correspond to the aspects of the Tabu Search developed and discussed in Section 4.4.2 and are defined below:

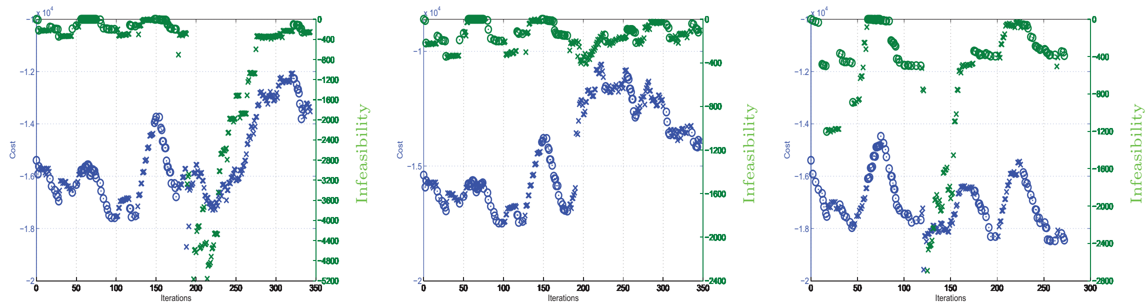
(i) Strategy C1, the threshold of infeasibility is adjusted to handle constraints;
(ii) Strategy C2, the number of iterations for minimisation of cost and minimisation of infeasibility are varied to handle constraints;
(iii) Strategy C3, feasible and infeasible solutions are allowed during the phase for minimisation of infeasibility;
(iv) Strategy D1, diversification by consecutive random moves;
(v) Strategy D2, diversification by consecutive restarts with the incumbent solution;
(vi) Strategy MOBJ1, evaluation of Pareto incumbent solutions;
(vii) Strategy MOBJ2, summing cost components of the objective function;
(viii) Strategy MP1, round robin and updating current solution;
(ix) Strategy MP2, round robin and updating solution with improving solution only;
(x) Strategy MP3, round robin and updating solution with improving solution only, and sampling all variables in one month if required;
(xi) Strategy MP4, round robin during the phase for minimisation of infeasibility;

Experiments with Strategies C1, C2 and C3 were developed to investigate the handling of constraints. Two diversification strategies D1 and D2 were experimented with. Experiments with Strategies MOBJ1 and MOBJ2 were developed to investigate the formation of Pareto incumbent solutions in the multi-objective and multi-period optimisation problem. Handling of the multi-period nature of the problem was investigated in Strategies MP1, MP2, MP3 and MP4. Each of these strategies is explained in detail in the following sections. The summary of the experimental results is given in Tables 7.1 and 7.2 in the appendix, for the cows and swines data instances, respectively.

Constraints Handling Strategy

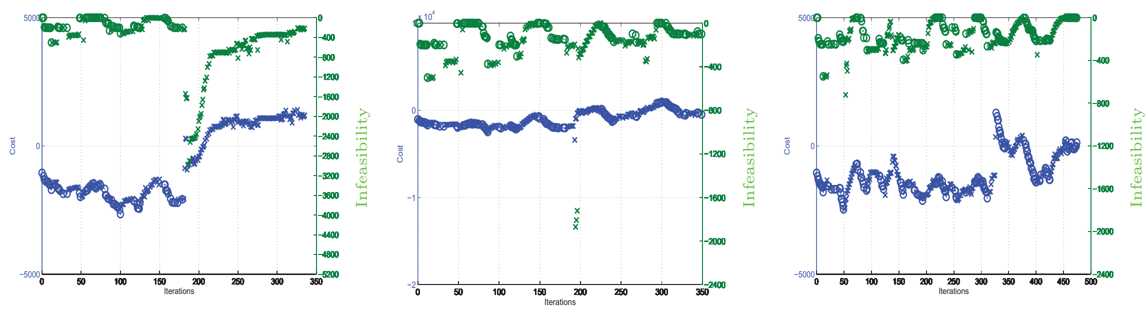
The aim of the experiments for constraint handling carried out in Strategies C1, C2 and C3, is to show that allowing infeasibility for a given set of parameters aids in moving towards an optimal solution faster. Two parameters are experimented with: (i) thresholds of infeasibility and (ii) number of iterations for which the cost or the infeasibility is minimised. The threshold is a value that limits the extent of infeasibility. This is required to prevent the solution from becoming too infeasible and therefore unable to return to a feasible region. In Strategy C1 the threshold of infeasibility is fixed. Three fixed thresholds are experimented with, for each of the data instances. These are S^{infeas}=-500, -200 and -100 for the cows data instance and S^{infeas}=-500, -205 and -100 for the swines data instance. The results of fixing the threshold of infeasibility to S^{infeas}=-200 for the cows data instance and to S^{infeas}=-205 for the swines data instance, are shown in Figures 4.3(a) and 4.4(a), respectively.

When the threshold is fixed to S^{infeas}=-500, the cost reaches low values. However these low values are in the infeasible regions. This is seen in Tables 7.1 and 7.2. The



(a) Fixed Threshold S^{infeas}=-200 (b) Varying Thresholds $S_{\text{o}}^{\text{infeas}}$=-200 (c) Varying Thresholds $S_{\text{o}}^{\text{infeas}}$=-300

Figure 4.3: Strategy C1 (Cows)



(a) Fixed Threshold S^{infeas}=-205 (b) Varying Thresholds $S_{\text{o}}^{\text{infeas}}$=-205 (c) Varying Thresholds $S_{\text{o}}^{\text{infeas}}$=-250

Figure 4.4: Strategy C1 (Swines)

costs of grid electricity for the current solutions are -18,278, -18,197, -19,091 and -19,949 at the 50$^{\text{th}}$, 100$^{\text{th}}$, 200$^{\text{th}}$ iterations and at termination, respectively for the cows data instance. The costs of grid electricity for the current solutions are -4327, -4131, -3844 and -3534 at the 50$^{\text{th}}$, 100$^{\text{th}}$, 200$^{\text{th}}$ iterations and at termination, respectively for the swines data instance. The resulting incumbent solutions have higher values of -16,854 for the cost of grid electricity of the cows data instance, and -4064 for the swines data instance. Fixing the threshold of infeasibility to a lower value of S^{infeas}=-200, for the cows data instance and S^{infeas}=-205, for the swines data instance, gives better incumbent solutions. Table 7.1 for the cows data instance shows that iterations 100, 200 and the termination condition have costs of grid electricity for the incumbent solutions of -16,130, -16,525, -16,627, -16,730 and -16,834. The current solution also reaches relatively low values of costs of grid electricity of -17,071 and -18,302 at the 50^{th} and 100^{th} iterations respectively. Better incumbent solutions are also obtained from the swines data instance at S^{infeas}=-205. This is shown in Table 7.2, where with S^{infeas}=-205, the incumbent solution has a cost of grid electricity of -4064 by the 50^{th} iteration, and at termination the incumbent solution has a cost of grid electricity of -4630. Fixing the threshold of infeasibility to a lower value of S^{infeas}=-100 does not result in significantly better incumbent solutions. At S^{infeas}=-100, the cost of grid electricity of the incumbent solution is -16,130, for the cows data instance, and -4209, for the swines data instance. This is because S^{infeas}=-100 is so low that it restricts the search to a local region. This is evidenced by the high values of the costs of grid electricity of the current solutions of -15,410, -13,739 and -13,022 at the 100^{th} and 200^{th} iterations, and at termination respectively, for the cows data instance (Table 7.1). The respective values of infeasibility are -155, -99 and -139. The costs of grid electricity are higher than those at S^{infeas}=-500 and -200, at the same number of iterations. With the swine data instance, the cost of grid electricity of the incumbent solution improves slightly from -4064 to -4209 (Table 7.2). This implies that the search remains in a local region. From these experiments, a good starting point for the threshold of infeasibility is identified as S^{infeas}=-200 for the cows data instance and S^{infeas}=-205 for the swines data instance.

Further investigation was required on the effect of varying the threshold of infeasibility, before a conclusion could be arrived at on the suitability of the strategy of fixing the threshold. Strategy C1 therefore also included experiments where the threshold of infeasibility was varied. The initial thresholds of infeasibility were set to $S_{\text{o}}^{\text{infeas}}$=-500, -300, -200 and -100 for the cows data instance and $S_{\text{o}}^{\text{infeas}}$=-500, -250,

-205 and -100 for the swines data instance. The thresholds of infeasibility were varied as follows:

$$S_{\mathrm{o}}^{\mathrm{infeas}} = -500; \quad S^{\mathrm{infeas}} \in \{-500, -400, -300, -200, -100, -50, -40, ..., -10\}, \tag{4.22}$$

$$S_{\mathrm{o}}^{\mathrm{infeas}} = -300; \quad S^{\mathrm{infeas}} \in \{-300, -200, -100, -50, -40, -30, -20, -10\}, \tag{4.23}$$

$$S_{\mathrm{o}}^{\mathrm{infeas}} = -250; \quad S^{\mathrm{infeas}} \in \{-250, -245, -240, -235, -230, -225, ..., 165\}, \tag{4.24}$$

$$S_{\mathrm{o}}^{\mathrm{infeas}} = -205; \quad S^{\mathrm{infeas}} \in \{-205, -200, -195, -190, -185, -180, ..., 120\}, \tag{4.25}$$

$$S_{\mathrm{o}}^{\mathrm{infeas}} = -200; \quad S^{\mathrm{infeas}} \in \{-200, -150, -100, -90, -80, -70, -60, ..., -10\}, \tag{4.26}$$

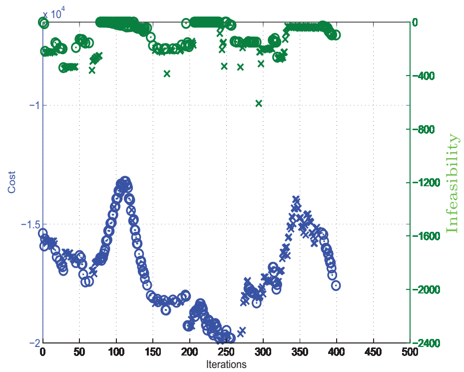
$$S_{\mathrm{o}}^{\mathrm{infeas}} = -100; \quad S^{\mathrm{infeas}} \in \{-100, -90, -80, -70, -60, -50, -40, -30, ..., -10\}, \tag{4.27}$$

where $S_{\mathrm{o}}^{\mathrm{infeas}}$ is the initial threshold of infeasibility and S^{infeas} is the varying threshold of infeasibility. The results of these experiments are shown in Figures 4.3(b) and 4.3(c), for the cows data instance and Figures 4.4(b) and 4.4(c) for the swines data instance. These results are summarised in Tables 7.1 and 7.2. Table 7.1 for the cows data instance shows that with Strategy C1 and with $S_{\mathrm{o}}^{\mathrm{infeas}}$=-500, the cost of grid electricity of the current solution reaches very low values. However these occur in the infeasible regions. With the same strategy and $S_{\mathrm{o}}^{\mathrm{infeas}}$=-500, the incumbent solution of the swines data instance does not improve from the 50$^{\mathrm{th}}$ iteration onwards (Table 7.2). For both data instances, the current solutions have high values of infeasibility with $S_{\mathrm{o}}^{\mathrm{infeas}}$=-500, compared to the other experiments with the other values of $S_{\mathrm{o}}^{\mathrm{infeas}}$. S_{o}^{infeas}=-500 is therefore too large a threshold to keep the solution in a feasible region. With $S_{\mathrm{o}}^{\mathrm{infeas}}$=-300, the incumbent solution obtained for the cows data instance is worse than with $S_{\mathrm{o}}^{\mathrm{infeas}}$=-500. The incumbent solution is the same for $S_{\mathrm{o}}^{\mathrm{infeas}}$=-500 and $S_{\mathrm{o}}^{\mathrm{infeas}}$=-300 for the swines data instance. These results can be explained as $S_{\text{o}}^{\text{infeas}}$=-300 being a large threshold of infeasibility, that keeps the solution in infeasible regions. With $S_{\text{o}}^{\text{infeas}}$=-100, there is no improvement in the incumbent solution for the swines data instance, whereas there is a slight improvement in the incumbent solution for the cows data instance. This is because $S_{\text{o}}^{\text{infeas}}$=-100 is too low for the search to move away from a local region. $S_{\text{o}}^{\text{infeas}}$=-200 and $S_{\text{o}}^{\text{infeas}}$=-205 for the cows and swines data instances, respectively, give the best results.

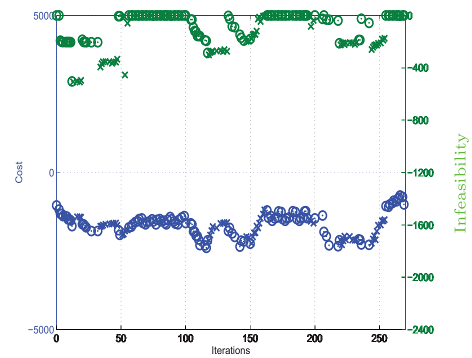
With regard to Strategy C1, a cost of grid electricity of -16,884 for the incumbent solution, is obtained, at $S_{\text{o}}^{\text{infeas}}$=-200, for the cows data instance (Table 7.1). S^{infeas}=-200 also gave the best incumbent solution for the cows data instance, for the experiments of fixing the threshold of infeasibility. Varying the threshold of infeasibility gives a better incumbent solution compared to fixing the threshold of infeasibility. For the swines data instance the incumbent solution is the same with $S_{\text{o}}^{\text{infeas}}$=$S^{\text{infeas}}$=-205 (Table 7.2), however this is the best incumbent solution from experiments of Strategy C1.

Figures 4.3(b) and 4.4(b), show a move towards lower costs at the beginning of the iterations, for $S_{\text{o}}^{\text{infeas}}$=-200, for the cows data instance and $S_{\text{o}}^{\text{infeas}}$=-205, for the swines data instance. As the iterations progress, the costs tend to increase. This is because of the progressive decrease in the threshold of infeasibility, leading to large decreases in infeasibility. Decreasing infeasibility has the reverse effect of increasing cost. The increasing cost means the solution is moving away from the optimal. Diversification Strategy D1 which involves making 5 consecutive random moves was being applied after 100 iterations, to move the search to a new region. This however did not impact the optimisation significantly and the incumbent solution was obtained before the 100^{th} iteration (Figures 4.3(b) and 4.4(b)). In order to obtain improving incumbent solutions after the 100^{th} iteration, diversification Strategy D2 was developed and used for subsequent experiments of Strategies C2, C3, MOBJ1, MOBJ2, MP1, MP2, MP3 and MP4. In Strategy D2, a restart was made with the incumbent solution, if there was no improvement in the incumbent solution after max_iter_div iterations. The discussion on the experiments of the diversification strategies is done in Section 4.5.2.

In Strategy C2, the number of iterations for the minimisation of cost and minimisation of infeasibility were varied. In the first experiment done, the same number of iterations were allowed for minimisation of cost and minimisation of infeasibility, i.e. max_iter_opt =max_iter_feas=50. The results are shown in Tables 7.1 and 7.2 for the cows and swines data instances respectively. These results are compared to those of Strategy C1 at $S_{\text{o}}^{\text{infeas}}$=-200 for the cows data instance (Figure 4.3(b)), and $S_{\text{o}}^{\text{infeas}}$=-205 for the swines data instance (Figure 4.4(b)), where max_iter_opt=50 and max_iter_feas=25. For both data instances, the incumbent solutions are better with max_iter_opt=50 and max_iter_feas=25 than with max_iter_opt=max_iter_feas=50. The experiments were repeated with: (i) max_iter_opt=75 and max_iter_feas=50, and (ii) max_iter_opt=max_iter_feas=75. For the cows data instance the best parameters for Strategy C2 were found to be max_iter_opt=75 and max_iter_feas=50 (Figure 4.5(a)). The cost of grid electricity of the incumbent solution for max_iter_opt=75 and max_iter_feas=50 was -20,545, whereas that with max_iter_opt=50 and max_iter_feas =25 was -19,504, for the cows data instance (Table 7.1). The best parameters for Strategy C2 with the swines data instance were found to be max_iter_opt=50 and max_iter_feas=25 (Figure 4.7(b)). The cost of grid electricity of the incumbent solution with max_iter_opt=50 and max_iter_feas=25 for the swines data instance was -5425, whereas that with max_iter_opt=75 and max_iter_feas=50 was -4123 (Table 7.2). These comparisons show that varying the number of iterations for which the minimisation of cost and the minimisation of infeasibility are carried out, impacts the incumbent solution.



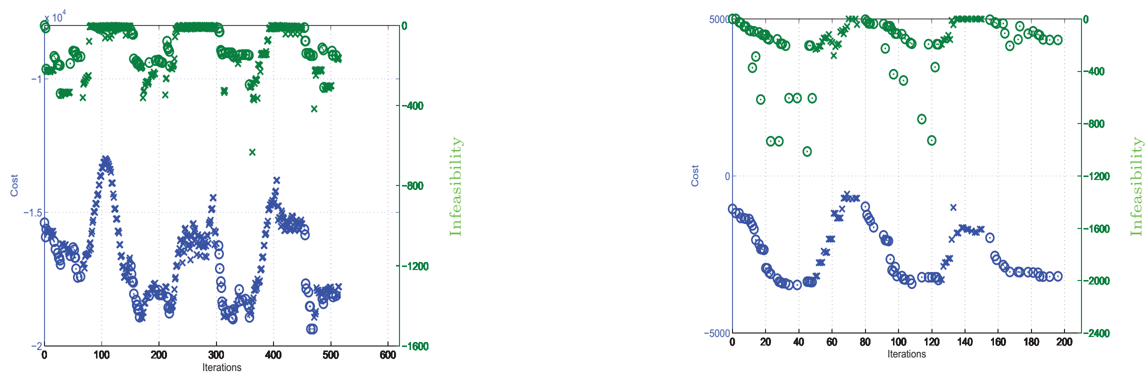
(a) Cows:max_iter_opt=75,max_iter_feas=50



(b) Swines:max_iter_opt=50,max_iter_feas=50

Figure 4.5: Strategy C2: Varying Number of Iterations for Minimisation of Cost and Minimisation of Infeasibility

The handling of feasible solutions that arise during the phase of minimisation of infeasibility is investigated in Strategy C3. In this strategy, both feasible and infeasible solutions (within the threshold of infeasibility) are allowed during the phase of minimisation of infeasibility. This is compared to what is done in Strategy C2. Although Strategy C2 investigated the number of iterations for minimisation of cost and minimisation of infeasibility, it uses a different method from Strategy C3 for handling feasible solutions that arise during minimisation of infeasibility. A comparison can therefore be made between Strategy C3 and C2. In Strategy C2 only feasible solutions are allowed during the phase of minimisation of infeasibility as a first priority. If there are no feasible solutions, then infeasible solutions within the threshold of infeasibility are allowed. The results of the experiment for Strategy C3 are compared with those of Strategy C2 (Tables 7.1 and 7.2). From Table 7.1, of the cows data instance, the cost of grid electricity of the incumbent solution for Strategy C3 is -18,308, whereas that of Strategy C2 with max_iter_opt=75 and max_iter_feas=50 is -20,545. For the swines data instance, the cost of grid electricity of the incumbent solution for Strategy C3 is -4870, whereas that of Strategy C2 with max_iter_opt=50 and max_iter_feas=25 is -5425 (Table 7.2). It can be deduced that the strategy of allowing only feasible solutions as a first priority, during the minimisation of infeasibility (Strategy C3) is better than allowing both feasible and infeasible solutions during minimisation of infeasibility.



(a) Cows (b) Swines

Figure 4.6: Strategy C3: Allowing All Solutions Within Threshold During Minimisation of Infeasibility

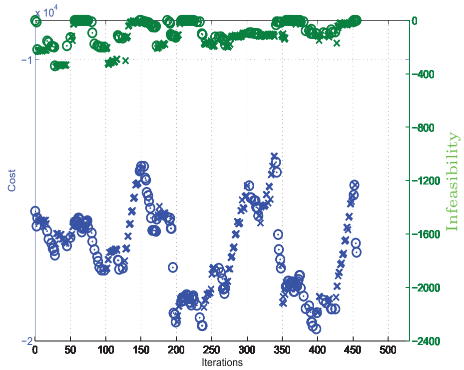
Diversification Strategy

Two strategies were applied to test diversification. In the experiments of Figures 4.3 and 4.4, diversification Strategy D1 was applied. In Strategy D1, diversification was applied if the incumbent solution did not improve for 100 iterations. The diversification was also subject to the current solution not improving for 5 consecutive iterations. Diversification was applied by making 5 consecutive random moves. The results for Strategy D1 (Figures 4.3 and 4.4 and Tables 7.1 and 7.2), show that this type of diversification does not result in an improvement in the incumbent solution, except in one case (Figure 4.4(c)). Experiments were performed with Strategy D2, where three consecutive restarts with the incumbent solution were performed, if the solution did not improve for 100 iterations, for the cows data instance and for 50 iterations, for the swines data instance. A different number of iterations for application of diversification was used for the cows and swines because the the data instances had different ranges. This meant the Tabu Search progressed at different rates for the two data instances. Strategy D2 is described by Pseudocode 1. Figure 4.7 shows that

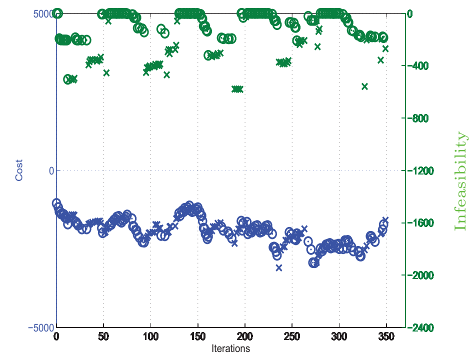
Pseudocode 1: Strategy D2

```
while iter ≤ max_iter do
   while iter ≤ max_iter_div do
      Perform Tabu Search
      Evaluate iterative solution S^current'
   end while
   iter_div_current ← 0
   while (iter_div_count ≤ n^nonimprov_div) and (S^current' < S^current) do
      Perform Tabu Search
      Evaluate iterative solution S^current'
   end while
   iter_restart ← 0
   while (iter_restart ≤ n^restart_div) and (S^incumbent ≤ S^current') do
      Replace current solution with incumbent solution S^current' ← S^incumbent
      Clear Tabu list T^list ← ∅
      Perform Tabu Search
      Evaluate iterative solution S^current'
   end while
end while
```

use of Strategy D2 for diversification results in an improvement in the incumbent solution. For the cows data instance, the cost of grid electricity of the incumbent solution is -16,884 with Strategy D1 and -19,504 with Strategy D2 (Table 7.1). For the swines data instance, the cost of grid electricity of the incumbent solution is -4630 with Strategy D1 and -5222 with Strategy D2 (Table 7.2).



(a) Cows:max_iter_opt=50,max_iter_feas=25

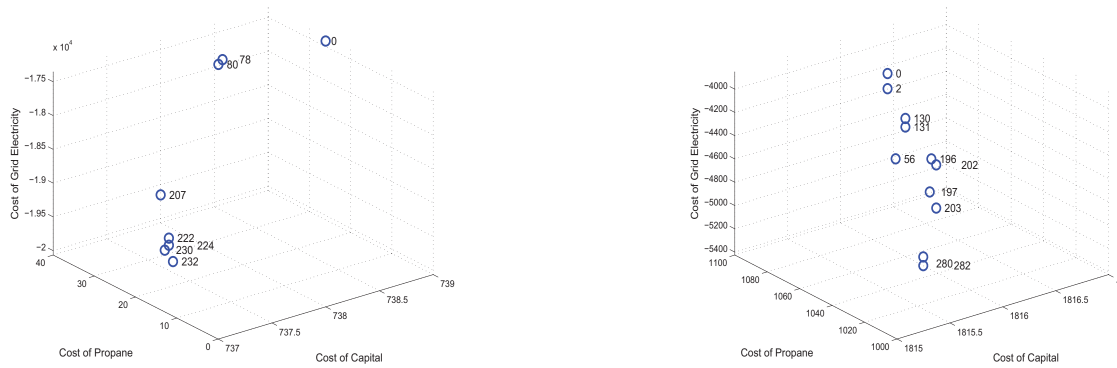


(b) Swines:max_iter_opt=50,max_iter_feas=25

Figure 4.7: Strategy D2+C2: Diversification by Restarting with the Incumbent Solution and Varying Number of Iterations for Minimisation of Cost and Minimisation of Infeasibility

Multi-objective Optimisation Strategy

The experiments in this section are to investigate Strategy MOBJ1, developed to evaluate the multi-objective function, on a Pareto incumbent front, while taking into consideration its multi-period nature. Strategy MOBJ1 is compared to Strategy MOBJ2. In Strategy MOBJ2, the sum of the cost components of the objective function is calculated and the solution with the least sum is selected as the current solution. In Strategy MOBJ1 the multi-period cost components of the objective function are evaluated for non-dominance and form a Pareto incumbent front. Figure 4.8 shows the improvement in the incumbent solution using Strategy MOBJ1. From Table 7.1 of the cows data instance, the cost of grid electricity of the incumbent solution for Strategy MOBJ1 is -20,545, whereas there is no improvement in the incumbent solution with Strategy MOBJ2. Table 7.2 for the swines data instance shows a cost of grid electricity of -5425 for the incumbent solution, with Strategy MOBJ1, and -5255 with Strategy MOBJ2. As such, Strategy MOBJ1 where a Pareto incumbent front is used to evaluate the objective function is better than Strategy MOBJ2 which sums the cost components of the objective function.



(a) Cows (b) Swines

Figure 4.8: Strategy MOBJ1: Multi-objective Optimisation using Pareto Incumbent Front

Multi-period Optimisation Strategy

The aim of the experiments in this section is to investigate the strategies for handling the multi-period nature of the optimisation problem, in a manner that will ensure continuity from one period to the next. The Tabu Search has two phases: (i) minimisation of cost and (ii) minimisation of infeasibility. Different strategies for handling multi-periodicity are applied to the different phases. Each of these strategies is discussed next under the appropriate phase of the Tabu Search.

Round Robin in Phase 1 of Minimisation of Cost

In Strategy MP1 round robin of the months is carried out while updating the current solution, whether it is improving or not as described in Pseudocode 2. The results of the experiments using Strategy MP1 are shown in Tables 7.1 and 7.2, for the cows and swines data instances respectively.

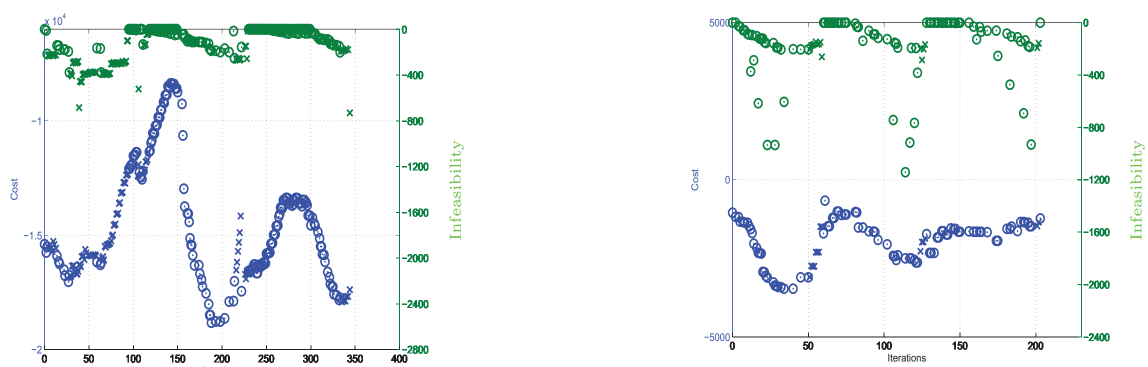
In Strategy MP2, round robin of the months is carried out while updating the current solution with an improved solution only (Pseudocode 3). The results of experiments using Strategy MP2 are shown in Figure 4.9 for both the cows and

Pseudocode 2: Strategy MP1

for iter = 1:12 **do**
  Select a variable u_i^m for optimisation
  Perform Tabu Search
  Evaluate iterative solution $S^{\text{current}'}$
  Update the current solution $S^{\text{current}} \leftarrow S^{\text{current}'}$
  Select the next month for which to carry out the optimisation $m \leftarrow m + 1$
  Select the index of the next variable to be optimised $i \leftarrow i + 1 (\text{mod } 3)$
end for

swines data instances.

The third multi-period strategy investigated is MP3, where round robin of the months is carried out and more than one variable is sampled in a given month, in order to obtain an improving solution. Strategy MP3 is described by Pseudocode 4. For the cows data instance, Strategy MP3 was investigated together with the Strategy C2 with max_iter_opt=75 and max_iter_feas=50. Similarly, for the swines data instance, Strategy MP3 was investigated together with the Strategy C2 with max_iter_opt=50 and max_iter_feas=25.



(a) Cows (b) Swines

Figure 4.9: Strategy MP2: Round Robin & Updating Current Solution with an Improving Solution Only

Pseudocode 3: Strategy MP2

```
for iter = 1:12 do
    iter_m ← 0
    Select a variable u_i^m for optimisation
    Perform Tabu Search
    Evaluate iterative solution S^{current'}
    while S^{current'} > S^{current} and iter_m ≤ 12 do
        Select the next month for which to carry out the optimisation m ← m + 1
        Select the index of the next variable to be optimised i ← i + 1(mod 3)
        Select a variable u_i^m for optimisation
        Perform Tabu Search
        Evaluate iterative solution S^{current'}
        iter_m ← iter_m + 1
    end while
    Update the current solution S^{current} ← S^{current'}
    Select the next month for which to carry out the optimisation m ← m + 1
    Select the index of the next variable to be optimised i ← i + 1(mod 3)
end for
```

Strategies MP1 and MP2 are compared to Strategy MP3. Table 7.1 shows that Strategy MP3 gives the best cost of grid electricity of -20,545 for the incumbent solution, for the cows data instance. Strategies MP1 and MP2 give costs of grid electricity of -17,169 and -17,534, respectively, for the same data instance. For the swines data instance (Table 7.2), the cost of grid electricity of the incumbent solution is -5425 with Strategy MP3. With Strategy MP2, the cost of grid electricity of the incumbent solution is -5160. Of the three strategies, Strategy MP1 gives the worst value of the cost of grid electricity of the incumbent solution, i.e., -4064. Strategy MP1 is not good because the search constantly updates the current solution with a poorer solution. The best strategy with regard to round robin, during the phase of minimisation of cost is MP3, where the current solution is updated with improving solutions only. This is done while trying out all the variables in turn in the same month, until the current solution improves or until after 12 iterations. A non improving solution is allowed only after the current solution has not been updated for 12 iterations. This strategy ensures that there is an attempt to find an improving solution in every month, and tries to build continuity from one month to the next during the optimisation.

Round Robin in Phase 2 of Minimisation of Infeasibility

Round robin is also investigated in Phase 2 where infeasibility is being minimised (Strategy MP4). The results are compared with those of Strategy MP3 (Tables 7.1 and 7.2). Strategy MP3 also investigated the selection of the month for which to carry out the optimisation, during the phase for minimisation of infeasibility. In Strategy MP3 optimisation of the variables is done for the month with the least infeasible solution. The incumbent solution with Strategy MP3, is better than with Strategy MP4 for both data instances. -20,545 is obtained as the cost of grid electricity with Strategy MP3 and -16,691 with Strategy MP4, for the cows data instance. For the swines data instance, -5425 is obtained as the cost of grid electricity of the incumbent solution, with Strategy MP3 and -5263 with Strategy MP4. During the minimisation of infeasibility, selection of the month with the most infeasible solution for optimisation (Strategy MP3) is therefore better than round robin of the months (Strategy MP4).

This chapter has explained the statement and formulation of the optimisation problem, and the Tabu Search algorithm developed. The experiments carried out to investigate the Tabu Search optimisation strategies have been described and the results analysed. It was found out that initial thresholds of infeasibility should be set and these should be varied during the optimisation. The multi-objective, multi-period function should be evaluated on a Pareto incumbent front. Different strategies should

Pseudocode 4: Strategy MP3

for iter = 1:12 **do**
  iter_m $\leftarrow 0$
  Select a variable u_i^m for optimisation
  Perform Tabu Search
  Evaluate iterative solution $S^{\text{current}'}$
  while $S^{\text{current}'} > S^{\text{current}}$ and iter_m ≤ 12 **do**
    while $i \leq 3$ and $S^{\text{current}'} > S^{\text{current}}$ **do**
      Select a variable u_i^m for optimisation
      Perform Tabu Search
      Evaluate iterative solution $S^{\text{current}'}$
      Select the index of the next variable to be optimised $i \leftarrow i + 1 (\text{mod } 3)$
    end while
    Select the next month for which to carry out the optimisation $m \leftarrow m + 1$
    Select the index of the next variable to be optimised $i \leftarrow i + 1 (\text{mod } 3)$
    Select a variable u_i^m for optimisation
    Perform Tabu Search
    Evaluate iterative solution $S^{\text{current}'}$
    iter_m $\leftarrow$ iter_m + 1
  end while
  Update the current solution $S^{\text{current}} \leftarrow S^{\text{current}'}$
  Select the next month for which to carry out the optimisation $m \leftarrow m + 1$
  Select the index of the next variable to be optimised $i \leftarrow i + 1 (\text{mod } 3)$
end for

be used for minimisation of cost and minimisation of infeasibility, and diversification should be done by performing random restarts with the incumbent solution. The subsequent Chapters, 5 and 6 describe the use of the Tabu Search algorithm developed to solve the objectives of the research, as set out in Chapter 1, i.e., (i) determination of the maximum revenue that can be obtained for a given herd size from a BWECS and (ii) specification of the threshold herd size at which a BWECS becomes commercially viable.

Chapter 5

Maximum Revenue from a BWECS for a given Herd Size

As described in Chapter 1, the first objective of the research carried out was to determine the maximum revenue that can be obtained for a given herd size from a BWECS. This objective is attained by optimisation of the BWECS, using the Tabu Search algorithm developed in Chapter 4. In order to maximise revenue, the objective function of the Tabu Search algorithm is expressed as a cost minimisation function. This chapter describes how this objective was attained.

5.1 Formulation of the Optimisation Problem for Determination of Maximum Revenue from a BWECS

This section describes the inputs, variables and parameters of the optimisation, followed by a description of the objective function.

5.1.1 Inputs of the BWECS for Determination of Maximum Revenue

The following is an explanation of how the inputs to the BWECS were determined. The inputs of the BWECS are: herd size, n_{herd}, electricity demand, d_{e}^{m}, heating demand, d_{h}^{m}, and volume flow rate of manure from the livestock, v_{in}^{m}, for $m \in M$.

A herd size, n_{herd}, was selected from a typical dairy farm in New York state [60]. The volume flow rate of manure from the livestock, v_{in}, was calculated from the volume flow rate of manure produced per animal [139]. The electricity demand d_{e}^{m}, was also obtained from the typical dairy farm in New York state [60].

The heating demand d_{h}^{m} includes the heating demand of the farm and the digester.

A monthly heating demand profile of the farm is generated based on the herd size. Heating demand on dairy farms comprises of space heating needs of the milking parlour, hot water for cleaning, and the digester's heating requirements. The space heating needs of the milking parlour were estimated using the software HOT2000 from Natural Resources Canada. The software takes into consideration the monthly variation in temperature. Weather data obtained from the software, for Binghamton weather station, in New York state, is used for space heating needs estimation. This is the closest weather station to the typical dairy farm whose characteristics were used as inputs to the BWECS. Hot water needs were estimated from studies carried out on milking parlour heating needs of dairy farms [140, 141]. The digester's heating requirement is modeled based on the heat losses from the walls, roof and floor of the digester, and the heat required to raise the temperature of influent manure to the operating temperature of the digester:

$$Q = Q_{\text{floor}} + Q_{\text{influent}} + Q_{\text{walls\_roof}} \qquad \text{W}, \tag{5.1}$$

where Q is the digester heating requirement, Q_{floor} are heat losses through the digester floor, Q_{influent} is the heat required to raise the temperature of the influent manure to the digester's operational temperature and $Q_{\text{walls\_roof}}$ are heat losses through the digester's walls and roof. An electrical circuit analogy is used to model the heat losses:

$$\begin{aligned} Q = (T_{\text{manure}} - T_{\text{air}})/(R_{\text{walls}}//R_{\text{roof}}) + \ &(T_{\text{manure}} - T_{\text{influent}})/R_{\text{influent}} \\ &+ (T_{\text{manure}} - T_{\text{soil}})/R_{\text{floor}} \qquad \text{W}, \end{aligned} \tag{5.2}$$

where T_{manure} is the temperature of manure in the digester, T_{air} is ambient air temperature, R_{walls} is thermal resistance to heat flow through the digester walls, R_{floor} is thermal resistance to heat flow through the digester floor, T_{influent} is the temperature of influent manure, R_{influent} is thermal resistance to heat flow to influent manure, T_{soil} is the soil temperature, and R_{roof} is thermal resistance to heat flow through the digester roof. The thermal resistances are calculated as follows:

$$R_{\text{floor}} = (1/h_{\text{manure\_concrete}} + t_{\text{concrete}}/k_{\text{concrete}} + t_{\text{therm\_bulb\_region}}/k_{\text{soil}})/A_{\text{floor}} \quad \text{K/W}, \quad (5.3)$$

$$R_{\text{influent}} = 1/(m_{\text{influent}}\, cp_{\text{influent}}) \quad \text{K/W}, \quad (5.4)$$

$$\begin{aligned} R_{\text{walls}} = {} & (1/h_{\text{manure\_concrete}} + t_{\text{concrete}}/k_{\text{concrete}} + t_{\text{insulation}}/k_{\text{insulation}} + \\ & (\sigma\epsilon_{\text{insulation}}(T^2_{\text{insulation}} + T^2_{\text{air}})(T_{\text{insulation}} + T_{\text{air}}) + h_{\text{insulation\_air}}))/A_{\text{walls}} \quad \text{K/W}, \quad (5.5) \end{aligned}$$

$$\begin{aligned} R_{\text{roof}} = {} & (1/(h_{\text{manure\_biogas}} + \sigma(T^2_{\text{manure}} + T^2_{\text{biogas}})(T_{\text{manure}} + T_{\text{biogas}})/ \\ & (1/\epsilon_{\text{manure}} + 1/\epsilon_{\text{biogas}} - 1)) + 1/h_{\text{biogas\_concrete}} + t_{\text{concrete}}/k_{\text{concrete}} + t_{\text{insulation}}/k_{\text{insulation}} \\ & +(\sigma\epsilon_{\text{insulation}}(T^2_{\text{insulation}} + T^2_{\text{air}})(T_{\text{insulation}} + T_{\text{air}}) + h_{\text{insulation\_air}}))/A_{\text{roof}} \quad \text{K/W}, \quad (5.6) \end{aligned}$$

where $h_{\text{manure\_concrete}}$ is the film coefficient of sludge to wall inside the digester, t_{concrete} is the concrete wall thickness, k_{concrete} is the concrete thermal conductivity, $t_{\text{therm\_bulb\_region}}$ is the thickness of the thermal bulb region in the soil, k_{soil} is the soil thermal conductivity, A_{floor} is the digester floor surface area, m_{influent} is the mass flow rate of influent manure, cp_{influent} is the influent manure's specific heat, $t_{\text{insulation}}$ is the insulation thickness, $t_{\text{insulation}}$ is the insulation's thermal conductivity, σ is the Stefan-Boltzmann constant, $\epsilon_{\text{insulation}}$ is the insulation emissivity, $T_{\text{insulation}}$ is the insulation temperature, T_{air} is the air temperature, $h_{\text{insulation\_air}}$ is the film coefficient of air outside the digester, A_{walls} is the digester walls' surface area, $h_{\text{manure\_biogas}}$ is the coefficient of convective heat transfer from manure to biogas, T_{manure} is the manure temperature, T_{biogas} is the biogas temperature, ϵ_{manure} is the manure emissivity, ϵ_{biogas} is the biogas emissivity, $h_{\text{biogas\_concrete}}$ is the film coefficient of biogas inside the digester and A_{roof} is the digester roof's surface area.

5.1.2 Optimisation Variables for Determination of Maximum Revenue from a BWECS

The BWECS being optimised is shown in Figure 4.1. Four variables were selected for use in the optimisation (Table 5.1). These variables are in line with those used to define the outline of the optimisation problem (6.3), (6.4), (6.5) in Section 4.2.1. An additional variable, u_4^m, is included, which defines the induction machine rating.

Table 5.1: Variables of the Optimisation

Variable	**Range**
u_1^m backup propane mass flow rate	0 - 0.0036kg/s
u_2^m biogas sharing ratio	0 - 0.99
u_3^m volume flow rate of manure from the lagoon	0 - 59m^3/day
u_4^m induction machine rating	10, 20, 50, 150, 200, 250hp

The maximum value of backup propane mass flow rate, (u_1^m), was obtained from the propane flow rate that meets the maximum heat demand when the boiler is combusting propane only, and when there is maximum volume flow rate of manure from the lagoon. This is because heating is required to raise the temperature of influent manure to the operating temperature of the digester.

The biogas sharing ratio, (u_2^m), is the ratio of biogas sent to the boiler. In selection of the maximum value of the biogas sharing ratio, it is ensured that biogas is sent to the engine for electricity generation at all times.

The maximum value of the volume flow rate of manure from the lagoon, (u_3^m), is determined using:

$$u_3^{\max} = v_{\text{in}}^m (n_{\text{days\_max}} + n_{\text{lagoon\_storage}})/n_{\text{days\_max}} \quad \text{for } m \in M \qquad \text{m}^3/\text{day}, \tag{5.7}$$

where $u_3^{\max}$ is the maximum volume flow rate of manure from the lagoon, v_{in}^m is the volume flow rate of manure from the cows, $n_{\text{days\_max}}$ is the maximum number of days in a month and $n_{\text{lagoon\_storage}}$ is the storage capacity of the lagoon. The ratings of the induction generator, (u_4^m), are based on engine-generator sets currently operational on dairy farms.

5.1.3 Parameters of the Optimisation for Determination of Maximum Revenue from a BWECS

The parameters of the optimisation for the determination of maximum revenue from a BWECS, for a given herd size are given in Table 6.1. These are used in addition to the Tabu Search parameters given in Table 4.3.

Table 5.2: Parameters of the Optimisation

Parameter	**Description**	**Value**
$C_{\text{cap\_in}}$	capacity incentive	1000 USD/kW [137]
$\max(C_{\text{cap\_in}})$	maximum capacity incentive	850,000 USD or 50% of engine cost [137]
x_{inc}	performance incentive	0.07 USD/kWh [137]
x_{anc}	factor for ancillary works	1.15
p	number of payments of capital cost	240
r	interest rate	12%

5.1.4 Objective Function for Determination of Maximum Revenue from a BWECS

The objective of the optimisation is to maximise revenue from a BWECS for a given herd size. In order to maximise revenue, costs are minimised, thus the objective function is expressed as a cost minimisation function, already given in Section 4.3.1, and repeated below:

$$z = \sum_{m=1}^{M} (C^m_{\text{capital}} + C^m_{\text{propane}} - C^m_{\text{incentives}} + C^m_{\text{grid\_electricity}}) \quad \text{for } m \in M \quad \text{USD,} \qquad (5.8)$$

where z is the minimal cost, C^m_{capital} is the capital cost amortized monthly, C^m_{propane} is the monthly cost of backup propane, $C^m_{\text{incentives}}$ is the value of incentives given monthly for generation of renewable energy and $C^m_{\text{grid\_electricity}}$ is the monthly cost of electricity obtained or sold to the grid. Section 4.3.1 described the cost components of the objective function, this section explains how these cost components are calculated.

The capital cost, C^m_{capital}, is obtained from the monthly amortization of the capital expenditure on the BWECS. The capital expenditure includes building of a digester and lagoon, and purchase of a boiler and engine-generator set. Estimation of the cost of building a digester and purchase and installation of an engine-generator set is based on a literature review [3, 123, 127, 142] and is given in Tables 5.3 and 5.4, respectively. Estimation of the cost of the boiler is based on a literature review [143] and is given in Table 5.5. The total capital expenditure on the BWECS is calculated by:

$$C_{\text{cost}} = (d_{\text{cost}} + g_{\text{cost}} + lg_{\text{cost}} + b_{\text{cost}} - C_{\text{cap\_in}}) x_{\text{anc}} \qquad \text{USD,} \qquad (5.9)$$

where C_{cost} is the total capital expenditure, d_{cost} is the digester cost, g_{cost} is the engine-generator set cost, lg_{cost} is the lagoon cost, b_{cost} is the boiler cost, $C_{\text{cap\_in}}$ is the capacity incentive and x_{anc} is an ancillary works factor. The total capital expenditure

Table 5.3: Cost Estimates for Plug Flow Digesters

Digester Size Range (m^3)	**Cost (USD)**
900 - 1200	95,000
1200 - 1500	125,000
1500 - 1800	200,000
1800 - 2100	290,000

Sources: The Minnesota Project 2002, Eastern Research Group, Inc. 2004 & 2005, Resource Strategies, Inc. 2004.

Table 5.4: Engine-generator Set Cost Estimates

Engine-generator Set Rating (hp)	**Cost (USD)**
10	30,000
20	40,000
50	80,000
150	250,000
200	300,000
250	330,000

Sources: The Minnesota Project 2002, Eastern Research Group, Inc. 2004 & 2005, Resource Strategies, Inc. 2004.

Table 5.5: Boiler Cost Estimates

Boiler Rating Range (kW)	**Cost (USD)**
53.62 - 97.57	3325
97.57 - 118.08	3405
118.08 - 150.60	4855
150.60 - 182.83	5310
182.83 - 212.13	5815

Source: Pumps and Pressure, 2011.

is amortized monthly by:

$$C^m_{\text{capital}} = rC_{\text{cost}}/(1 - (1/(1 + r))^p) \quad \text{for } m \in M \qquad \text{USD,} \tag{5.10}$$

where C_{capital} is the capital cost amortized monthly, r is the annual interest rate, C_{cost} is the capital expenditure and p is the number of payments.

Another cost component of the objective function is the monthly cost of propane, C^m_{propane}, obtained from the unit cost of propane [144], and the monthly consumption of propane.

The cost of incentives, $C^m_{\text{incentives}}$, in the objective function is calculated by:

$$C^m_{\text{incentives}} = \sum_{h=1}^{n_{\text{hours}}} x_{\text{inc}}\, y_1 h \quad \text{for } m \in M \qquad\qquad \text{USD}, \tag{5.11}$$

where $C_{\text{incentives}}$ is the monthly cost of incentives, h is hours, n_{hours} is the number of hours for which the system generates electricity, x_{inc} is the performance incentive and y_1 is the power output.

The cost of electricity from the grid is calculated using the electricity tariff [145], and the electrical energy obtained from the grid. The farm may sell electricity generated from biogas, to the utility company, or may have a net metering contract. In the net metering contract, the value of electrical energy sent to the grid is subtracted from the user's monthly electricity bill.

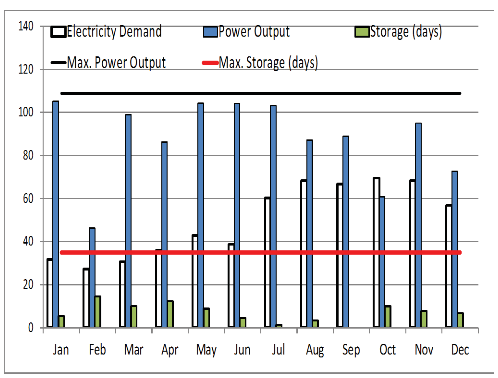
The Tabu Search algorithm used in the optimisation has been described in Chapter 4, therefore the results of the optimisation carried out to determine the maximum revenue from a given herd size, are discussed in the following section.

5.2 Results of the Optimisation

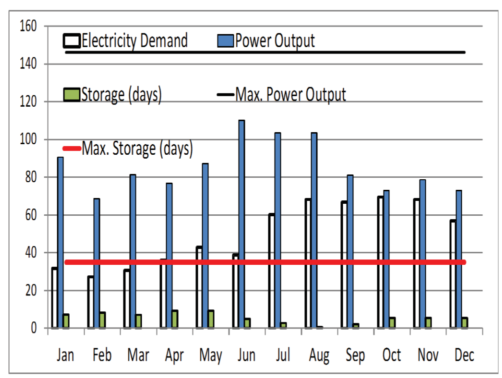
The maximum revenue from a BWECS was determined for a herd size of 500 cows. This section presents and analyses the results of the Tabu Search optimisation carried out. The BWECS from A.A. dairy farm [60], with a herd size of 500 cows, was selected for comparison with the Tabu Search algorithm results. A.A. Dairy farm has a 130kW engine-generator set and a 1133m^3 plug flow digester that processes 85,000 gallons of manure daily [60].

5.2.1 Electrical Energy Generation

The tariff structure [145] in the Tabu Search is such that the considered cost of energy is higher in the months of January, February, June, July, August, and December for an 8 hour on-peak period. The results of the Tabu Search optimisation show high generation of power in these months for the 150hp, 200hp and 250hp engine-generator sets (Figures 5.1(a), 5.1(b) and 5.2(a) respectively), with some exceptions. It is beneficial to the farmer to generate as much electricity as possible during these months, for sale to the utility company.



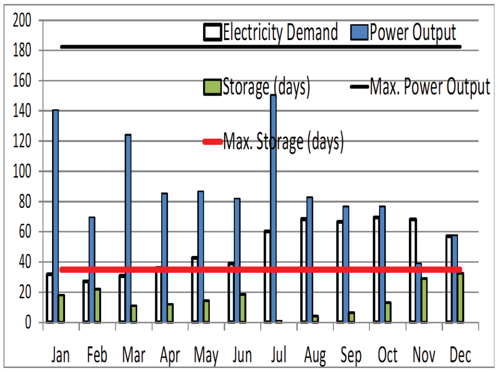
(a) 150hp



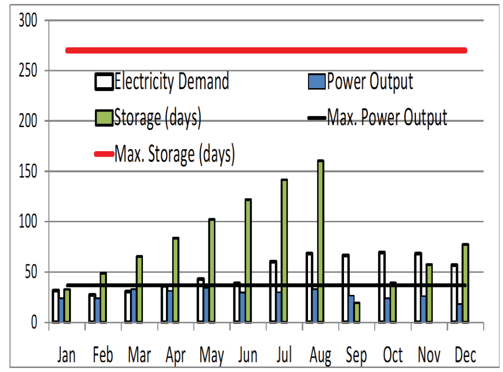
(b) 200hp

Figure 5.1: Power Output Profile of Engine-Generator Set

For the 150hp engine-generator set, there are discrepancies in the months of February and December. The month of February has a low power output because the lagoon is building up manure storage for power production during the high demand months



(a) 250hp



(b) 50hp

Figure 5.2: Power Output Profile of Engine-Generator Set

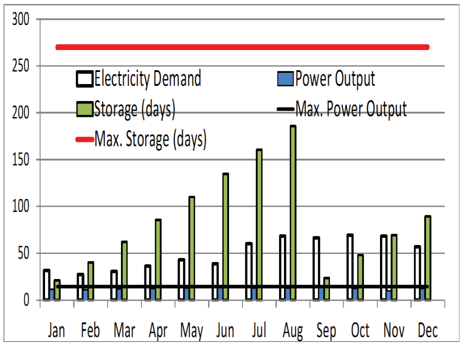
of March, April and May. The Tabu Search algorithm maximises revenue and thus avoids solutions that would lead to electricity production that does not meet the demand, hence the build up of manure storage. Manure storage is also being built up for use in the months of June, July and August when tariffs are high. The month of December has a low power output because manure is being stored in the lagoon for use in January. Since the electricity tariff for December and January is the same, the result is acceptable because the manure is used to generate electricity in January, when it is sold to the utility company at a high tariff.

The 200hp engine-generator system has high electricity generation in January, June, July and August in line with the high electricity tariffs for these months. The months of February and December have lower than expected electricity production for this engine-generator set. This is because manure is being built up in the lagoon to generate electricity in January, June, July and August.

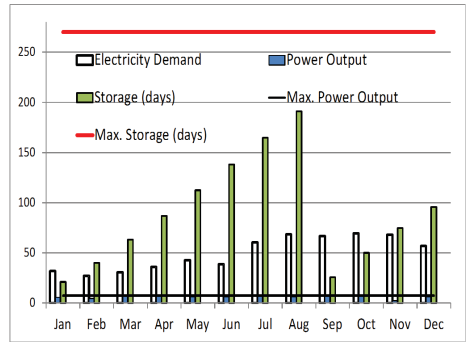
The electricity generation profile for the 250hp engine-generator set is shown in Figure 5.2(a). Of all the engine-generator set systems, the 250hp system gives the highest revenues from the renewable energy incentives and sale of electricity as shown in Table 5.6. The 200hp system gives a revenue of USD 68,654 and the 250hp system gives a revenue of USD 72,978, whereas the 150hp engine-generator set system gives a revenue of USD 70,457. The high revenue of the 250hp engine-generator system is offset by its high capital cost. The highest net revenue is obtained from the 150hp engine-generator system. Electricity generation is not maximised for the 200hp and 250hp engine-generator systems. This is due to an insufficient supply of biogas. Figure 5.1(b) for the 200hp system shows that the lagoon almost empties in August, and has very little manure left in July and September, yet maximum electricity generation is not achieved for any of the months. This applies to the 250hp system as well. Figure 5.2(a) for the 250hp system shows that the lagoon empties in July, yet maximum electricity generation is not achieved for any of the months. Thus the system with the 150hp engine generator set is the most suitable for a farm with a herd size of 500 dairy cows.

The electricity generation profiles of the 50hp and 20hp engine-generator sets are as expected (Figure 5.2(b) and 5.3(a) respectively). There is almost maximum electricity generation for all the months. These are engine-generator sets of low power rating and therefore electricity production is maximised in order to meet the farm's needs. It is assumed that production begins in September in the first year of use. The lagoon storage size is set to 90 days, hence the build up of manure stored from September of one year to August of the next year. The lagoon will always have a large amount of manure left over at the end of the period, which is taken as September in this case.

The 10hp engine-generator set's electricity generation profile (Figure 5.3(b)) also shows maximisation of power generation throughout the year except for the month of November. This discrepancy is attributed to the parameters used in the Tabu



(a) 20hp



(b) 10hp

Figure 5.3: Power Output Profile of Engine-Generator Set

Search optimisation. These are the same parameters as those used for the 20hp engine-generator set system, which has double the power rating. The parameters of the Tabu Search optimisation require further tuning for the 10hp engine-generator set system.

5.2.2 Heat Generation

The heat production profile vs. heat demand profile for the 150hp engine-generator set system is shown in Figure 5.4. The profile shows that heating demand is met at all times. This applies to all the engine-generator systems.

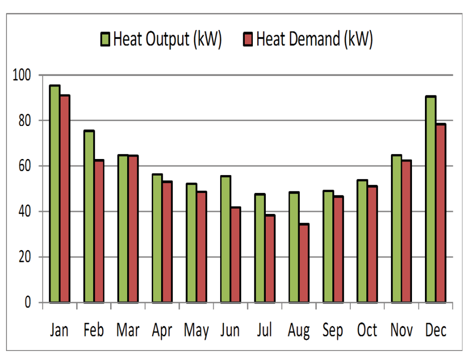


Figure 5.4: Heat Output Profile and Cost of Propane for 150hp Engine-Generator Set

5.2.3 Evaluation of Maximum Revenue

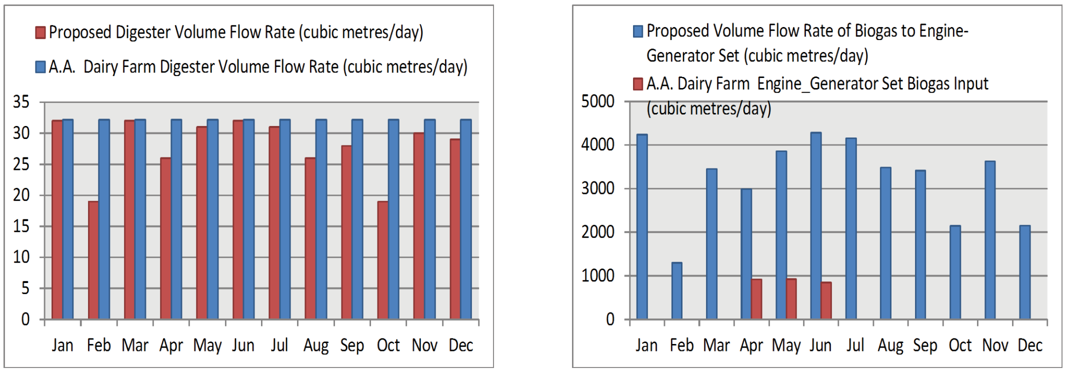
The maximum revenue that can be obtained from a BWECS on a sample farm, A.A. Dairy, with a herd size of 500 dairy cows is calculated. Table 5.6 summarises the revenue from the BWECS with the different engine-generator set ratings.

Table 5.6: Summary of Costs for Different Engine-Generator Set Ratings

Engine-Gen. Set Rating (hp)	**Cost of Capital (USD)**	**Cost of Propane (USD)**	**Value of Incentives (USD)**	**Cost of Grid Electricity (USD)**	**Total Revenue (USD)**
10	21,436	0	-3,668	19,301	37,069
20	21,821	2	-7,529	16,537	30,831
50	24,499	7	-17,086	9,847	17,267
150	36,526	49	-53,967	-16,490	-33,882
200	38,455	0	-52,570	-16,084	-30,199
250	40,613	62	-54,999	-17,979	-32,303

The 50hp, 20hp and 10hp engine-generator sets not only do not meet the electricity demand of the farm, but are unable to use all the manure generated. This results in the need to buy electricity from the utility company. For example, it is estimated that the farm will spend USD 9847 per annum on electricity (Table 5.6), with the 50hp engine-generator set BWECS. The farm will however earn USD 17,086 from renewable energy generation incentives. The capital costs of the system have to be factored in (Table 5.6), resulting in a net negative revenue of USD 17,267 per annum. This analysis applies to the 20hp and 10hp engine-generator systems. Systems with engine-generator sets of 50hp, 20hp and 10hp ratings are therefore not economically viable for a farm of herd size 500 cows.

From Table 5.6 the solution with the 150hp engine-generator set gives the maximum revenue for a herd size of 500. The sizing of the components of the 150hp engine-generator set system is a digester of capacity 1350m^3, a lagoon of 40 days storage capacity and a boiler rated at 133kW. The proposed digester volume flow rate and biogas volume flow rate to the engine-generator set are shown in Figures 5.5(a) and 5.5(b) respectively.



(a) Manure from Lagoon

(b) Biogas to Eng. Genset

Figure 5.5: Volume Flow Rate

The sample farm A.A. Dairy, approximated its digester volume flow rate at 85,000 gallons per day [60], which translates to 32m^3/day for 500 cows, in contrast to the value used of 28m^3/day for 500 cows [139]. This explains the higher digester volume flow rate for the A.A. Dairy farm (Figure 5.5(a)).

The cost of propane from the proposed system is shown in Table 5.6. The minimal cost of propane is explained by the fact that heat is supplied from combusting biogas in the boiler and from exhaust heat captured by the heat exchanger. The Tabu Search optimisation therefore minimises the cost of propane.

Data for the volume flow rate of biogas to the engine-generator set on the A.A. Dairy farm was only available for three months of the year hence the missing data in Figure 5.5(b). The data available shows that a lower volume of biogas is sent to the engine-generator set, despite the farm's engine generator set having a higher rating than the proposed engine-generator set. This is also reflected in the lower electricity production in April, May and June (Figure 5.6), on the A.A. Dairy farm.

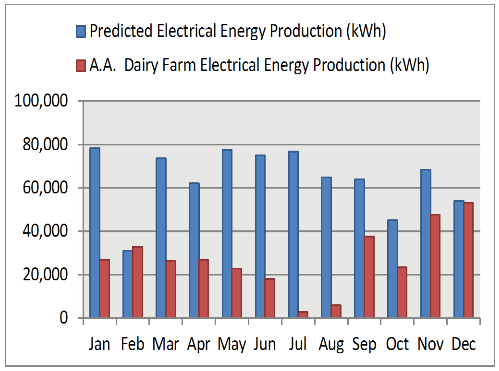
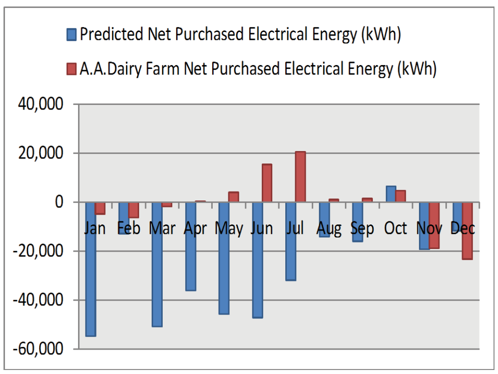
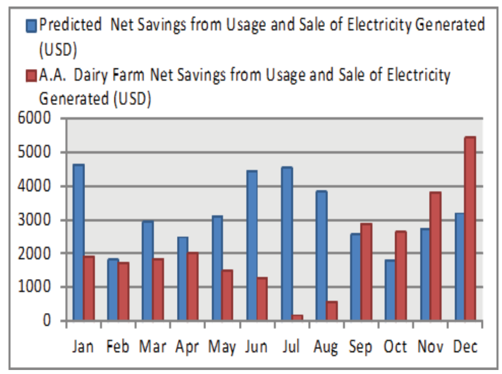


Figure 5.6: Electrical Energy Production



(a) Net Purchase



(b) Net Savings

Figure 5.7: Electrical Energy

The installed energy generation capacity of the A.A. Dairy farm is 175hp. It is more than what is required to generate maximum revenue from a system with a herd size of 500. This capacity is not being fully utilised. This is reflected in the net savings shown in Figure 5.7(b). The sample farm saves USD 25,815 per annum and the Tabu Search optimisation predicts a maximum revenue of USD 38,133 per annum from the sale of electricity and avoidance of usage of grid electricity. The sample farm is saving much less money than what is predicted for a 150hp engine-generator set system. Based on the analysis of the Tabu Search optimisation carried out, better utilisation of the installed generation capacity will lead to 48% more cost savings for the sample farm.

The first objective of the research, i.e., determination of the maximum revenue from a BWECS for a given herd size has been attained in this chapter. A farm of herd size 500 cows was selected and the Tabu Search algorithm developed in Chapter 4 was used to optimise the BWECS for this farm. A maximum annual revenue of USD 38,133 for a herd size of 500 cows, was predicted from the optimisation. The results of the optimisation were compared to the the performance of a BWECS on a sample farm. It was found out that the sample farm could realise 48% more cost savings from better utilisation of its BWECS. A sensitivity analysis on how the predictions of biogas generation, electricity and heat production, and maximum revenue would change for different input characteristics and model component parameters, has not been done. The cost savings for A.A. dairy farm and the maximum revenue obtained for a herd size of 500 cows may be different if the input characteristics and model component parameters are changed. In attaining the objective of determination of maximum revenue for a given herd size, an optimisation framework for biomass waste to energy conversion systems has been developed. The next chapter describes how the second objective of the research, i.e., threshold herd size at which a BWECS becomes commercially viable, was attained.

Chapter 6

Threshold Herd Size for Commercial Viability of BWECS on Rural Farms

6.1 Introduction

This chapter describes the solution to the problem of determination of the threshold herd size at which BWECS become commercially viable. The systems are considered commercially viable if they have a positive net present value [146]. The threshold of commercial viability is the herd size below which the NPV is negative. The threshold herd size is determined by optimising the BWECS for different herd sizes. The problem is solved by taking into consideration the following:

(i) co-digestion of manure and food waste,
(ii) cleaning of biogas,
(iii) electricity tariffs and
(iv) separation of digestate into solids and liquids.

Co-digestion increases the biogas yield.

Cleaning of biogas is done to remove hydrogen sulphide. Biogas contains hydrogen sulphide that corrodes internal combustion engines. Cleaning of biogas increases the lifetime of the engine-generator set. This reduces the replacement, operations and maintenance costs of the internal combustion engine. The cost of cleaning biogas has to be weighed against the cost of replacing the engine-generator set.

Electricity tariffs determine the cost of electricity from the grid and therefore are considered in the optimisation. States or provinces sometimes offer incentives for use of electricity from the anaerobic digestion of farm waste [137, 147]. Such incentives are offered for a limited period of time. The Government of Canada for example stopped signing contribution agreements for the ecoENERGY for Renewable Power Program in March 2011 [147]. Another form of encouraging renewable energy generation is to offer a higher tariff for renewable energy sold to the utility. In order to determine the price the utility company will pay for renewable energy, the proposed increment in the electricity tariff is assigned as a variable of the optimisation. Some utilities provide net metering contracts where the farm sends energy to the grid. The energy sent to the grid is netted off the farm's monthly energy usage. If the farm generates more energy than it can use in a given month, this is kept as an energy credit for use in subsequent months. The net metering contract currently available in Quebec requires the farm to use the energy credit within a 24 months period [148]. This is disadvantageous to the farm if more energy than what is consumed is generated within the 24 months period. Another disadvantage is that one of the eligibility criterion for the net metering contract is that the electricity generation capacity should not exceed 50kW or the maximum power demand of the farm [148]. Inclusion of net metering contracts as a possible cost saving would set a limit to the amount of electricity that should be generated in order to benefit from net metering. The concept of net metering is however incorporated in the optimisation by providing for feeding excess electricity into the grid for sale.

The digester effluent can be separated into solids and liquids using a screw press. The solid effluent can be used in place of conventional animal bedding. Freund Dairy [149] and EL-VI Farms [150] are examples of farms that use digestate solids as animal bedding. Freund Dairy has 250 milking cows and saved USD 7000 [149] annually in animal bedding costs, by use of digestate solids as animal bedding. EL-VI Farms has 800 cows and saved USD 30,000 [150] annually by using digestate solids as animal bedding. Inclusion of a screw press to separate liquid and solid digestate, therefore gives the farm the option of saving on the cost of animal bedding.

6.2 Review of Research on Commercial Viability of Waste to Energy Conversion Systems

A literature review of research undertaken on determination of commercial viability of waste to energy conversion systems was carried out. Research where optimisation was used to determine maximum revenue was also reviewed. The following is a discussion of previous research undertaken. There are three marked differences with the research undertaken and the research reviewed. These are: (i) use of the Tabu Search heuristic, (ii) mathematical modeling based on the energy conversion processes and (iii) method of determination of commercial viability.

This research on the threshold herd size for commercial viability of a BWECS, uses the Tabu Search heuristic [131]. The Tabu Search heuristic is suitable for solving the problem due to the complexity and non-linearity of the functions used to model the energy conversion processes, the problem's discrete optimisation variables and its non-convex constraints. The merits of the Tabu Search heuristic for use in optimisation of complex, non-linear, non-convex optimisation problems, like BWECS was discussed in Sections 1.6.3 and 4.1.

Modeling and optimisation of energy conversion systems has been done for purposes of economic analyses. These models base the analyses on energy flows and not the energy conversion processes. In [151], a multi-period mixed integer linear programming optimisation was applied to a district heating system. The objective of the optimisation was to minimise the cost of the heating system. The optimisation used mass and heat balance analyses to calculate the energy flows as opposed to thermodynamic models. Another technique used for optimisation of energy systems is MIND (Method for analysis of INDustrial energy systems), which is a decision support technique. The MIND method is used in [152] for optimisation of energy systems in a dairy industry and a pulp and paper mill. The energy systems were also modeled as energy flows and not as energy conversion processes. Similarly, in [153] a polygeneration plant fuelled by natural gas and renewable energy sources was designed and optimised. The energy generated from the biomass was determined from the specific fuel consumption of the biomass and the overall gasification efficiency. Mathematical modeling of the energy conversion processes was not used to determine the power output of the polygeneration plant. The system model used in the research being carried out is different in that it is based on the energy conversion processes in each of the system components. The models used to calculate the energy output from the conversion processes are: a digester, an internal combustion engine and an induction machine, a boiler and a heat exchanger. The ADM1 [50] and the GISCOD (General Integrated Solid Waste Co-Digestion) [71] models are used to calculate the energy conversion processes in the digester. The ADM1 was developed for prediction of biogas generated from anaerobic digestion of wastewater. The biomass waste to energy system model used for determination of the threshold herd size, considers co-digestion of manure and food waste. Prediction of biogas generated from co-digestion of food waste and manure requires modification of some of the ADM1 parameters to allow for the different compositions of carbohydrates, proteins and lipids, and different hydrolysis rates. In [71] the GISCOD model that generates inputs to the ADM1 for co-digestion of different types of waste was developed. The GISCOD model is used together with the ADM1 to predict biogas generated from the co-digestion of manure and food waste. The internal combustion engine model used in the optimisation is obtained from the ADVISOR software [56]. The induction machine is modeled in the *dq* (direct-quadrature) synchronous reference frame and is based on the transient model of the induction machine [57]. The boiler and heat exchanger are modeled using heat transfer equations [58, 59]. Details of the equations used in these models are given in Chapter 2.

The determination of the commercial viability of biomass waste to energy conversion systems is done in different ways, which include: payback period, overall production cost, NPV and profitability. In [154] the feasibility of electricity production from biogas on a pig farm used the payback period as an economic indicator. An economic and environmental assessment of the energetic valorization of organic material for a municipality in Quebec was studied in [155]. The payback period was also used as an economic indicator. Study [156] did a thermo-economic analysis of a biomass trigeneration plant. The study used the overall plant production cost as a measure of the cost effectiveness of the production process. The NPV was used as a measure of economic viability in [146], where an assessment of the technological development and economic potential of photobioreactors was done. The research undertaken uses NPV as an indicator of commercial viability. This is because the objective of the research is to determine the threshold herd size at which the system becomes commercially viable. This threshold value is determined as the herd size below which the system's NPV is negative.

The literature review on determination of commercial viability of waste to energy conversion systems is followed by the description of the system model developed to solve the problem of the second objective of the research.

6.3 BWECS Model for Determination of Threshold Herd Size for Commercial Viability

This section describes the BWECS model used in the determination of the threshold herd size for commercial viability (Figure 6.1). The basic BWECS consists of a lagoon, a digester, a boiler, a propane tank and the electricity grid. These are the basic components of the system, because with these, heat and electricity can be provided to the farm. The heat can be obtained from combustion of biogas in the boiler and electricity can be obtained from the grid. The heating load and electrical load demands can be met with these basic components. The lagoon is included in the basic system to allow for storage of manure. The propane tank is a backup fuel supply for the boiler, if insufficient biogas is generated. The other components of the system shown in Figure 6.1, which are discussed next, are optional. They include: an engine-generator set, a heat exchanger, co-digestion with food waste, a screw press and a biogas filter. These components are included in order to maximise revenue from the BWECS. The farmer can generate electricity for sale by including an engine-generator set in the system. A heat exchanger is used to capture exhaust heat which can be added to the heat generated by the boiler. Co-digestion of manure and food waste increase the yield of biogas. Tipping fees obtained from acceptance of off-site food waste increase revenue from the BWECS. The screw press separates the digester effluent into liquids and solids. The solids can be used as bedding for the animals, which saves the farm the cost of animal bedding. The separated liquid digestate can be spread on land as fertiliser. Use of the separated liquid digestate as fertiliser has not been included in the optimisation. This is because there are no case studies to quantify the cost savings from this practice, since the liquid digestate

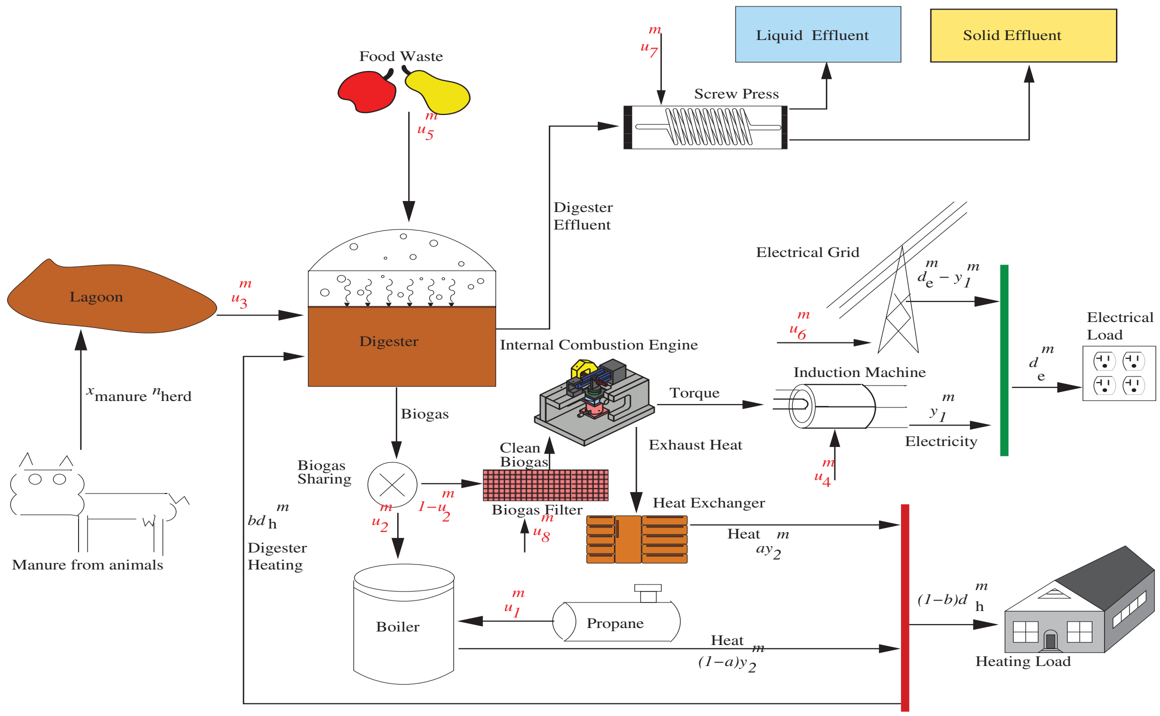


Figure 6.1: BWECS Model

is used to supplement commercial fertilisers and is spread on land when required. Similarly, liquid digestate that is not separated into solids and liquids, is stored in lagoons and spread on land when required. Biogas contains hydrogen sulphide which corrodes the internal combustion engine. Cleaning biogas increases the lifetime of an engine-generator set and reduces replacement, operation and maintenance costs. Cleaning of biogas is an additional cost, and this has to be balanced with the cost of replacement of the engine-generator set. A biogas filter for cleaning the biogas is thus included in the system as an optional component. The decision on which of the optional components to include and how to operate the resulting system, is made using optimisation. A variable is attached to each of the components of the BWECS. The details of the optimisation problem are given in Section 6.4.

6.4 Description of the Optimisation Problem

This section describes the optimisation problem. The statement of the optimisation problem is given, followed by a description of the optimisation variables, inputs and outputs of the BWECS. The formulation of the objective function and the constraints are also described.

6.4.1 Formulation of the Optimisation Problem

In solving the problem of the determination of the herd size at which the BWECS becomes commercially viable, the system has to be optimised. As described in Section 4.2.1, the optimisation problem consists in dimensioning the BWECS for a given manure input in a given time period $m \in M$. M is a set of the number of months in the multi-period dimensioning problem. The optimisation problem is expressed as a cost minimisation problem by:

$$\min f^{\text{cost}}(u_1^m, u_2^m, u_3^m, u_4^m, u_5^m, u_6^m, u_7^m, u_8^m) \text{ for } m \in M \text{ for a herd size } n_{\text{herd}}, \tag{6.1}$$

$$\text{subject to: } C_{\text{BWECS}}(u_1^m, u_2^m, u_3^m, u_4^m, u_5^m) \leq 0 \quad \text{for } m \in M, \tag{6.2}$$

$$\text{such that: } u_1^m \in \{0, 0.0001,\ 0.0002, ..., 0.0036\} \quad \text{for } m \in M \quad \text{kg/s}, \tag{6.3}$$

$$u_2^m \in \{0,\ 0.01,\ 0.02, ..., 1\} \quad \text{for } m \in M, \tag{6.4}$$

$$u_3^m \in \{1,\ 2,\ 3, ..., u_3^{m,\max}\} \quad \text{for } m \in M \quad \text{m}^3/\text{day}, \tag{6.5}$$

$$u_4^m \in \{0, 60, 100, 120, 130, 135, 140, 145, 180, 200, 225, 230, 260, 300, 375, 400, 406, 450, 500, 600, 625, 700, 750\} \quad \text{for } m \in M \ \text{kW}, \tag{6.6}$$

$$u_5^m \in \{0,\ 0.1,\ 0.2, ..., 2.8\} \quad \text{for } m \in M \quad \text{m}^3/\text{day}, \tag{6.7}$$

$$u_6^m \in \{0,\ 0.1,\ 0.2, ..., 1\} \quad \text{for } m \in M \quad \%, \tag{6.8}$$

$$u_7^m \in \{0,\ 1\} \quad \text{for } m \in M, \tag{6.9}$$

$$u_8^m \in \{0,\ 1\} \quad \text{for } m \in M, \tag{6.10}$$

$$u_4^{m,\max} = V_{\text{capacity\_lagoon}}\, n_{\text{herd}}\, x_{\text{manure}}/n_{\text{days}}^m \quad \text{for } m \in M \qquad \text{m}^3/\text{day}, \tag{6.11}$$

where u_1^m is the variable backup propane mass flow rate, u_2^m is the variable biogas sharing ratio, u_3^m is the variable volume flow rate of manure from the lagoon, u_4^m is the variable induction machine rating, u_5^m is the variable volume flow rate of food waste, u_6^m is the variable percentage increase in electricity tariffs, u_7^m is the variable that denotes the inclusion or exclusion of a screw press, u_8^m is the variable that denotes the inclusion or exclusion of a biogas filter, $V_{\text{capacity\_lagoon}}$ is the storage capacity of the lagoon, n_{herd} is the herd size, x_{manure} is the volume flow rate of manure produced per animal and n_{days}^m are the number of days. The bounds and the step sizes of the variables are determined from the inputs to the BWECS and literature review carried out. The maximum value of backup propane mass flow rate $u_1^{m,\max}$ is obtained from the flow rate that meets the maximum heating demand, when the boiler is combusting propane only. This is also obtained using the maximum digester volume flow rate $(u_3^{m,\max} + u_5^{m,\max})$, since heat is needed to raise the temperature of influent waste to the digester's operating temperature. The variable u_4^m comprises of discrete values from typical engine-generator set ratings on farms. A value of 0 kW is included for the case where no electricity is generated and all the biogas is combusted in the boiler or flared. The maximum value of the variable, volume flow rate of food waste, $u_5^{m,\max}$ is determined from the estimate of garbage generated by residential units [157].

As defined in Chapter 4, the inputs to the BWECS are the herd size, n_{herd}, the electrical load, d_{e}^m, and the heating load, d_{h}^m. The herd sizes are determined from typical dairy and swine farms in Quebec province. The electrical load is derived from electrical loads on typical dairy farms [60] and swine farms [158]. The heating load of the dairy farms was simulated using the HOT2000 software from Natural Resources Canada, whereas the heating load of swine farms was obtained from a typical swine farm [138]. The digester's heating load was calculated from the heat required to maintain the operating temperature of the digester at its optimum, and to heat the influent manure (5.3), (5.4), (5.5), (5.6). The outputs of the BWECS are electricity, y_1^m, and heat, y_2^m.

The Tabu Search algorithm used in the optimisation is described in Section 4.4. The description of the formulation of the objective function is given in the following section.

Table 6.1: Parameters of the Optimisation

Parameter	**Description**	**Value**
n_{days}^m	number of days in month $m \in M$ (days)	varies
n_{period}	number of periods for which interest rate will be charged (periods)	120
n_{year}	number of years over which the loan will be paid (years)	10
n_{repair}	number of years after which repairs of the engine are required (years)	5 (cleaned biogas) 2 (uncleaned biogas)
n_{cycle}	life cycle of the BWECS (years)	20
i_{rate}	interest rate of loan (%)	6
x_{rate}	power sizing exponent of the digester and engine-generator set	0.6 [122]
c_{propane}	unit cost of propane	1.98 USD/m^3 [144]
$c_{\text{lagoon\_unit}}$	unit cost of an unlined lagoon (m^3/day)	2.47 [159]
c_{bedding}	unit cost of animal bedding (USD/animal)	50 (cows) [27] 2.49 (swines) [160]
c_{tipping}	tipping fees (CAD/kg)	0.13 (Quebec) [161] 0.074 (Ontario) [162]
$x_{\text{installation}}$	factor to allow for system installation costs	1.15
δ_{h}	allowance for heating demand constraint (kW)	15
x_{manure}	volume flow rate of manure produced per animal of average weight 544kg/cow [139] and 70kg/swine [163] (m^3/day)	0.0566 (cows) [139] 0.0497 (swines) [163]
x_{food}	maximum ratio of food waste in the digester	0.25 [164]
P_{rated}	power rating of induction machine (kW)	varies
ω_{mech}	speed of engine-generator set (rad/s)	188.5
$V_{\text{capacity\_lagoon}}$	storage capacity of the lagoon (days)	varies with herd size
HRT	hydraulic retention time (days)	20
LHV_{propane}	lower heating value of propane (kJ/kg)	46,300 [136]
η_{HEX}	heat exchanger efficiency (%)	70
η_{boiler}	boiler efficiency (%)	70
T_{water}	temperature of water in the heat exchanger (°C)	35
max_iter	number of iterations for stopping condition of the Tabu Search	150

6.4.2 Objective Function

This section defines the objective function of the optimisation problem. Since the objective is to determine the threshold herd size at which BWECS become commercially viable, the objective function is expressed as a cost minimisation function:

$$\min f^{\text{cost}} = \sum_{m=1}^{M} (C^m_{\text{capital}} + C^m_{\text{grid\_electricity}} + C^m_{\text{propane}} - C^m_{\text{bedding}} - C^m_{\text{tipping}} + C^m_{\text{catalyst}}),$$
$$\text{for } \ m \in M \qquad \text{USD}, \tag{6.12}$$

where C^m_{capital} is the monthly cost of capital of the biomass waste to energy conversion system, $C^m_{\text{grid\_electricity}}$ is the monthly cost of grid electricity, C_{propane} is the monthly cost of propane, C^m_{bedding} is the monthly cost of animal bedding, C^m_{tipping} is the monthly revenue from food waste tipping fees and C^m_{catalyst} is the monthly cost of the catalyst used to clean the biogas. The following is an explanation of the derivation of the cost components of the objective function. The monthly cost of capital is obtained by amortization of the capital expenditure of the BWECS. The capital expenditure of the BWECS is calculated by:

$$C_{\text{cost}} = (c_{\text{digester}} + c_{\text{eng\_gen}} + c_{\text{lagoon}} + c_{\text{boiler}}$$
$$+ c_{\text{biogas\_filter}} + c_{\text{screw\_press}}) x_{\text{installation}} \qquad \text{USD}, \tag{6.13}$$

where C_{cost} is the capital expenditure, c_{digester} is the cost of the digester, $c_{\text{eng\_gen}}$ is the cost of the engine-generator set and associated switchgear, c_{lagoon} is the cost of the lagoon, c_{boiler} is the cost of the boiler, $c_{\text{biogas\_filter}}$ is the cost of the biogas filter, $c_{\text{screw\_press}}$ is the cost of the screw press and $x_{\text{installation}}$ is a factor to allow for installation costs. Costs of the digester and the engine-generator set were obtained from the literature on existing BWECS [3, 9, 123, 126, 127, 142, 165–167]. Not all the costs of the different digester sizes and engine-generator set ratings were available from literature, thus cost estimating was done, by scaling the costs (3.21) as described in Section 3.2.4. The cost of the lagoon is calculated from the unit cost of an unlined lagoon, $c_{\text{lagoon\_unit}}$ (Table 6.1) [159]. The cost of boilers of different ratings was obtained from [143]. The cost of the biofilter for cleaning biogas was obtained from [168]. The cost of a screw press is obtained from [126]. It is assumed that the BWECS will be financed by a loan taken over an n_{year} period. The monthly repayments are calculated using [122]:

$$C^m_{\text{payments}} = C_{\text{cost}} i_{\text{rate}} (1 + i_{\text{rate}})^{n\ \text{period}} / ((1 + i_{\text{rate}})^{n_{\text{period}}} - 1) \text{ for } m \in M \quad \text{USD}, \quad (6.14)$$

where C^m_{payments} is the monthly loan repayment, C_{cost} is the principle loan amount which is the capital expenditure on the BWECS, i_{rate} is the monthly interest rate and n_{period} is the number of periods for which interest will be paid over the n_{year} duration of the financing. When using biogas in an engine-generator set, the cost of replacement of the engine is significant and is included in the optimisation. It is significant because biogas contains hydrogen sulphide that corrodes the engine, which reduces the lifetime of the engine-generator set. Cleaning biogas reduces the frequency of replacement of the engine-generator set. When using cleaned biogas, the engine-generator set is replace every 5 years, and when using uncleaned biogas the replacement period is reduced to 2 years [154]. As such the annual cost of replacement is calculated by averaging the engine-generator set cost over n_{repair} years. The cost of replacement of the engine-generator set is added to the monthly loan repayment to obtain the monthly cost of capital C^m_{capital}.

The monthly cost of grid electricity $C^m_{\text{grid\_electricity}}$, is calculated based on Hydro-

Québec Rate G. Rate G is the general rate of electricity supplied to small power contracts whose minimum billing demand is less than 100kW [148]. Although farms are subject to the supply of electricity at the domestic Rate D [148], Rate G was selected for the optimisation, for two reasons. The first reason is that farms billed at the domestic Rate D, that do not use the electricity for a dwelling or the farm activities, will require an additional meter, billed at the appropriate general rate, for example, Rate G. If there is no additional meter, then Rate D may be applied only when the additional installed capacity, other than the dwelling and the farm, does not exceed 10kW [148], otherwise the appropriate general rate will apply. A BWECS has parasitic electric loads from the equipment used to run the system. These loads include: a mixer, a screw press, a food shredder and a recirculating pump. These parasitic loads are not considered under dwelling or farm loads, as they are used to generate electricity for sale. Depending on the size of the BWECS, these parasitic loads may exceed 10kW, and would require a separate meter, billed at the general rate. In the optimisation, provision has not been made for two billing rates because it is desirable to take advantage of the higher energy tariff of Rate G, on selling electricity to the grid (see Table 6.8). This also explains the second reason for selection of Rate G, for the optimisation. With regard to the calculation of the cost of electricity obtained from the grid, both the cost of maximum demand and the energy obtained from the grid are included. For electricity fed to the grid, the calculation used assumes that the farm will only be paid based on the energy sent to the grid. The maximum demand cost does not apply to electricity fed to the grid.

The monthly cost of propane, C^m_{propane}, is calculated from the unit cost of propane, c_{propane}, obtained from [144] and given in Table 6.1.

Inclusion of the screw press in the system saves the farm the cost of animal bedding. The avoided cost of animal bedding is calculated from the unit cost of bedding per animal, c_{bedding} [27, 160] (Table 6.1).

The monthly revenue from tipping fees, C^m_{tipping}, included in the objective function is calculated from an estimate of the tipping fees in Quebec province landfills [161] (Table 6.1).

The monthly cost of the biogas filter used for cleaning biogas, C^m_{catalyst}, was obtained from [169].

The formulation of the objective function has been described in this section. The following section defines the constraints of the optimisation.

6.4.3 Constraints

The optimisation of the BWECS is done subject to the constraints $C^m_{\text{BWECS}}(u^m_1, u^m_2, u^m_3, u^m_4, u^m_5)$, for $m \in M$, defined by (6.15), (6.16), (6.17), (6.18), (6.19) and (6.20). The following is an explanation of the derivation of the constraints. The manure from the animals is stored in a lagoon. The volume flow rate of manure from the lagoon into the digester, u^m_3, varies from month to month. Constraint (6.15) is set to ensure that the net volume of manure in the lagoon is not negative. With Constraint (6.15), the volume of manure that goes into the lagoon in month m, should not be greater than the sum of the volume of manure that was in the lagoon the previous month, and the volume of manure from the animals, in month m. In addition the volume of manure in the lagoon should not be greater than the storage capacity of the lagoon. Constraint (6.16) ensures that the food waste added to the digester is within a ratio, x_{food}, of the total volume of waste in the digester [164]. Constraint (6.17) is set to ensure that the total volume of waste in the digester is not greater than the volume of the digester. The digester model uses non-linear differential equations to model the anaerobic digestion processes. The differential equations can be found in [50]. The biogas generated is shared between the internal combustion engine and the boiler. The variable u_2^m determines the sharing of biogas. Combustion of biogas in the internal combustion engine generates an output torque. The output torque is obtained by applying the Newton-Raphson method to a two dimensional linear interpolation function, multiplied by the available torque. The details of the functions, ICE used in the internal combustion engine model can be found in [56]. The internal combustion engine is coupled to an induction machine of rating, u_4^m, that generates output electricity, y_1^m. The induction machine is modeled using non-linear differential equations detailed in [57]. The electricity generated is a function of the output torque, which is in turn a function of the mass flow rate of biogas to the internal combustion engine. Constraint (6.18) is therefore set to limit the mass flow rate of biogas to not more than what is required to generated rated power of the induction machine. The heat produced by the boiler is calculated from the mass flow rate of biogas and propane to the boiler, and the LHV of biogas and propane. Exhaust heat captured by the heat exchanger is calculated from the temperature and the mass flow rate of the exhaust gases. Constraint (6.19) is set to ensure that the heat output of the BWECS meets the heating demand of the farm and the digester. Constraint (6.20) is set to ensure that the heat to be generated by the boiler is not greater than the boiler rating. The contribution of the heat captured by the heat exchanger is subtracted from the heat output of the boiler in formulation of Constraint (6.20). The boiler rating is calculated by a non-linear equation (2.44).

$$0 \leq (x_{\mathrm{manure}}\, n_{\mathrm{herd}}\, n^m_{\mathrm{days}} + V^{m-1}_{\mathrm{lagoon\_manure}} - u^m_3 n^m_{\mathrm{days}}) \leq V_{\mathrm{lagoon\_storage}}\, x_{\mathrm{manure}}\, n_{\mathrm{herd}}, \tag{6.15}$$

$$0 \;\; < u^m_5 \;\; \leq \;\; u^m_3\, x_{\mathrm{food}}/(1 - x_{\mathrm{food}}), \tag{6.16}$$

$$(V_{\mathrm{D}} - (u^m_3 + u^m_5)\,\mathrm{HRT}) \;\; \geq \;\; 0, \tag{6.17}$$

$$(u^m_4/\omega_{\mathrm{mech}} - \mathrm{ICE}(LHV^m_{\mathrm{biogas}},\, \omega_{\mathrm{mech}}, (1 - u^m_2) m^m_{\mathrm{biogas}})) \;\; \geq \;\; 0, \tag{6.18}$$

$$d^m_{\mathrm{h}} \leq (\eta_{\mathrm{HEX}}\, m^m_{\mathrm{exh}}\, cp^m_{\mathrm{exh}}(T^m_{\mathrm{exh}} - T_{\mathrm{water}}) + (u^m_1\, LHV_{\mathrm{propane}} + u^m_2\, m^m_{\mathrm{biogas}}\, LHV^m_{\mathrm{biogas}})\, \eta_{\mathrm{boiler}}) \leq (d^m_{\mathrm{h}} + \delta_{\mathrm{h}}), \tag{6.19}$$

$$(b_{\mathrm{r}} - d^m_{\mathrm{h}} + \eta_{\mathrm{HEX}}\, m^m_{\mathrm{exh}}\, cp^m_{\mathrm{exh}}(T^m_{\mathrm{exh}} - T_{\mathrm{water}})) \;\; \leq \;\; 0, \tag{6.20}$$

for $m \in M$.

where x_{manure} is the volume flow rate of manure produced per animal, n_{herd} is the herd size, n^m_{days} is the number of days, $V^{m-1}_{\mathrm{lagoon\_manure}}$ is the volume of manure in the lagoon, u^m_3 is the variable volume flow rate of manure from the lagoon, $V_{\mathrm{lagoon\_storage}}$ is the storage capacity of the lagoon, u^m_5 is the volume flow rate of food waste, x_{food} is the maximum ratio of food waste in the digester, V_{D} is the volume of the digester, HRT is the hydraulic retention time of the digester, u^m_4 is the power rating of the induction machine, ω_{mech} is the speed of the internal combustion engine, ICE is the function used to calculate the torque output of the internal combustion engine, LHV^m_{biogas} is the lower heating value of biogas, u^m_2 is the variable biogas sharing ratio, m^m_{biogas} is the mass flow rate of biogas, d^m_{h} is the heating demand, η_{HEX} is the efficiency of the heat exchanger, m^m_{exh} is the mass flow rate of the exhaust gases, cp^m_{exh} is the specific heat capacity of the exhaust gases, T^m_{exh} is the temperature of the exhaust gases, T_{water} is the temperature of water, u^m_1 is the mass flow rate of backup propane, LHV^m_{propane}

is the lower heating value of propane, η_{boiler} is the efficiency of the boiler, δ_{h} is an allowance for the heating constraint and b_{r} is the boiler rating.

6.5 Results of the Optimisation

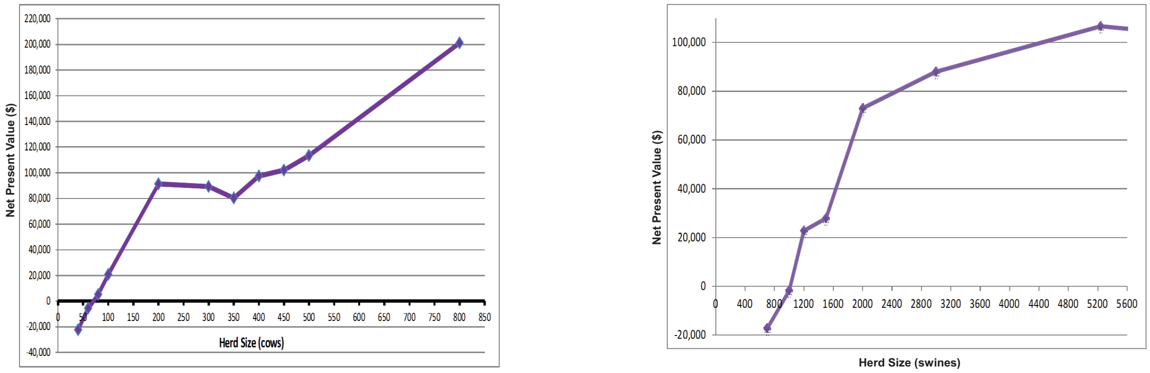
This section presents the results of the optimisation. The threshold herd size at which the BWECS becomes commercially viable is determined for both Quebec and Ontario provinces. The threshold herd size is determined for two different conditions, (i) co-digestion of manure and food waste and (ii) digestion of manure only. A case study of a dairy farm in Quebec is reviewed to assess the commercial viability of a BWECS on this farm.

6.5.1 Threshold Herd Size for Dairy Cows and Swine Farms

The NPV of the BWECS is used to determine its commercial viability. The NPV is calculated by [170]:

$$\text{NPV} = \sum_{t=0}^{n_{\text{cycle}}} A_{\text{t}}(1 + i_{\text{rate}})^{-t} \qquad \text{USD}, \tag{6.21}$$

where NPV is the net present value of the BWECS, n_{cycle} is the life cycle of the BWECS in years, t is the year under consideration, A_{t} is the annual cash flow and i_{rate} is the interest rate. The herd sizes below which the NPV of the BWECS becomes negative (threshold herd sizes) were found to be 80 cows and 1200 swines (Figure 6.2), for Quebec province, when co-digesting manure and food waste. The threshold herd size was found to be 100 cows (Figure 6.3), for Ontario province, when co-digesting manure and food waste. This is subject to the inclusion of food waste and a screw



(a) Cows

(b) Swines

Figure 6.2: Threshold at which a BWECS becomes Commercially Viable in Quebec Province when Co-digesting Manure and Food Waste

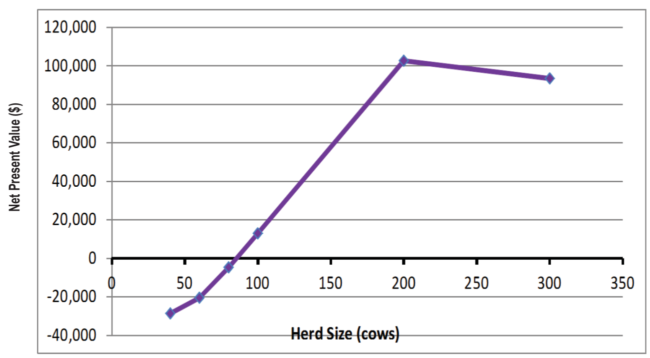
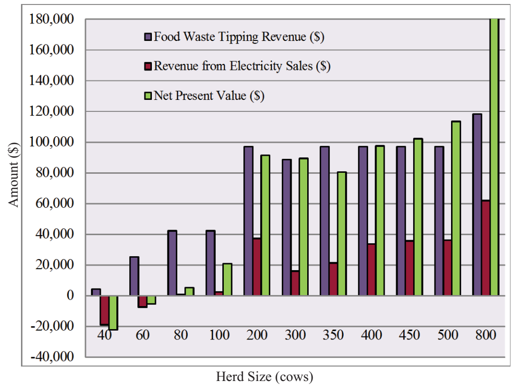


Figure 6.3: Threshold at which a BWECS becomes Commercially Viable in Ontario Province when Co-digesting Manure and Food Waste

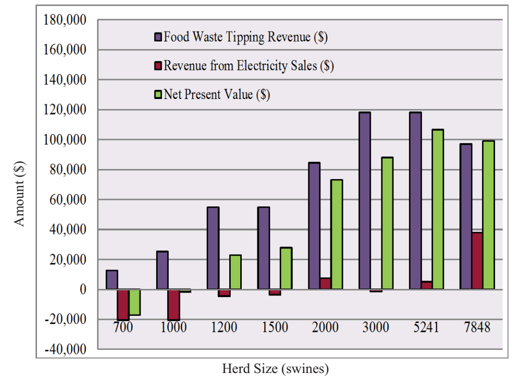
press in the BWECS. The food waste should be a maximum of 25% of the total waste in the digester.

As explained in Section 6.1, the threshold herd size is determined by taking into account additional revenue from: (i) co-digestion of manure and food waste, (ii) cleaning of biogas, (iii) separation of digestate into solids and liquids and (iv) electricity tariffs. The following is an analysis of the effect of each of these factors on the NPV of the BWECS in Quebec province.

Figure 6.4 shows that the revenue from food waste tipping fees contributes significantly to the NPV of the system.



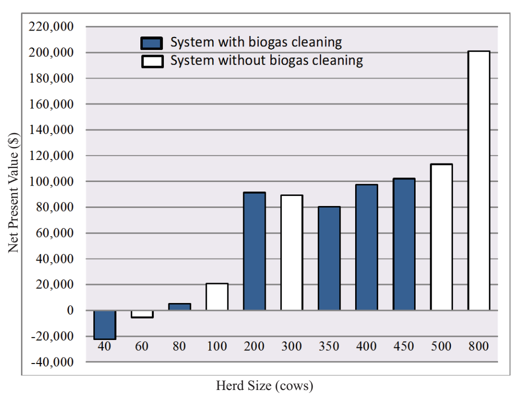
(a) Cows



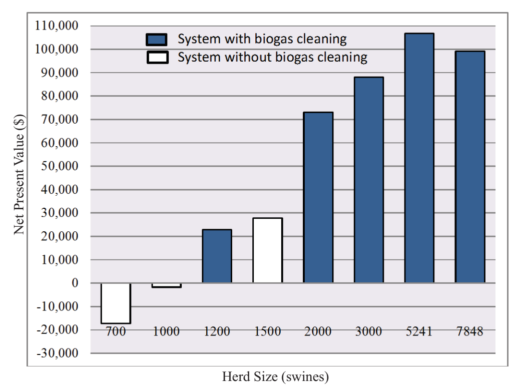
(b) Swines

Figure 6.4: Analysis of Net Present Value of the BWECS

Tables 6.2 and 6.3 show the impact on the NPV of the inclusion of biogas cleaning in the biomass waste to energy conversion systems in Quebec province. This is also illustrated in Figure 6.5, which shows that cleaning of biogas in order to reduce the replacement cost of the engine, has no significant effect on the NPV of the BWECS. There is an increase in the NPV of the BWECS with increase in herd size, irregardless of whether biogas cleaning is included or not.



(a) Cows



(b) Swines

Figure 6.5: Analysis of the Impact of Biogas Cleaning on the Net Present Value of the BWECS

Table 6.2: Impact of Cleaning of Biogas and Separation of the Digester Effluent in a BWECS using Cow Manure

Herd Size (cows)	Biogas Filter	Screw Press	Tariff Increment (%)	Net Present Value (USD)
40	✓	✓	1	-22,287
60	×	✓	0	-5,426
80	✓	✓	1	5,250
100	×	✓	1	20,921
200	✓	✓	1	91,341
300	×	✓	3	89,383
350	✓	✓	1	80,407
400	✓	✓	1	97,470
450	✓	✓	1	102,170
500	×	✓	1	113,484
800	×	✓	1	201,258

Table 6.3: Impact of Cleaning of Biogas and Separation of the Digester Effluent in a BWECS using Swine Manure

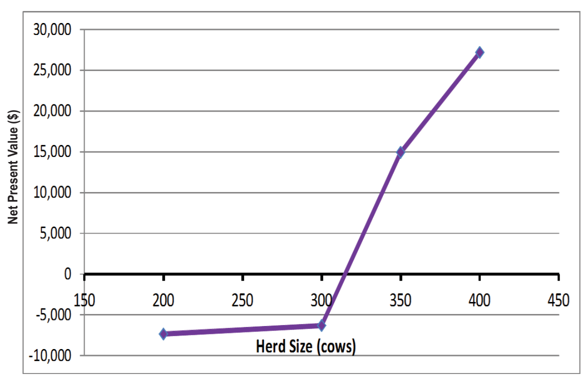
Herd Size (swines)	Biogas Filter	Screw Press	Tariff Increment (%)	Net Present Value (USD)
700	×	✓	0	-17,199
1000	×	✓	0	-1,684
1200	✓	✓	1	22,818
1500	×	✓	1	27,877
2000	✓	✓	1	73,118
3000	✓	✓	1	88,017
5241	✓	✓	1	106,741
7848	✓	✓	1	99,168

With regard to the separation of liquids and solids using a screw press, Tables 6.2 and 6.3 show that all the systems that were optimised for maximum revenue, included a screw press. This is because use of the solid effluent saves the farm the cost of animal bedding.

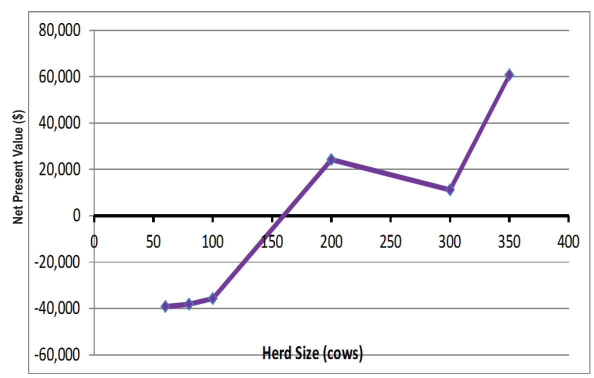
Tables 6.2 and 6.3 show that a 1% increase in the electricity tariff is required for commercial viability at the threshold herd size of 80 for dairy cows and 1200 for swines, in Quebec province. This can be explained by the fact that too large an increase would mean that the farm would have to pay more when it uses electricity from the grid. No increase in the electricity tariff would reduce the farm's revenue from sale of electricity to the grid.

The difference in the threshold herd size for Quebec and Ontario provinces is explained by the different electricity tariffs, food waste tipping fees and heating requirements. It has been shown that food waste tipping fees significantly impact the NPV and thus the threshold herd size. The food waste tipping fees in Quebec province (130cents/tonne) are significantly higher than in Ontario province (74cents/tonne). This explains why the threshold herd size is lower for Quebec province compared to Ontario province, when co-digesting manure and food waste.

The threshold herd sizes for Quebec and Ontario provinces were also determined for BWECS that digest manure only (Figure 6.6). The threshold herd size with digestion of manure only was found to be 350 cows for Quebec province and 200 cows for Ontario province. When digesting manure only, the threshold herd size in Ontario



(a) Quebec Province



(b) Ontario Province

Figure 6.6: Threshold at which a BWECS becomes Commercially Viable when Digesting Manure Only

province is now lower than that in Quebec province. This is because the electricity tariffs significantly impact the NPV and subsequently the threshold herd size, when digesting manure only. The electricity tariff structure used in the optimisation for Quebec province is given in Table 6.8 of Section 6.5.2. The average electricity tariff in Quebec province is 8.78cents/kWh [148], for electricity supplied at the general Rate G used in the optimisation. The electricity tariffs in Ontario province are lower than in Quebec province. Ontario province has a feed-in tariff program for electricity generated from renewable energy sources. The tariff structure is shown in Table 6.4 [171]. The Ontario province feed-in tariff structure also includes a peak performance factor. With the peak performance factor, the payments for electricity fed into the grid are higher during on-peak hours. The on-peak performance factor is 1.35 of the normal tariff, from 11a.m. to 7p.m. on business days. The off-peak performance factor is 0.9 of the normal tariff. Projects that operate for 24 hours a day, every day of the year, will however earn the same total revenue as if they earned the posted feed-in tariff price.

Table 6.4: Threshold Herd Sizes - Comparison of Quebec and Ontario Provinces

Ontario Province	**Quebec Province**
Ontario has feed-in tariff program [171] On-farm project $\leq$ 100kW 19.5cents/kWh 100kW $<$ on-farm project $\leq$ 250kW 18.5cents/kWh Biogas projects $\leq$ 500kW 16.0cents/kWh 500kW $<$ on-farm project $\leq$ 10MW 14.7cents/kWh	Hydro-Québec offers net metering contracts at the same tariff as other energy sources Average of 8.78cents/kWh for Rate G [148]
Projects up to 10MW generation capacity eligible for feed-in tariff program	Projects $\leq$ 50kW or less than maximum demand eligible
Threshold herd size 100 cows when co-digesting manure and food waste	Threshold herd size 80 cows when co-digesting manure and food waste
Threshold herd size 200 cows when digesting manure only	Threshold herd size 350 cows when digesting manure only
Tipping fees of 74cents/tonne	Tipping fees of 130cents/tonne

Following the determination of the threshold herd sizes at which BWECS become commercially viable, a dairy farm in Quebec province was analysed to validate the results.

6.5.2 Case Study of a Dairy Farm in Quebec Province

The experience of a dairy farm in Quebec province, Gasser farm was reviewed in order to validate the threshold herd size for commercial viability, determined in this research. In 1982 Gasser farm installed a BWECS, consisting of a plug flow digester and a 130kW engine-generator set. The details of the BWECS installed on Gasser farm [23, 24] are given in Table 6.5. The following is a description of the operation of the system.

Table 6.5: Gasser Farm BWECS installed in 1982

Description	**Value**
Herd size (cows)	220
Digester dimensions (m)	11 x 20 x 4
Engine-generator set rating (kW)	130
Hydraulic retention time (days)	25
Volume flow rate of biogas (m^3/day)	575[10]
System cost (USD)	200,000

The peak electricity demand of Gasser farm in 1984 was 48kW, which occurred during milking time [23]. The farm used electricity from the grid in addition to the electricity generated from combustion of biogas, but was not allowed to feed electricity into the grid. Exhaust heat from the engine was captured and used to heat the digester, the workshop and other areas of the barn. There was a boiler that used a backup fuel supply to generate heat in the event of engine failure. Since the farm was not sending electricity back to the grid, only electricity required was generated. This required the storage of a large volume of gas. Excess biogas was often produced and

[10] when the flow of manure to the digester was continuous

stored in balloons. The farm did not always realise cost savings on their electricity bill [24]. This was because the farm was not allowed to feed electricity into the grid and therefore only generated electricity during peak demand. The engine-generator set was run for 14 hours a day and was shut down at night when demand was low [23]. The Hydro-Québec tariff rate structure for farms in 1984 was such that the users were not billed for the first 35kW [24] of electricity demand. If Gasser farm went above the 35kW demand, it was billed significantly for electricity demand. The electricity demand of the farm was above 35kW between 5:00am - 9:00am and 3:00pm - 7:00pm [23], which was why the BWECS operated during peak electricity demand periods. Since the farm did not always realise cost savings, the BWECS was shut down and is currently non-operational. The threshold herd size for commercial viability of a biomass waste to energy conversion system that uses manure from dairy cows and food waste has been determined as 80 cows. Gasser farm currently has 240 dairy cows housed next to the digester, which is above the threshold for commercial viability. The following is an analysis of possible savings by Gasser farm from re-installation of the BWECS.

The optimisation of a BWECS was carried out for Gasser farm. Gasser farm's electrical load was estimated from the farm's electricity bills from May 2011 to April 2012. The farm's digester heating requirement was calculated based on the existing digester dimensions given in Table 6.5. The barn where the cows are housed is also used as a milking parlour and therefore no heating is required for the milking parlour. This is because the cows generate heat. Propane is currently used to heat water for use on the farm, therefore the hot water requirements of the farm were included in calculation of the total heat demand of the farm. Since the digester exists, its cost was excluded from the cost of capital. The existing digester size was used in the optimisation. From the optimisation carried out, the BWECS recommended for Gasser farm is summarised in Table 6.6.

Table 6.6: Proposed BWECS for Gasser Farm

Description	Value
Herd size (cows)	240
Lagoon storage capacity (days)	29
Digester dimensions (m)	11 x 20 x 4
Hydraulic retention time (days)	20
Volume flow rate of biogas (m^3/day)	1667
Engine-generator set rating (kW)	100
Boiler rating (kW)	41
Food waste (m^3/day)	2.3
Screw press	included
Biogas filter	included
Proposed increase in electricity tariff (%)	1

It is predicted that Gasser farm can generate an average of 1667m^3 of biogas per day with a herd size of 240 cows, compared to 575m^3 of biogas per day that was being produced in 1984, with a herd size of 220 cows (Figure 6.7). The predicted volume

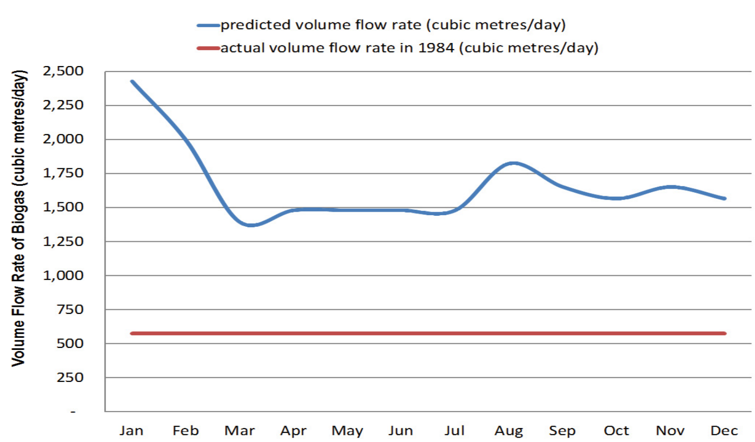
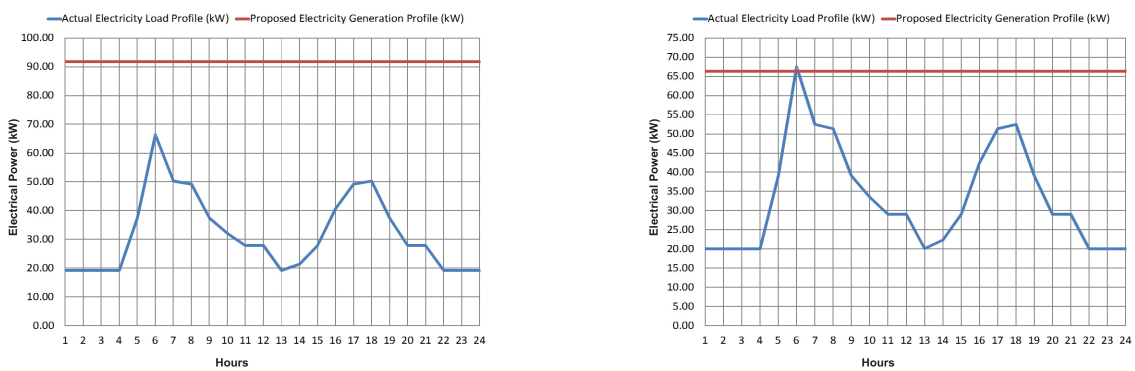


Figure 6.7: Volume Flow Rate of Biogas from Digester

flow rate of biogas is to be produced from co-digestion with up to 25% food waste.

In the past Gasser farm operated its BWECS during peak demand [23], because electricity generated was not being fed into the grid for sale. With the net metering contract currently available from Hydro-Québec [148], electricity can be fed to the grid and will be netted off the electrical energy used over a period of 24 months. Renewable energy generators are however not paid for energy generated in excess of their total energy demand over a period of 24 months. Gasser farm can therefore obtain revenue from electricity fed to the grid, especially if the utility company agrees to buy back all the electricity generated in excess of the total energy demand of Gasser farm, over a 24 months period. The proposed electricity generation profile is such that electricity is generated throughout the 24 hour period and throughout the year. The daily electricity generation and load profiles for selected months are shown in Figures 6.8 and 6.9. It is proposed to generate maximum electricity in the month of

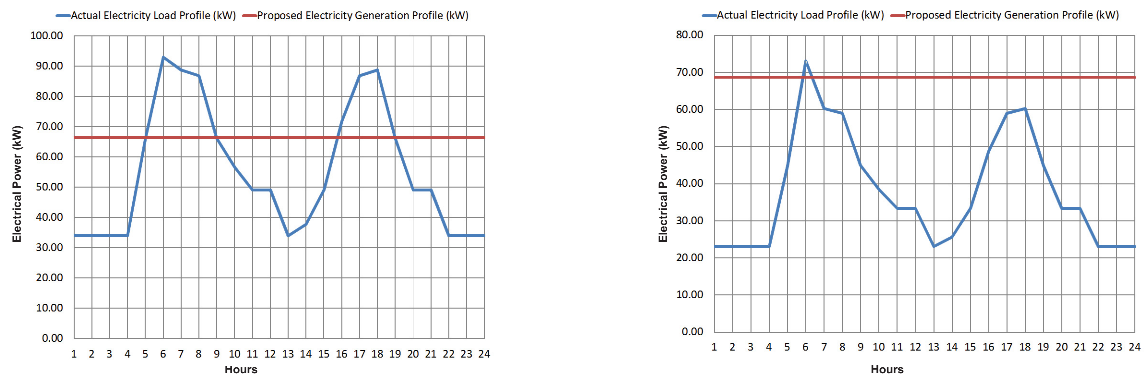


(a) January

(b) April

Figure 6.8: Proposed Electricity Generation Profile

January because it was assumed that manure is left over in December of the previous year and there is a lot of manure for electricity generation. In the months of April and October, the maximum electricity demand is almost met due to the availability of manure and the need to sell excess electricity to the grid. In the month of July, the electricity peak demand is very high at 93kW, compared to the other months that averaged a demand of 71.8kW. The manure and food waste available is not sufficient



(a) July

(b) October

Figure 6.9: Proposed Electricity Generation Profile

for continuous electricity generation at the peak demand of 93kW. The optimum electricity output is therefore found to be 67kW in line with the other months, based on available manure and food waste.

The predicted revenue from the sale of electricity to the grid by Gasser farm is shown in Figure 6.10 and summarised in Table 6.7. It is predicted that Gasser

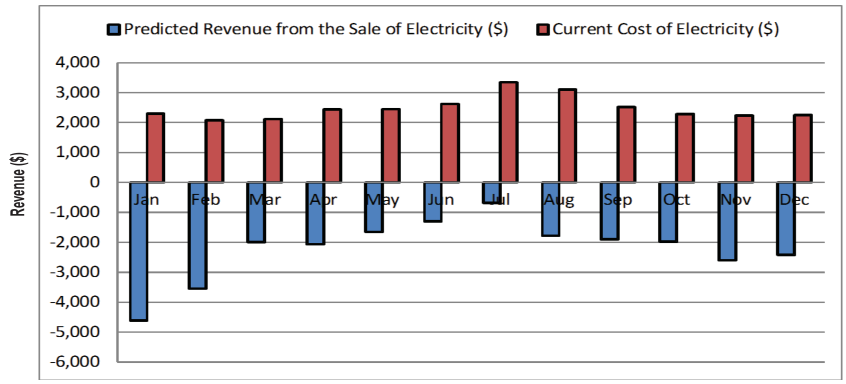


Figure 6.10: Predicted Electricity Generation Revenue for Gasser Farm

farm will receive revenue from selling electricity to the grid throughout the year. The proposed increase in tariffs is 1%. With the increase in the electricity tariff, Gasser farm will pay more to the electricity utility company for energy consumed, it will

Table 6.7: Predicted Electricity Generation Revenue from Proposed Gasser Farm BWECS

Month	**Predicted Revenue from Sale of Electricity (USD)**	**Current Cost of Electricity (USD)**
Jan	-4606.40	2294.84
Feb	-3544.40	2077.35
Mar	-1991.10	2119.45
Apr	-2066.30	2437.14
May	-1654.20	2448.71
Jun	-1301.50	2626.38
Jul	-681.80	3342.62
Aug	-1781.70	3102.05
Sep	-1900.30	2519.92
Oct	-1977.30	2283.20
Nov	-2599.70	2239.77
Dec	-2420.60	2250.03

also receive a higher revenue for electricity sold to the grid. Currently Gasser farm is being metered under Rate D for electricity distribution [148]. The predictions in revenue have been made based on Rate G metering. The comparison between Rate D and Rate G is given in Table 6.8. The tariff per kWh is higher for Rate G than

Table 6.8: Electricity Distribution Tariffs

	Rate G	**Rate D**
Fixed charge	12.33 USD/month	40.64 cents/day (12.192 USD/month)
First 15,090kWh	8.78 cents/kWh	-
First 30kWh/day (900 kWh/month)	-	5.39 cents/kWh
Remaining consumption	4.85 cents/kWh	7.51 cents/kWh
Billing demand in excess of 50kW	15.54 USD/kW	1.26 USD/kW (in summer) 6.21 USD/kW (in winter)

Source: Hydro-Québec, April 2011

for Rate D, so Gasser farm will receive a higher revenue for sending electricity back to the grid. This gives the farm an incentive to generate their own electricity, as well as sell more energy to the grid. The utility company however has to allow the farm to send net energy to the grid, greater than what it consumes, over a longer period. With the net metering contract currently available the utility company does not buy back electricity in excess of the farm's consumption over a 24 months period. In addition the net metering contract does not apply to generation of electricity in excess of 50kW or in excess of the maximum demand contract, whichever is the lesser of the two [148]. This provision is unfavourable to Gasser farm whose maximum demand is greater than 50kW. The predicted electricity generation revenues are subject to the farm being allowed to send electricity to the grid, in excess of its maximum demand contract, and without the 50kW demand cap.

In this chapter the Tabu Search Algorithm developed has been used to attain the second objective of this research, i.e., specification of the threshold herd size at which a BWECS becomes commercially viable. This was done for the provinces of Quebec and Ontario in Canada. The BWECS becomes commercially viable at a herd size of 80 dairy cows and 1200 swines in Quebec province. For Ontario province the threshold herd size is 100 cows. In both cases, this is subject to co-digestion of manure and food waste, and inclusion of a screw press. The recommended increase in the electrical energy tariff in Quebec province is 1%. When digesting manure only, the threshold herd size in Quebec province is 350 cows and that in Ontario province is 200 cows. It was concluded that farms in Quebec province should be offered more favourable net metering contracts. These net metering contracts should allow the sale of electricity to the utility in excess of the net energy demand over a 24 months period, and in excess of 50kW or the farm's maximum demand. A sensitivity analysis on how the threshold herd size changes for different input characteristics and model component parameters has not been done. In Section 1.3 the temperature of water circulating in the heat exchanger was identified as one of the parameters that may impact the predictions of the optimisation tool developed. In calculating the heat output of the heat exchanger, the temperature of the water circulating in the heat exchanger was set to 35°C, which is the same value as the operating temperature of the digester. The typical temperature difference between the manure in the digester and the water circulating in the heat exchanger is 7.2°C [172]. Use of the same value of temperature means that in practice there is no heat transfer from the water circulating in the heat exchanger to the manure in the digester. The calculated heat output of the heat exchanger is greater than what is practical. This is because the heat output of the heat exchanger was calculated from the temperature difference between the exhaust gases of the engine-generator set, and the water circulating in the heat exchanger. The transfer of this heat to the manure was not calculated, as it was assumed that the heat from the exhaust gases is available for transfer to the manure. This impacts the cost of propane which is a cost component of the objective function, of the optimisation problem. More propane than what was calculated would be required. This discrepancy does not affect the electricity generated, as during the optimisation priority was given to the use of biogas for generation of electricity. If the heating demand could not be met by the combustion of biogas in the boiler and the heat from the exhaust gases, propane was combusted in the boiler. Similarly, the discrepancy does not affect the threshold herd sizes and the maximum revenue determined by the optimisation tool. This is because the magnitudes of the cost of propane are very low in comparison to the magnitudes of the other cost components of the objective function. The heat transfer process from the exhaust gases of the engine-generator set to the manure in the digester however needs to be remodeled to closely depict what happens practically. A sensitivity analysis would also address the issue of selection of more practical parameters in modeling of the biomass waste to energy conversion system.

Chapter 7

Conclusion

7.1 Conclusions from the Research Undertaken

The threshold herd sizes at which BWECS become commercially viable were determined, as 80 dairy cows and 1200 swines in Quebec province, and 100 dairy cows in Ontario province. This was with co-digestion of manure and food waste. When digesting manure only, the threshold herd sizes were determined as 350 dairy cows in Quebec province and 200 dairy cows in Ontario province. It was determined that biogas cleaning in order to avoid engine corrosion and increase the lifetime of the engine, does not have a marked impact on the net present value of the BWECS. Inclusion of a screw press in the BWECS allows for separation of the digestate into solids and liquids, the former of which can be used as animal bedding. The farms therefore avoid the cost of animal bedding. All the BWECS that resulted in positive net present values included screw presses. The inclusion of a screw press therefore has a positive impact on the net present value of the BWECS. An increase in the energy tariff was also established as a requirement for high revenues and net present values of BWECS. The component of the BWECS that contributed significantly to the net present value was co-digestion with food waste. All the systems have to include co-digestion with food waste if they are to fall within the threshold herd size for commercially viability. Co-digestion with food waste increases the biogas yield and the farmer also gets revenue from food waste tipping fees. The food waste must however not be more than 25% of the total waste in the digester. A sample farm in Quebec province with a herd size of 240 cows, was analysed to validate the findings.

The results of the optimisation for the sample farm showed that the farm could obtain revenue of USD 26,525 annually, from the sale of electricity to the utility company throughout the year. It is recommended that a net metering contract that allows sale of electricity in excess of the net energy demand over a 24 months period be considered. The net metering contract should also apply to renewable energy generators who generate electricity in excess of their demand or in excess of 50kW. The Tabu Search algorithm is sufficiently reliable for commercialisation into a sofware that can be used by policy makers and farms investing in BWECS.

The Tabu Search algorithm developed was also used to determine the maximum revenue that can be obtained from a BWECS, for a given herd size. In determination of the maximum revenue, a sample farm of herd size 500 dairy cows was analysed. The results obtained showed that maximised revenue is obtained with use of a 150hp engine-generator set, a 1350m^3 digester, a lagoon of 40 days storage capacity and a boiler rated at 133kW. The predicted cost savings were compared to actual data from the sample farm. It was found that the farm is under utilising its currently installed BWECS. From the Tabu Search optimisation carried out, better utilisation of the installed generation capacity will lead to 48% more cost savings for the sample farm. A sensitivity analysis was not done to determine the change in the predictions of the optimisation tool, if the waste characteristics and system parameters are changed. The results of the optimisation should therefore be viewed as indicative of the output of an optimisation framework for BWECS.

The developments to the basic Tabu Search were designed to handle constraints, multi-objectives, multi-periods and diversification. Experiments were done with two different types of herds (cows and swines), to test the adaptations developed. It was found out that for optimisation of BWECS, constraints are best handled by alternating between allowing feasible and infeasible solutions. The minimisation of cost should also be alternated with the minimisation of infeasibility, for different numbers of iterations. Diversification should be applied by performing restarts with the incumbent solution. It was also found out that evaluation of the multi-period cost components of the objective function on a Pareto incumbent front, is better than summing the cost components of the objective function. During minimisation of cost, a round robin strategy of the months, should be applied, whereas during minimisation of infeasibility the period with the most infeasible solution should be selected for optimisation.

MATTEUS, a program for analysis of BWECS, was used to predict the amount of biogas generated from the anaerobic digestion of organic waste. Generation of biogas predicted by MATTEUS was compared with actual yields on two farms. Ultimate analysis data was calculated from measurable manure characteristics. The specification of the percentage reduction in TVS was identified as important when using MATTEUS. This is because of the method used by MATTEUS to obtain the percentage reduction in TVS. This is key to obtaining practical predictions of biogas generation. The percentage errors in predicted and actual biogas yields for two farms that were analysed, were within acceptable ranges, however the values of reduction in TVS, used by MATTEUS were low. The formulation of the mass balance equation for the prediction of biogas generation in the MATTEUS software should be modified. The methane content predicted for both farms was low. The errors in prediction of methane content are attributed to the estimation of the reduction in percentage TVS. One of the farms included CO_2 in the estimation of methane content of biogas, which increased the percentage error. The following section summarises the contributions of the research undertaken.

7.2 Contributions of the Research Undertaken

In carrying out this research, a contribution has been made in the development of an optimisation tool to determine the threshold herd size at which BWECS become commercially viable. Such a tool is currently unavailable. This is therefore an important contribution to the planning of programs for promotion of installation of BWECS on rural farms. A contribution has also been made in the determination of the maximum revenue from a BWECS for a given herd size. The optimisation tool was developed by making adaptations to the Tabu Search heuristic for solving this complex, non-linear, non-convex optimisation problem. The research also involved the review of tools used to model biomass waste to energy conversion processes. MATTEUS, a software for analysis of conversion of organic waste into energy was used to predict biogas generation. A method was devised for transformation of measurable waste characteristics into inputs that can be used for prediction of biogas generation by MATTEUS.

7.3 Future Work

The research undertaken has made significant contributions in the determination of commercial viability and maximum revenue from BWECS. There is further work that can be done in this area to build on the contributions made, as highlighted below.

The Tabu Search algorithm should be modified to specify hourly energy generation profiles, hourly biomass waste volume flow rates and hourly biogas volume flow rates. This is required to take advantage of the differentiated electricity tariffs. More electricity can be generated during on-peak periods when the electricity tariff is higher. The optimisation should therefore provide an hourly mode of operation of the BWECS.

The commercial viability of BWECS in other regions of Canada and the world should be determined. This involves modification of the BWECS to suite the regions for which the optimisation is being carried out. BWECS in hot climates will not require heating and those not connected to the grid will have significantly different threshold herd sizes. The use of subsidies should also be factored into the determination of the threshold herd size, for regions where generation of renewable energy is subject to subsidies.

The calculation of the reduction in TVS done by MATTEUS can be modified to allow users to specify the reduction in TVS of the organic waste. The determination of the coefficients of the mass balance equation, used by MATTEUS to calculate biogas yield can also be further developed. This will minimise the percentage errors in prediction of biogas generation by MATTEUS.

A sensitivity analysis to determine the impact of the waste characteristics and the system parameters on the predictions of the optimisation tool should be done. This will give an indication of the accuracy of the predictions of the optimisation tool. It will also give an indication to decision makers of how the economic parameters like: the period over which the capital cost is paid, the lifetime of the engine-generator set, the life cycle of the BWECS, the interest rate, the power sizing component used for cost estimation, and the factor used for installation costs, impact the predictions.

The modeling of the heat transfer process from the exhaust gases of the heat exchanger to the manure in the digester should be improved. This should take into account the temperature difference between the manure in the digester and the water circulating in the heat exchanger.

Appendix

This section summarises the results of the experiments described in Section 4.5. Table 7.1 gives results of the experiments for the cows data instance whereas Table 7.2 gives results of the experiments for the swines data instance.

Table 7.1: Experiments for Adapted Tabu Search Optimisation - Cows Data Instance

	iter=50			iter=100			iter=200			Stopping Condition			
	S^{current}	S^{infeas}	S^{inc}	S^{current}	S^{infeas}	S^{inc}	S^{current}	S^{infeas}	S^{inc}	S^{current}	S^{infeas}	iter	S^{inc}
C1 S^{infeas}=-500	14 -18278	-873	0 -16130	16 -18197	-492	0 -16130 23 -16854	0 -19091	-500	0 -16130 23 -16854	25 -19949	-465	274	0 -16130 23 -16854
C1 S^{infeas}=-200	11 -17071	-128	0 -16130	19 -18302	-201	0 -16130 17 -16525 18 -16627 19 -16730 21 -16834	110 -16410	-4213	0 -16130 17 -16525 18 -16627 19 -16730 21 -16834	52 -14318	-245	344	0 -16130 17 -16525 18 -16627 19 -16730 21 -16834
C1 S^{infeas}=-100	13 -17099	-90	0 -16130	13 -15410	-155	0 -16130	45 -13739	-99	0 -16130	65 -13022	-139	262	0 -16130
C1 $S_{\text{o}}^{\text{infeas}}$=-500	14 -18278	-873	0 -16130	16 -18197	-492	0 -16130 23 -16854	35 -19081	-395	0 -16130 23 -16854	27 -19209	-390	274	0 -16130 23 -16854
C1 $S_{\text{o}}^{\text{infeas}}$=-300	12 -17193	-279	0 -16130	16 -17883	-188	0 -16130 18 -16618	38 -16682	-200	0 -16130 18 -16618	51 -12937	-219	265	0 -16130 18 -16618
C1 $S_{\text{o}}^{\text{infeas}}$=-100	13 -17099	-90	0 -16130	24 -15786	-134	0 -16130	45 -12428	-92	0 -16130	49 -13764	-32	262	0 -16130
C1+D1 $S_{\text{o}}^{\text{infeas}}$ =-200	**11 -17071**	**-128**	**0 -16130**	**19 -18199**	**-201**	**0 -16130 17 -16525 18 -16627 20 -16678 21 -16884**	**113 -13591**	**-343**	**0 -16130 17 -16525 18 -16627 20 -16678 21 -16884**	**57 -14713**	**-101**	**347**	**0 -16130 17 -16525 18 -16627 20 -16678 21 -16884**
C2+D2 max_iter_opt =50 max_iter_feas =25	**11 -17071**	**-128**	**0 -16130**	**19 -18199**	**-201**	**0 -16130 17 -16525 18 -16627 20 -16678 21 -16884**	**18 -20087**	**-127**	**0 -16130 17 -16525 18 -16627 20 -16678 21 -16884**	**42 -17631**	**0**	**445**	**0 -16130 17 -16525 18 -16627 20 -16678 21 -16884 33 -19369 38 -19407 39 -19504**
C2 max_iter_opt =50 max_iter_feas =50	11 -17071	-128	0 -16130	29 -14412	-16	0 -16130 17 -16525 18 -16627 19 -16730 20 -16782	58 -16244	-14	0 -16130 17 -16525 18 -16627 19 -16730 20 -16782	35 -18934	-265	230	0 -16130 17 -16525 18 -16627 19 -16730 20 -16782
C2+MP3+ MOBJ1 max_iter_opt =75 max_iter_feas =50	**11 -17071**	**-128**	**0 -16130**	**36 -14708**	**-17**	**0 -16130 25 -17183 26 -17285**	**19 -20050**	**-184**	**0 -16130 25 -17183 26 -17285**	**50 -18374**	**-96**	**400**	**0 -16130 25 -17183 26 -17285 27 -19651 33 -20022 35 -20230 37 -20335 38 -20439 39 -20545**
C2 max_iter_opt =75 max_iter_feas =75	11 -17071	-128	0 -16130	36 -14708	-17	0 -16130 25 -17183 26 -17285	32 -19070	-201	0 -16130 25 -17183 26 -17285 37 -17913 39 -17918 40 -18162 41 -18212	40 -17416	-15	300	0 -16130 25 -17183 26 -17285 34 -17323 35 -18048 40 -18162 41 -18212
C3	11 -17071	-128	0 -16130	41 -14096	-23	0 -16130 25 -17183	47 -18865	-174	0 -16130 25 -17183 39 -18208 41 -18308	43 -18565	-152	515	0 -16130 25 -17183 39 -18208 41 -18308
MOBJ2	18 -16754	-237	0 -16130	36 -13912	-141	0 -16130	20 -17332	-267	0 -16130	29 -17289	-153	273	0 -16130
MP1	17 -18329	-174	0 -16130	52 -14409	-125	0 -16130	31 -18500	-226	0 -16130	54 -17438	-103	380	21 -17169
MP2	13 -16634	-385	0 -16130	35 -12305	-3	0 -16130	20 -19530	-200	0 -16130	22 -18142	-726	344	0 -16130 6 -17302 7 -17534 9 -17404
MP4	13 -17285	-192	0 -16130	28 -16564	-7	0 -16130	23 -17986	-182	0 -16130	44 -16320	-806	399	0 -16130 10 -16157 12 -16519 13 -16691

Table 7.2: Experiments for Adapted Tabu Search Optimisation - Swines Data Instance

	iter=50			iter=100			iter=200			Stopping Condition			
	$S^{current}$	S^{infeas}	S^{inc}	$S^{current}$	S^{infeas}	S^{inc}	$S^{current}$	S^{infeas}	S^{inc}	$S^{current}$	S^{infeas}	iter	S^{inc}
C1 S^{infeas} =-500	1021 -4327	-500	1071 -4064	1037 -4131	-576	1051 -3372 1071 -4064	973 -3844	-502	1051 -3372 1071 -4064	990 -3534	-500	263	1051 -3372 1071 -4064
C1 S^{infeas} =-205	1065 -4866	-6	1071 -4064	1044 -5515	-316	1066 -4630	1018 -3253	-2023	1066 -4630	1047 -1664	-214	335	1066 -4630
C1 S^{infeas} =-100	1051 -4928	-542	1071 -4064	1049 -4926	-101	1062 -4209	1034 -4266	-148	1061 -4016 1062 -4209	1006 -1347	-442	365	1061 -4016 1062 -4209
C1 S^{infeas}_{o} =-500	1021 -4327	-500	1071 -4064	927 -1572	-576	1051 -3372 1071 -4064	927 -1572	-421	1051 -3372 1071 -4064	926 -1699	-411	263	1051 -3372 1071 -4064
C1 S^{infeas}_{o} =-250	1019 -5308	-225	1071 -4064	1048 -3897	-291	1071 -4064 1059 -3799	1079 -4795	-273	1071 -4064 1059 -3799	1044 -2731	-1	479	1044 -3069 1056 -4348
C1 S^{infeas}_{o} =-100	1051 -4928	-542	1071 -4064	1040 -4679	-253	1062 -4209	970 -5087	-5235	1058 -3959 1062 -4209	983 -1272	-494	262	1058 -3959 1062 -4209
C1+D1 S^{infeas}_{o} =-205	**1065 -4866**	**-6**	**1071 -4064**	**1045 -4844**	**-401**	**1066 -4630**	**1018 -4511**	**-191**	**1061 -4240** **1066 -4630**	**1035 -2130**	**-10**	**362**	**1042 -2062** **1061 -4240** **1066 -4630**
C2+D2 MOBJ2 +MP3 max_iter_ opt=50 max_iter_ feas=25	**1065 -4866**	**-6**	**1071 -4064**	**1045 -4844**	**-401**	**1066 -4630**	**1032 -4529**	**-32**	**1044 -4472** **1045 -4763**	**1037 -4437**	**-270**	**349**	**1041 -4873** **1049 -5425**
C2 max_iter_ opt=50 max_iter_ feas=50	1065 -4866	-6	1071 -4064	1066 -4488	0	1066 -4630	1024 -4299	0	1024 -4375 1066 -4630	1063 -3873	0	277	1024 -4375 1024 -4729
C2 max_iter_ opt=75 max_iter_ feas=50	1065 -4866	-6	1071 -4064	1059 -3522	0	1059 -3922 1071 -4064	1013 -4739	-193	1059 -3922 1071 -4064	1029 -3905	0	211	1029 -4123
C2 max_iter_ opt=75 max_iter_ feas=75	1065 -4866	-6	1071 -4064	1059 -3522	0	1059 -3922 1071 -4064		n/a		1028 -4363	-279	167	1059 -3922 1071 -4064
C3	1001 -6006	-230	1071 -4064	1029 -6030	-112	1054 -3599		n/a		1011 -6018	-161	198	1035 -4870
MOBJ2	1001 -5914	-198	1071 -4064	1031 -5258	-132	1056 -4739		n/a		1028 -4225	-34	195	1041 -5255
MP1	1038 -2710	-329	1071 -4064	1017 -3385	-222	1062 -3553 1071 -4064	1036 -1504	-321	1062 -3553 1071 -4064	1054 -2499	0	218	1062 -2499 1062 -3553 1071 -4064
MP2	1003 -5924	-205	1071 -4064	1019 -4749	-118	1029 -4551	977 -4275	-182	1016 -5160	999 -4047	0	203	999 -4047 1016 -5160
MP4	1001 -5914	-198	1071 -4064	1026 -5393	-136	1021 -2806 1055 -3614 1064 -3975 1065 -4870 1067 -4983 1069 -5020	1073 -2752	-81	1021 -2806 1049 -3254 1055 -3614 1064 -3975 1065 -4870 1067 -4983 1069 -5020 1070 -5263	1071 -555	0	214	1021 -2806 1049 -3254 1055 -3614 1064 -3975 1065 -4870 1067 -4983 1069 -5020 1071 -5263

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