KTH Industrial Engineering
and Management

Energy Modeling for an Eco-City with focus on Biogas Potential

Johanna Siewert Delle

Anton Julin

Bachelor of Science Thesis
KTH School of Industrial Engineering and Management
Energy Technology EGI-2013-XX
SE-100 44 STOCKHOLM

KTH Industrial Engineering and Management	**Bachelor of Science Thesis EGI-2013** **Energy Modeling for an Eco-City with focus on Biogas Potential** Johanna Siewert Delle Anton Julin	
Approved 2013-05-07	Examiner Catharina Erlich	Supervisor Omar Shafqat
	Commissioner	Contact person

ABSTRACT

The Sino-Swedish Eco-City in Wuxi is the result of a collaboration between the Chinese local government and several Swedish stakeholders aiming to create a sustainable urban infrastructure comprising environmentally conscious energy systems. The purpose of this report set forth is to investigate in how biogas production can be integrated into a possible energy system of this eco-city.

This report groups the proposed energy system into three parts: the collection of organic waste from the city residents, the production of biogas at a central facility and the transformation of the biogas into an applicable form of energy. Technologies that are investigated and analyzed according to set learning objectives of this report, are the Envac vacuum system and the food-waste-disposer for the collection phase, the anaerobic digestion process for the production phase, in addition to the Combined-Heat-and-Power plant and the refinery plant for the transformation phase. In order to fully elaborate the energy system of this report, both a conceptual model as well as a simulative model have been created.

The final suggestion brought forward for the composing of the appropriate energy system for the Sino-Swedish Eco-City includes the Envac vacuum system in the collection phase, an anaerobic digestion process in the production phase and a Combined-Heat-and-Power plant for the transformation phase. However, the discussion regarding the validity of the results has highlighted the possibility of expanding the biogas system to encompass a larger area than only the Eco-City. Enabling users from the surrounding areas to connect to the energy system may create incentives for the use of a refinery plant instead of a CHP plant. The final results of the model showed a potential capacity for biogas production of 600 000 m^3 which in turn could be transformed into either 380 000 m^3 or 1 280 MWh electricity and 1 900 MWh heat.

Kandidatarbete EGI-2013

KTH Industrial Engineering and Management

Energisystemsmodellering för en miljöstad med fokus på biogaspotential

Johanna Siewert Delle

Anton Julin

Approved	Examiner	Supervisor
	Catharina Erlich	Omar Shafqat
	Commissioner	Contact person

SAMMANFATTNING

Med det gemensamma målet att skapa en hållbar, urban infrastruktur med nytänkande energisystem, skapades det svensk-kinesiska initiativet att bygga en miljö-stad i Wuxi i Kina. Med bakgrund av detta samarbete som initierades av den kinesiska regeringen och ett flertal svenska intressenter, har denna rapport som övergripande ändamål att undersöka hur produktion av biogas kan på bästa sätt integreras i ett möjligt energisystem i denna kinesiska miljö-stad.

Rapporten delar in det föreslagna energisystemet i tre olika delar: Uppsamling av organiskt avfall i staden, produktion av biogas på en central anläggning samt omvandling av biogas till mer användbara energi-former. I linje med de utsatta målen för denna rapport, har ett flertal teknologier undersökts och analyserats. För uppsamlingsdelen undersöktes vakuumsystemet Envac och avfallskvarnen, för produktion av biogas undersöktes rötningsprocessen samt för omvandlingsdelen undersöktes kraftvärmeverket och uppgraderingsverket. För att på ett underbyggande vis kunna utveckla det föreslagna energisystemet har en konceptuell modell tagits fram i kombination med en simulerad modell.

Det slutgiltiga energisystemet som föreslås för den svensk-kinesiska miljöstaden i Wuxi innehåller vakuumsystemet Envac för insamling av organiskt avfall, rötningsprocess i tankar för produktion av biogas samt ett kraftvärmeverk för produktion av värme och elektricitet. Dock har diskussionen i denna rapport möjliggjort ett annat tänkbart scenario där produktion av biogas till biobränsle, framför elektricitet och värme, skulle vara fördelaktigt, om möjligheten till större dimensioner och fler användare i systemet fanns. De slutgiltiga resultaten av modellen visar på en kapacitetspotential för biogasproduktion på 600 000 m^3 som kan användas till att antingen generera 380 000 m^3 biobränsle alternativt 1 280 MWh elektricitet och 1 900 MWh värme.

Table of Contents

List of Figures

List of Tables

NOMENCLATURE

Throughout the report these variables and definitions will be in use, and the symbol and unit of each variable or definition is explained here.

Name	Symbol	Unit
AD residence time	R	days
American dollar	-	$
Amount of organic waste in the city	W_o	kg/year
Amount of raw biogas produced	B_{raw}	m^3/year
Amount of sewage waste in the city	W_s	m^3/year
Biogas distribution to CHP	B_{CHP}	%
Biogas distribution to refinery	B_{ref}	%
British pound	-	£
Density of organic waste	d_o	kg/m^3
Efficiency of AD-plant (Food)	η_o	%
Efficiency of AD-plant (Sewage)	η_s	%
Efficiency of CHP-plant (electricity)	η_{chp-el}	%
Efficiency of CHP-plant (heat)	$\eta_{chp-heat}$	%
Efficiency of refinery plant	η_{ref}	%
Efficiency of similar technology without CHP	α	**%**
Effective electricity efficiency	ε_{EE}	**%**
Energy	I, H	kwh
Energy content of raw biogas	e_b	kWh/m^3
Heating value	ht	Btu/unit
Length	m	meters
Mass	m	kg
Methane leakage factor	M_{loss}	%
Net useful power output (CHP technology)	W_E	MW
Net useful thermal output (CHP technology)	$\sum Q_{TH}$	MMBtu/hr
Normal volume of gas	-	Nm^3

Organic waste per person	w_o	kg/person
Overall CHP system efficiency	η_{CHP}	%
Population	P	#
Pressure	-	bar
Sewage waste per person	w_s	m^3/person
Sludge content of sewage	s_s	$m^3_{sludge}/m^3_{sewage}$
Temperature	-	C^o
Total fuel energy input (CHP technology)	Q_{FUEL}	MMBtu/hr
Upgraded biogas	$B_{refined}$	m^3
Variation	V	Distribution factor
Volume	-	m^3

ABBREVIATIONS

Anaerobic Digestion	AD
Biochemical Oxygen Demand	BOD
British Thermal Unit	Btu
Chemical Oxygen Demand	COD
Combined-Heat-and-Power	CHP
Food-waste-disposer	FWD
Gross Domestic Product	GDP
Gross-Domestic Product	GDP
Key Performance Index	KPI
Natural Gas Vehicle	NGV
Operation & Management	O&M
Pressure Swing Absorption	PSA
Purchasing Power Parity	PPP
Revolutions per minute	RPM
Separate Heat-and-Power	SHP
Sino-Singapore Tianjin Eco-City	SSTEC
Sino-Swedish Eco-City	Eco-City
STELLA simulation program	STELLA
Swedish krona	SEK
The Royal Institute of Technology	KTH

PREFIX

Name	**Symbol**	**Size**
Giga	G	10^9
Mega	M	10^6
Kilo	k	10^3

1 INTRODUCTION

1.1 Background

The industrial revolution of the 19th and 20th centuries reflects a time period where people discovered groundbreaking designs and machinery that enabled the society to enter a path into a world of expanding auto-mobilization and urbanization. The combination of new industries, major construction progresses and an increasing consumption created a world with endless possibilities. However, this progress came with a price. Moving into the 21th century it becomes painfully clear that we have to acknowledge how our discoveries and developments in the past affect our present and our future. We have to improve our structures in several sectors of the society, so that new design and innovations are accomplished in a sustainable way. The awareness regarding sustainable solutions is increasing amongst corporations and consumers, and the amount of environmentally friendly alternatives is speeding up in several regions of the world as we move into the new century. However, the concerns regarding the sustainability status of the world today are several, and there are still many problems to solve if the size of the society's urbanization and industrialization is to continue to expand at this speed.

One issue that is of particular concern is the risk that the world's natural resources might not be sufficient for the future generations to come, due to an ever-increasing population in several regions. One country facing significant population increase over the next fifty years is China. The forecasted shift from people living in rural areas to urban environments is substantial, and it is of great importance that the shift can be handled in a sustainable way. A given solution already undertaken by several countries facing the same situation in addition to China is the building of eco-cities. Eco-cities are created with the ambition to minimize their environmental impact through the use of clean energy, energy efficient technologies and prioritizing alternative energy sources. This sustainability mission is undertaken without affecting the level of living standards for the inhabitants, and as an extension, their quality of life.

Inspired by the innovative green initiative of modern living exemplified in Hammarby Sjöstad in Stockholm, Sweden, a new eco-city[1] is commissioned for construction in the eastern part of China. Serving as a suburb to Shanghai, is the city of Wuxi where an eco-city will be built in the city district of Taihu New District. It will be called the Sino-Swedish Eco-City ("Eco-City") and will not only be a superior showcase of modern clean technologies, but as well offer contemporary housing for both Chinese and foreign professionals.

The building of the eco-city was initiated with the collaboration between the Chinese and Swedish government in addition to the support from several stakeholders, such as The Royal Institute of Technology ("KTH") in Sweden and several corporations. The project aims to build a city area that can serve as a role-model platform of sustainable technologies and innovation with the use of state of the art systems for energy efficiency. Where similar earlier green city

[1] *Referring to the sustainable city, where infrastructure, inhabitants and technologies are designed in order to minimize energy usage, greenhouse gas emissions and increase energy efficiency and thus minimize the overall negative environmental impact.*

projects may have failed to either create a profitable infrastructure or inhabit their residential areas, this Chinese eco-city ambitions to achieve a long-term sustainable foundation whilst staying economically viable. This is much due to the advantageous geographical location and the careful considerations undertaken in how to form the energy systems and subsystems of the city.

When planning an eco-city, there are several factors contributing to the future success of the city. It is important to include the structuring of the actual energy systems, create scenarios with different parameters and select superior solutions and technologies. For the Sino-Swedish Eco-City in Wuxi a sampling of possible solutions for different subsystems must be analyzed, tested and evaluated in order to contract the right actors for the actual building.

The range of sustainable technologies and renewable energy sources available today is far from satisfying. There is still substantial development needed and further innovation sought for the creation of a future sustainable city benchmark. Smart grid, solar cells, wind power plants and cars running on electricity are a few examples of the many technologies that can be utilized in an eco-city, however the sustainability solution of particular interest to the subject of this report is the possibility to be energy efficient through the production and use of biogas. Biogas is a less conventional choice of fuel that creates less negative impact on the environment and the climate when integrated in the energy systems of a city.

The value chain for biogas production starts with collection. Collection of biomass materials from several sources is undertaken in order to use each source in the best way possible. Next, the waste material goes to the production phase, and it is at this stage the actual biogas is produced. After separating useful outputs of the generated gases and residues, a transformation of the biogas must be performed. Several cities, serving as show-cases within this area, have refined the whole value chain among their inhabitants and industrial actors in order to create an energy system that is cyclical – where people use electricity and heat that is generated from their own garbage.

1.2 Purpose

The overall purpose set forth is to:

Investigate how biogas production can be integrated into an energy system of a Chinese eco-city.

1.3 Learning objectives

In order to achieve the purpose stated above, the following learning objectives are set fourth.

- Investigate the potential for biogas production as a sustainable energy source to be used in the Sino-Swedish Eco-City;
- Determine relevant system boundaries in order to investigate the sustainablility as well as the economical perspective;

- Suggest an innovative way of structuring a value chain where the city's waste management is interconnected with biogas production;
- Add to the energy system by evaluating appropriate application technologies on how to use the biogas; and
- Build a supportive model in the simulation program STELLA; by
    - Illustrating a qualitative mode; in addition to
    - Simulating a quantitative model showing a given set of scenarios.

2 LITERATURE STUDY

2.1 Energy systems

"A system isn't just any odd collection of things. A system is an interconnected set of elements that is coherently organized in a way that achieves something." (Meadows, 2008)

Almost everything in the world around us can be seen as a system. A bathtub that is being filled with water can be regarded as a system. A dog, a school or a wastewater facility is a system. What is relevant is to define what elements are included in the system, how they are interconnected to one another and finally, what the purpose of the system is (Meadows, 2008). In this specific chapter, the system definition will help in defining and describing the energy system that will be relevant information for subsequent analysis of this report. In addition to a more general description of an energy system, the chapter will also include the more quantitative way of describing a system, by introducing systems dynamics. Systems dynamics is a renowned methodology use to understand complex systems by simplifying various variables as well as introducing specific terminology.

2.1.1 Introduction to energy systems

When describing an energy system, a predominantly frequent way of defining it is by mentioning its three main parts; production[2], distribution and usage. Raw fuels (e.g. wind, biomass, coal or oil) are initially gathered for the generation of energy, which can subsequently be either stored or distributed, before finally reaching the end-user. However, even though only describing it in a relatively general manner, an error can already be detected. The system is still a system, but a clever reader might see that the choice of raw materials, largely affects how the energy system will come to behave. If coal or oil is chosen for a specific energy system, the actual rate of extraction of these sources will come to decide how fast the source will be completely exhausted. By this distinct difference between choice of energy source for an energy system, another definition can be derived; the definition of the renewable energy system.

The renewable energy system refers to an energy system where the source for energy production is completely renewable and the system sustainable over time. Sources such as wind, heat from the sun and biomass can be extracted time after time, and the only delay in the process depends on the length of the generation cycle. As for the sources of the sun and wind, the rate at which energy can be extracted is mainly affected by weather conditions and our own technology. In cases where the source is biomass products, the rate at which energy is produced is mainly driven by at which rate the trees or the plants can grow again.

Another concept of an energy system is the sustainable energy system. In this case, the requirements of what can be called a sustainable energy system are multiple. Criteria for the production part can be factors such as achieving a higher efficiency and the existence of a

[2] *Throughout this paper the term production will refer to the generation of energy carriers and therefore not contradict the first law of thermodynamics which states that energy can be neither destroyed nor created*

renewable energy source being in place. When examining how the energy is distributed, the system is sustainable if it can show smaller energy losses in transition phases as well as minimization of negative impact on surrounding nature when distributing. Finally, from the usage perspective, factors such as energy efficiency and technologies that have low energy demand are rewarded. (World Wide Fund for Nature, 2011)

From a global perspective, it is becoming increasingly obvious that the need for constructive sustainable energy systems is more important than ever. As described in chapter 2.2 on eco-cities, it is largely due to a growing urbanization, however, other factors not relating to the growing proportion changing from rural to urban areas, are equally creating this need. The world's non-renewable energy sources will not be enough for all future generations to come, and additionally they are affecting the global climate of today in a negative way. The traditional energy sources such as coal and oil have for decades been the subject of discussion regarding if they will run out, however the discussion relating to their negative impact on our atmosphere and climate is also highly alarming. The ambition to increase energy production from the world's renewable energy sources is high on several political and economical agendas.

By defining the energy system and that of the sustainable energy system, the reasons for establishing eco-cities might have been further strengthened. However, the definition stated above only gives a qualitative description of how a system works, and especially how the energy system works. In order to create a wider image of how the system works, the next chapter will investigate in the phenomena of systems thinking and systems dynamics.

2.1.2 Systems dynamics

As stated in the learning objectives of this report, the answer to whether there is potential for integration of biogas production in the Sino-Swedish Eco-City, is of both qualitative nature as well as of quantitative. First, a qualitative energy system must be formed, adjusted and adapted for the Sino-Swedish Eco-City's conditions with clarification of which elements are within the system borders and which are not. Second, in order to understand if this energy system can be environmentally efficient as well as economically viable, it is crucial to underpin any arguments for the energy system with some quantitative measurements. In order to generate these measurements, the internal system dynamics must be investigated.

When aiming to create several scenarios of how a certain system may function, one will gain from creating a general model of the system. This model can be then be changed and adapted by changing different parameters and interconnections to simulate different scenarios. As they say of perfect teams, a system is more than the sum of its parts (Meadows, 2008). As with system dynamics models, they are described to explore possible futures and can be used to ask different questions regarding different outcomes. *"Model utility depends not on whether its driving scenarios are realistic, but on whether it responds with a realistic pattern of behavior"* (Meadows, 2008).

The reason system dynamics is a valuable resource for this specific report, is because it sees systems as a defined set of components, which can be adapted, changed or adjusted for different scenarios. This will be helpful when examining the energy system for integration of biogas production in the Sino-Swedish Eco-City. In addition, the systems dynamics terminology and structure is closely correlated to the way that systems thinking is undertaken in the STELLA simulation program. When achieving a quantitative model in the STELLA program, different components are necessary in the building of a model that defines inputs, outputs and formulas. For a more elaborate description of the system dynamics a terminology presentation is necessary and can be seen below. In addition to this, the simulation process in STELLA for this report will be discussed further in chapter 3 and 4.

According to Meadows, the terminology of systems dynamics includes the following definitions: (Meadows, 2008)

System	A set of components that interacts and forms a pattern over time with a predestined function or purpose
Stock	Stock is material or information that is being accumulated over time, increasing or decreasing depending on inflow's size versus outflow's size
Flow	Information or material leaving or entering the stock
Dynamic Equilibrium	When all inflows equal all outflows and the stock is un-changing under a period over time
Feedback loop	Depending on the level of the stock, the feedback loop is a closed chain of causal connections from the stock that changes the stock due to different feedback and information.
Linear relationship	A set of events that are proportional to each other over a given period of time.

2.2 Eco-cities and sustainable urbanization

This chapter describes the increasing global urbanization of today and explains how a sustainable approach to the problem might solve many of the issues regarding the use of natural resources in urban areas. The chapter introduces the definition of the eco-city followed by the description of the increased Chinese need for sustainable urbanization because of its current significant urban growth. The chapter then exemplifies the phenomena of the eco-city with two case studies; the Sino-Singapore eco-city of Tianjin and the Swedish sustainability initiative in Hammarby Sjöstad.

2.2.1 Definition of an eco-city

With more than a decade into the 21st century, it is obvious that the world's history of rural living is about to alter, and at a significant speed. The world's urban population growth is set to double to around 4.9 billion in 2030, triggering the world's urban areas to triple in size between

2000 and 2030 (Engineering News, 2012). While acknowledging that half of today's population already lives in cities (Engineering News, 2012), it is obvious that the approaching transition between rural and urban conditions is deemed to require a few changes in how we see urban living today. One of the present approaches towards handling the alarming increase in urban areas that is most distinguishable is the one promoting sustainable urbanization with eco-cities. With several eco-cities around the world already built, or commissioned to be built, and technology continuously moving forward, environmental as well as economical solutions are constantly improved.

The definition of what constitutes an eco city is reasonably wide, yet a few descriptions are more frequently used than the others. The eco-city can be referred to as a completely sustainable city system, where infrastructure, inhabitants and technologies are designed in order to minimize energy usage, greenhouse gas emissions and increase energy efficiency. All these efforts will minimize the overall negative impact on the city's surroundings. Another way of defining the eco-city approach is to observe it as a system of its own, where a majority of its need of natural resources is meet by its own bioregions (Ecocity Builders, 2011). The eco-city should strive towards implementing and maintaining systems and ways of living that do not generate more waste, or use more energy than it can assimilate or reproduce by itself (Ecocity Builders, 2011).

However, the realization of an eco-city includes far more considerations than the purely environmental ones. In order to create synergy between the actual urban living and that of sustainable living, one must acknowledge the economic and social dimension as well as the environmental (Rapoport & Vernay, 2011). When handling extensive decision-making regarding how to establish an eco-city, all three dimensions must be fairly considered. Building an eco-city involves several stakeholders that all may have dissimilar ideas in how to plan the city's sustainable technologies, building design and economical governance.

Returning to the initial discussion on how to define the eco-city, the more conceptual approach to eco-cities is the possibility to use it as a model to illustrate the implementation of innovative solutions. Many of today's eco-cities in the post-building phase have gained significant attention worldwide and several models of eco-city systems show a modern and refreshing way of thinking and building sustainably. However, with this approach it is fairly obvious that the environmental dimension obtains the most attention, with technologies and processes that has the ability to inspire other eco-city initiatives. Especially for the eco-cities built in Hammarby Sjöstad, Sweden, Dongtan, China and Malmö, Sweden it has been clearly obvious that the environmental parameters has been the dominant ones (Rapoport & Vernay, 2011).

2.2.2 Drivers for Chinese eco-cities

With more than half of the world's population living in urban environments, precautions as well as immediate actions have been taken worldwide to ensure a future sustainable agenda to preserve our natural resources. Considering that a majority of the urban growth is emerging in developing countries, it is evident that it is in these regions that environmental measures need to be incorporated in urban projects at an early stage. A clear example of a region in need of further sustainable efforts is China. Since 1978, experiencing the greatest migration from rural to urban living, China has doubled its urban population rate and by the end of the last decade, the country has more than half of its inhabitants living in cities (Hald, 2009). Urbanization is presently of high priority for the Chinese government and the rapid growth process brings many opportunities for new technologies and improvements (Hald, 2009).

Looking at the last few decades, immense changes can be seen in Chinese development. Realizing that the last twenty years have brought significant increase in social benefits and economic growth has caused the Chinese government to understand that it comes with an environmental price tag on it (The Climate Group, 2012). In order to create a sound growth for towns that go from small rural neighborhoods to large-scale cities, the solution may come in the form of sustainable cities. The drivers for China to implement an infrastructure and technology that promotes sustainability are several, however three main areas will be discussed further in the following paragraphs; First, China needs to improve its overall national energy efficiency level, followed by an aim to lower its coal dependency and finally find effective ways to handle the country's increasing problems with waste management. (Hald, 2009; The Climate Group, 2012)

Introducing the Chinese problem regarding inefficient energy use, the obvious coupling is with the Chinese dependency on oil and coal. China is considered the largest energy consumer in the world, and a majority of this energy is traced back to being produced mostly by coal or oil (U.S. Energy Information Administration, 2012). Being just after the United States, China is the second-largest consumer of oil as of 2009. Running out own their own natural resources, China is also becoming increasingly dependent on foreign oil imports (U.S. Energy Information Administration, 2012). In combination with its oil consumption, China produces and consumes more coal than any other country in the world. These numbers present a substantial challenge for China, both in decreasing its coal-and oil dependency as well as in integrating an energy usage system that has a higher efficiency rate.

Another issue connected to China's vast coal and oil usage is the hazardous pollutants that accompany this use of resources. Out of the twenty most polluted cities in the world, China is home to 16 of them. The pollution in combination with environmental degradation is serving China a national cost equivalent to 8 to 12 percent of GDP per year (Hald, 2009). In addition to these figures, Chinese air and water quality is decreasing, combined with China being the third most problematic region regarding acid rain (China following North America and Europa), (Hald, 2009).

The final area in need of a sustainability makeover is the Chinese waste management. The country's increasing population implicates major waste management problems and insufficient processes in handling such amounts. Roughly two-thirds of Chinese cities dispose more garbage than what their infrastructure can handle resulting in significant landfill issues (Hald, 2009).

Summarizing all environmental alarm clocks presented above for the Chinese region leads to the following conclusion; In order to motivate and stabilize the growing urbanization and population in China today, the government and the country's corporations need to meet the growing demand for sustainable city solutions. By integrating different stakeholders such as the government, national and international corporations, researchers and educational facilities, China has the potential to ease off the negative development in energy production and consumption and to step up towards becoming a future role model for sustainable urbanization. Chinese eco-cities are already becoming a reality and they demonstrate that urbanization is possible without interfering negatively on the environment and thus show that urban growth and development can be a sustainable process (Hald, 2009).

2.2.3 The Sino-Swedish Eco-City in Wuxi

Not far from the big city of Shanghai in Eastern China, is the city of Wuxi. Inspired by the modeling and design of eco-city Hammarby Sjöstad in Stockholm, Sweden, Wuxi has assigned an area of 2,4 square kilometers in its city district of Taihu New District, to be the location for a completely new showcase of modern and sustainable living. The agreement for building the eco-city was signed in July 2010, and formed as collaboration between the Wuxi government and several Swedish stakeholders (Yanfeng, 2011). Due to its characteristics with prominent dual interests, the eco-city in Wuxi is named the Wuxi Sino-Swedish Eco-City ("Eco-City"). The ambition is to create an eco-city that serves as both a role-model flagship for eco-cities as well as an educational showcase for future peers (Yanfeng, 2011). The Eco-City is destined to be the home for approximately 20 000 inhabitants (Fulco, 2011).

The fact that this Sino-Swedish initiative has been taken, and subsequently commissioned for construction, is by no means a surprise. With China being Sweden's second largest export market for environmental technology it is clearly a beneficial deal for both parties. Especially Swedish technology for renewable energy and city planning services has been contributing to the Chinese sustainability focus (Fulco, 2011). The Eco-City in Wuxi will in addition to the Swedish technologies, use the best systems and processes available in order to create an urban environment that is minimizing its negative environmental impact without affecting the quality of the city's residents.

Although the project is in its initial phase, many of the goals and targets for its success are already clearly defined. The integrated system of sustainability that the Eco-City forms, will go beyond only including facilities and also come to comprise the awareness of sustainability with the people living in it. A large chunk of what the eco-city can achieve has do to with how much the people living in it understand and embrace the mission that the city is set out to fulfill. An example that can be given will be that of the Eco-City's transportation. The plan is to assign eighty percent of the total commuting in the area to public transport, and by doing so, encouraging the residents to travel by buses or trains in order to lower total emissions. Roughly fifty percent of the transportation vehicles are set to run on renewable energy sources (Yanfeng, 2011). Another goal for the Eco-City that is exemplifying the local inhabitants cooperation is that of local waste management. In order to effectively handle all the city household waste, pipelines will be installed (see more in section 2.3.3.1) in a thought-through network in the city infrastructure. By educating and promoting sound recycling and proper discharge of household organic waste and combustibles, the systems can work in a superior way, were energy, gas and other rest products can be extracted from the waste (Yanfeng, 2011).

As mentioned earlier, many believers and collaborators of the Sino-Swedish Eco-City claims that this Wuxi installation will be an outstanding example of a modern Chinese eco-city, unlike any of its prior peers. Yet, when stating such a proclamation, one must be able to justify why. Considering not everyone believes in keeping an eco-city completely environmentally friendly at the same time as being economically viable, it is preferable to be able to define what it is about this eco-city that makes it original. Presently China lacks a system of evaluation standards in the environmental sector and it is important to ensure that eco-cities create substantial results, and not only become guidelines and formalities (Yanfeng, 2011). It is justified to regard the eco-city development in China as being in its preliminary stage, where regulations, standards and more mature system has to back up the innovation and technologies planned for further eco-city projects. However, the Sino-Swedish Eco-City does stand out due to its collaboration with KTH.

Sponsored by the Swedish Energy Agency's STEM program, KTH is included in the Sino-Swedish Eco-City project as a stakeholder that will contribute solutions within the area of energy efficiency and sustainability. The results and technologies that will be included in the showcase will further strengthen the idea of the Eco-City as a hotbed for innovation development and large-scale implementation (Department of Energy Technology KTH, 2012). Collaborators at KTH describe their involvement as two main parts; (i) Analyzing the eco-city as an energy system using a systems thinking approach (see section 2.1.2); (ii) Focusing on innovation diffusion in the context of urban environments.

The first part is further described as the idea to analyze the energy system and then fractionate the system into several subsystems. KTH will also perform qualitative and quantitative analysis that can create dynamic models, explaining systems and projecting different scenarios for the Eco-City. Secondly, the innovation diffusion part includes the investigation of different stages of innovation in eco-cities processes (Department of Energy Technology KTH, 2012; DECC, 2013).

2.2.4 Case-Studies

Two case studies have been conducted as apart of this report; Firstly the Eco-City of Hammarby Sjöstad, Sweden is presented and secondly the Eco-City of Tianjin, China.

2.2.4.1 Eco-city of Hammarby Sjöstad

Short facts - Located in the southeast part of Stockholm lies the city district Hammarby Sjöstad. Serving as both an inspirational platform for sustainable urbanization as well as a home and work place for about 35 000 people, Hammarby Sjöstad spreads out over 1,6 km^2 of land (Cederquist, Facts and Figures on Hammarby Sjöstad, 2009). The Hammarby Sjöstad district includes both areas of 290 000 m^2 for office space, as well as room to several residential areas comprising 10 800 apartments. The projected number of actual inhabitants is 24 000 people for 2017, where there will be an average of 2,27 persons per apartment (Cederquist, 2009).

History of the project - Compared to several capital cities of Europe, Stockholm has for a long time developed modern ways of building, living and overall thinking environmentally friendly. Perhaps it was no surprise that the Hammarby Sjöstad project became such a success story, considering its basis of planning, structuring and creating of bold visions that started back in 1990 (Fränne, 2007). The city district that had the advantages of being close to the water inlets of Stockholm in addition to the challenges of being an old industrial- and harbor area, was originally also considered the Stockholm ambition to be the host of the Olympic Games 2004 (Stockholm Stad, 2013). The idea was to develop an area suitable for both the actual games as well as presentable to all the media that the commerce will bring.

Hammarby Sjöstad never hosted the Olympic Games, however it did become the hotbed for sustainable innovation that was needed to add further fuel to the surrounding world's efforts in handling its growing urbanization. Through the project of building Hammarby Sjöstad, strict guidelines were applied to all choices concerning which materials to use, which machines to install as well as what components to build the transport infrastructure with (Fränne, 2007). In 1997 the official environmental program was defined, and this was also in the same time as proper handicap installments were carried out (Cederquist, 2013). The Hammarby Sjöstad project is also considered unique due to its initial integrated planning phase. Where other large-scale construction projects might involve different stakeholders at different, multiple stages in time in a project, the project team of Hammarby Sjöstad took on a different approach. With the ambition to integrate the ideas and opinions of the relevant building managers, architects, politicians, environmental experts and engineers, they were all included in the initial discussions and workshops of the project. This way, Hammarby Sjöstad could at an early stage be clearly conceptualized and therefore continue to fulfill the visions that was originally set out. (Cederquist, 2013)

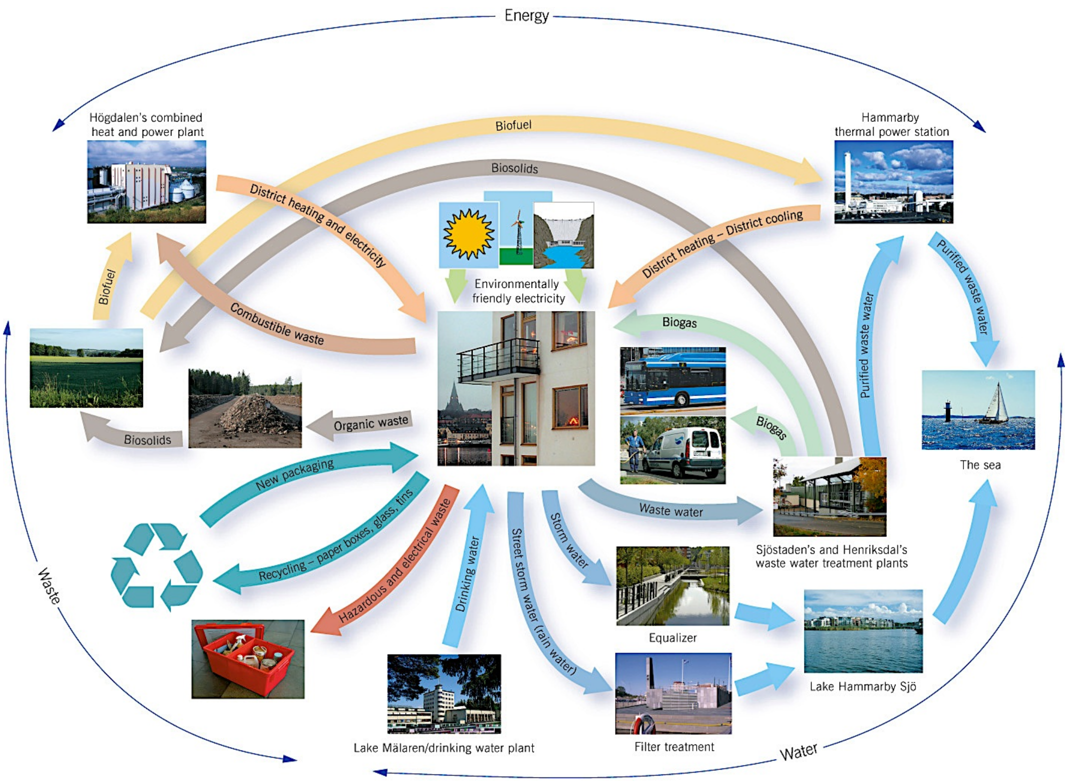


Figure 1 – The Hammarby Sjöstad model as depicted 2007 (Fränne, 2007).

The Hammarby Model - As a result of the efficient way of integrating all stakeholders in the planning process of the project, Hammarby Sjöstad could subsequently illustrate their very own eco-cycle. Simply called the Hammarby Model, the model shows the different ways that all included processes and facilities interconnect with each other – one subsystem's output becomes another subsystem's input. This way all processes are linked to another and it all works in a cyclical route to bring back input stock to the people living in Hammarby Sjöstad.

Renewable energy for electricity – One of the main environmental goals for the Hammarby Sjöstad project was to ensure that the local residents would produce half of the energy that they need. In order to satisfy this goal, several renewable energy sources have been applied to the energy system in addition to efficient reuse of waste heat, biogas products and improved energy efficiency in buildings (Fränne, 2007). The city district has deployed both solar cells and solar panels at the top of its buildings, where the effect might not satisfy the entire energy need of the building's residents, however it is an educational tool in demonstrating the method and partly also test the technology. The majority of the energy consumption will be traced from elsewhere. Firstly, as the Hammarby Sjöstad Model illustrates, both combustible waste and organic waste will be sorted, treated and then burned in Högdalen's combined heat-and-power plant (for more on CHP, see section 2.5.1). The CHP plant will generate both electricity and district heating, that will partly make its way back to the inhabitants of Hammarby Sjöstad (Fränne, 2007). Secondly, the model shows how another subsystem will serve as producer for both district heating and district cooling. The input for this system will be in the form of the city district's wastewater. As a part of the wastewater treatment process, the water will be purified at the Henriksdal wastewater treatment plant then transported to the Hammarby heat plant for the final production (Fränne, 2007).

Intelligent pipeline network for waste management – A vital part on any environmentally thinking process, recycling and waste separation must be considered. The Hammarby Model shows how, after separating hazardous waste and electrical waste, the waste in the forms of plastics, glass, paper, carton and metallic can be transported to a facility for proper recycling. Waste is no longer just something that people dispose of and extract from the system – in contrary it is an important source of energy. The waste management of Hammarby Sjöstad is advanced in its ambition to make use of every different form of waste, yet still simple for its users. All waste generated by the residential areas of Hammarby Sjöstad is separated and then disposed in three different units (combustible, organic, paper mass). With the ambition to save energy and emissions from unnecessary transport vehicles collecting rubbish at multiple stations, Hammarby Sjöstad have employed a mobile collection of their waste. Using a pipeline system developed by the company Envac (read more on Envac in section 2.3.3.1), the waste will be transported with vacuum suction to central collection points. The waste is gathered to sufficient amounts for export to the recycling plant.

Biogas serving many purposes – When examining the Hammarby Model one can conclude that the production of biogas is a phenomenon the city district is well oriented with. The model shows the subsystem where residents' organic waste can be digested and its rest products used for several applications. After the anaerobic digestion ("AD") (read more on AD in section 2.4), rest products are used as fertilizer and the actual biofuel is subsequently used in a combined-heat-and-power facility. Hammarby Sjöstad is also involving the production of biogas in its wastewater treatment system. At the Henriksdal facility, both biogas for end-users and biogas for transport fuel are generated (Fränne, 2007).

2.2.4.2 Eco-city of Tianjin

Short facts - The large cities of Tianjin and Beijing are located in the Chinese region of Bohai Bay. Serving as one of the major growth engines in China, this region is significantly increasing in number of inhabitants. As the circumstances might disclose, it is an area subject to future development in how to handle the growing number of people moving to the larger cities. Zooming in further, to the region of Tianjin Binhai New Area that where the Sino-Singapore Eco City of Tianjin. With a city area of thirty square kilometers, the eco-city is located 40 kilometers from the Tianjin City Centre, and 150 kilometers from the large city of Beijing. The eco-city was initiated due to the same reasons as many other green cities as a way of handling the growing urbanization in China in a sustainable way. The city is the second collaboration between Singapore and China resulting in an eco-city. Before the Tianjin eco-city, was the Suzhou Industrial Park. The Sino-Singapore Eco-City of Tianjin was commissioned for construction in 2007, after the Singapore senior Minister Goh Chok Tong and the Chinese Prime Minister Wen Jiabao decided to combine their urbanization agendas. The city is projected to be fully finished in 2020, with a total population of 350 000 inhabitants (Government of Singapore, 2013).

History and planning of the project - The official beginning of the eco-city project took place when China and Singapore decided upon the collaboration in 2007. A couple of months after, in October 2007, the search for potential regional candidates generated four plausible regions; Tianjin, Tangshan, Baotou and Urumqi. A month later, Tianjin was selected and a Framework Agreement was signed by related parties for the execution of an eco-city to be built in Tianjin. From then up until now, the actual process has been including several Joint Working Committee meetings, where related parties, such as politicians, engineers and building companies have been deciding upon relevant key performance indicators ("KPI's") for the Tianjin Eco-City, and in 2008 the Master Plan was worked out on a meeting in Singapore (Government of Singapore, 2013).

The actual developer of the Tianjin Eco-City is the Sino-Singapore Tianjin Eco-City and Development Co., Ltd ("SSTEC"). Due to the collaboration's equally weighted influence on the project, SSTEC was formed as a joint venture between a Chinese Consortium led by Tianjin TEDA Investment Holding Co. Ltd, and a Singapore Consortium led by the Keppel Group. (SSTEC, 2011). Sharing the ownership equally, between them, this collaboration represents the part of the project relating to the private sector. In combination with this is the public sector involvement, as of the agreements between the Singapore government and the Chinese government, deciding on equally plausible regulations and requirements for the city (Government of Singapore, 2013)

At the start of the project, the further planning on the city focused on the adequate proportion of attention to the land-use, transport issue and the Green and Blue network planning (Government of Singapore, 2013). First, the land-use was to be compact and serving as a good mix of different land-usages. It was especially important to ensure that local amenities, jobs and urban city areas was closely located to where the residents where to live.

Second, was the transport initiative to create a sustainable transport infrastructure, where green transport was highly valued, and all forms of public transport, walking or bicycling was made important issues when planning the actual space for motorized and non-motorized roads. Third, the ambition of the Green and Blue network planning was to create a substantial amount of green vegetation at the core of the city. As a metaphor it was supposed to symbolize a green lung in the middle of the city, subsequently creating green corridors throughout to the city periphery. In addition to this, a water network, creating circulation of water was designed. The existing wastewater pond was to be rehabilitated and created into a fresh water pond again (Government of Singapore, 2013).

A city of eco-cells - An especially interesting aspect of the structure of the Tianjin Eco-City is their choice of dividing their city into something called Eco-cells. The function of the system is that it creates a benchmark for how to measure size and inhabitants of different dimensions in the city. The Tianjin Eco-city is made up out of four Eco-districts. Each Eco-district comprises several Eco-communities. The Eco-community includes about 9 000 dwelling units ("DUs" *describes the residential unit predominantly made for residential living.*) Fragmenting the city further is the fact that the Eco-community includes four Eco-cells. Each Eco-cell contains 2 500 DU's which holds for roughly 8 000 residents. An image of the city structure made up out of Eco-cells is illustrated in Figure 2 (SSTEC, 2011).

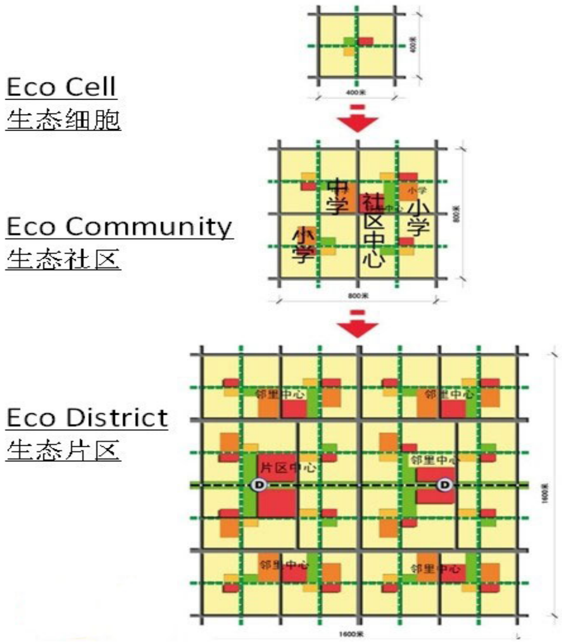


Figure 2 – Tianjin Eco-City is made out of eco-cells. The Eco-city consists of four Eco-districts (SSTEC, 2011).

A city of values - The Tianjin Eco-City and the goals it emphasizes are not only about preserving natural vegetation and water bodies in the ambition to create an environmentally sustainable urban living solution. The pronounced vision of the city is to be; *A thriving city which is socially harmonious, environmentally friendly and resource-efficient – a model for sustainable development* (Government of Singapore, 2013). As one may detect, the part about being a city that is also socially harmonious is of equally big importance to the people stating the original plan of the eco-city. The social responsibility and sustainability of the city can be summarized in two aspects; the Three Harmonies and the Three Abilities (Government of Singapore, 2013).

The Three Harmonies focus on how the people live in harmony with each other as well as with the economic activities occurring in the city. It should also be harmony in the way the residents and the city's business relate to the environment in which they house and act. Following are the Three Abilities, which argue for the importance of having a city where the sustainable technologies and systems work in the peoples' favor, by being practicable and easy-to-use. In order to fulfill its purpose, everybody using the technologies must feel able to understand how they work and for what good. The next ability is for the city's principles and models to be replicable. As for all equations and experiments in science and engineering, all instructions must be able to be copied and then giving the identical result. More practically speaking, this means that more cities can learn from and remake the Tianjin Eco-city structure in other regions. Last, the ability for the principles and systems are to be scalable. They must be functioning whether the dimensions are larger or smaller than the original sizes (Government of Singapore, 2013).

All of the Tianjin Eco-City's arguments for keeping high standards on social responsibility as well as that of the environment make for high expectations on its city leaders and especially on its inhabitants.

2.3 Collection of waste

This section investigates the different characteristics of waste management. It begins with explaining the general definition of waste and waste management, followed by discussing the many benefits extracted from keeping a well-structured waste management. The section finishes with describing the two waste collection techniques that are chosen as suitable technologies for the objectives of this report. The techniques are the Envac vacuum system and the food-waste-disposer ("FDW").

2.3.1 Waste management

Waste management can be defined in numerous ways, however it is often the term waste that needs further clarification. Waste is more than just a by-product and it is not until it is seen as a separate entity that it can be handled as one with proper routine and management. UN defines waste as *"materials that are not prime products or which the initial user has no further use in terms of his/her own purposes of production, transformation or consumption, and of which he/she wants to dispose."* (United Nations, 1997).

After the initial definition of the term, waste can be separated into different categories. Each category has its own characteristics and therefore need to be handled in different ways. The most distinct waste categories are hazardous waste, municipal waste and bio-medical waste. (European Parliament, 2008) The point of interest for this report is municipal waste, which also can be broken down into the groups household, commercial and demolition waste. As a way of narrowing the scope further, the municipal waste that will be studied is organic and biodegradable waste. Biodegradable waste is waste that can be fragmented and decomposed by microorganisms during a certain period of time (European Commission, 2012).

When examining how a waste management system works it initially seems as if the focus is on which standards that the system should uphold. The European Union has its own definition of what criteria an effective management system should meet: "*It requires that waste be managed without endangering human health and harming the environment, and in particular without risk to water, air, soil, plants or animals, without causing a nuisance through noise or odors, and without adversely affecting the countryside or places of special interest.*" (European Parliament, 2008)

This statement from the EU covers the standards of what a waste management system must uphold. It encompasses the usual human, water and environmentally related aspects, but also mentions especially the countryside and areas of special interest. With definitions like this, unacceptable waste management is singled out, such as simply mounting up waste at urban landfill sites without acknowledging nearby surroundings and effects of the waste. As mentioned in previous quote, special consideration must be taken for the environment and the creatures living in it, and this consideration may often dictate the techniques used.

Options for waste management (Smith et al., 2001):

- Landfill- *the heaping and burial of waste*
- Incineration- *the burning of waste for energy production*
- Recycling- *the collection and re-use of waste products*
- Composting- *the natural decomposition of materials*
- Anaerobic digestion- *the breaking down of biodegradable waste with the use of microorganisms (for more see Anaerobic Digestion in section 2.4)*
- Mechanical biological treatment- *a prolonged composting process*

Since the Eco-City is located in the rapidly growing country of China, a certain increase in waste is expected. China experiences significant economic development and has the third largest GDP in terms of PPP after the United States and the European Union. (Themelis, 2010) This growth will increase the living standards in China and can results in an increased consumption of goods. With this growing consumption follows even greater amounts of waste that must be disposed of. In 2004 China managed to surpass the United States as the world's largest waste generator and is projected to generate twice as much as the United States by the year of 2030 (Hoornweg & Bhada-Tata, 2012).

2.3.2 Benefits of waste management

The benefits extracted from keeping a well-structured waste management system can mainly be found in three areas; the economical, social and environmental areas of the society. The economic benefits focus on the actual money saved or earned from having an implemented waste management system. The social aspects refer to how waste planning can contribute to better living conditions and simplify everyday life for the users. The final and probably the most significant benefit that is generated when keeping a responsible waste management system is the environmental impact on society.

Economically there is much to be gained through the use of integrated waste management system. When the waste transports, costs and investment are optimized funding needed for vehicles can be decreased. The British municipalities saved a significant amount of government money when installing food waste disposers in the homes of the British people. The money that could be saved equaled to £19 per installed unit per year (Insinkerator, 2012). Waste management can also be made further profitable due to the products and services that the waste can produce when handled correctly. E.g. are the production of biogas and the extraction of fertilizers, in addition to subsequent generating of heat and electricity (Themelis, 2010).

Apart from the pure economical benefits there are also major social incentives. An innovative system can simplify everyday tasks including taking out the trash and the sorting of recyclables. It is easily taken for granted however it is much thanks to a functional management system for waste that a society can enjoy a clean and healthy environment. Towns and cities can also benefit from the positive marketing that a well-planned waste management system can generate.

Environmentally, the benefits are mainly the prevention of negative aspects linked with badly kept waste management. Problems such as air pollution, emissions of greenhouse gases, contamination of water bodies and depletion of non-renewable resources are problems, which are made worse when adding the issues of irresponsible waste disposal. With the help of careful planning and installation of an effective waste management system, these negative affects can be minimized and in some cases eliminated altogether.

2.3.3 Collection techniques

The previous section made it clear that the collection of waste has great impact on the subsequent utilization of the waste for more profitable purposes. The focus of this report is directed towards to techniques that are hypothesized to be the most suitable choices for the waste collection process of the Eco-City. The first technology is the Envac system, which has already been approved for implementation in the Eco-City (Shafqat, 2013). The other technology of interest is the food waste disposer, which can be placed in the sink of the household and simply grinds down all organic leftovers. Even though the Envac system is chosen for implementation, it is still not certain that the system will be the main technology for the collection of organic waste. In this report the two technologies will be compared and discussed separately.

2.3.3.1 Envac system

The Envac system is a waste management system that utilizes the power of vacuum pipes to optimize the waste collection process. The suction process operates through transportation of the waste from local chutes through underground pipes to central collection terminals. At the central terminals the waste is then compressed before being collected in order to save space and time during the collection process. These pneumatic stationary systems use a built up vacuum pressure to efficiently move the waste to the desired location. This pressure is built up with the help of fans that pump out air before the transportation occurs. When enough waste has been built up, the valve at the individual collection sites are opened which creates a flow of air from the individual sites to the central collection station. (Envac AB, 2009)

The stationary vacuum system can handle different types of waste simultaneously, such as organic, combustible and paper waste. Every individual waste flow has its own chute meaning that the different waste types are emptied individually. A central station can handle between two and four different waste types within the same collection pipes. (Envac AB, 2009) At the central stations the waste flows are emptied into separate containers automatically. Since the waste flows occur at separate intervals the system can ensure that the waste is properly sorted into the correct containers as long as the sorting at the collection sites has been done correctly.

History - The first waste suction system was installed in 1961, when the entrepreneur Olof Hallström from the company Centralsug AB integrated it into the Sollefteå Hospital in Sweden. Inspired by the central vacuum systems used for dust collection, Hallström asked himself if the same could be done with household waste. The system at Sollefteå Hospital is still in use today with many original parts still intact. Only four years later the first suction system for residential purposes was installed outside of Stockholm. (Envac AB, 2013)

Today the company once founded by Olof Hallström has changed its name to Envac AB and has expanded throughout the world. Envac AB has 35 offices in 20 countries around the world, ranging from Europe to Asia and Australia. The offices are divided into four geographical divisions: North Europe, South Europe and the Americas, Middle East and India, Asia Pacific and Australia (Envac AB, 2013).

The collection cycle - The collection cycle is initiated when the fans are put into operation, creating a vacuum in the system of pipes. Simultaneously, the hydraulic unit in the compactor and the rotating screen on the separator are started (Envac AB, 2009). Next the air valves for the first type of waste are opened, creating a forceful airflow throughout the pipes. A regulatory system regulates the speed of the air in order to ensure a secure transportation.

When the correct airspeed has been reached the valves to the actual waste are opened. Gravitation combined with negative pressure ensures that the waste falls down into the pipe system and is then transported to the central stations. These valves are then closed before the valves for the next type of waste is opened and the process is repeated. When all sorts of waste have been collected the sequence is repeated at all the individual sites. (Envac AB, 2009)

At the central stations the air is separated from the waste through a cyclone type separator and a rotating screen. (Envac AB, 2009) Gravitation forces the waste to fall from the separator screen down into the waste-compression unit. Organic waste is blown directly into containers because it is considered to already have a sufficient density. When the containers are full a signal is sent to either the central control system or the personnel at the station. (Envac AB, 2009)

Operation – The operation of the system is almost fully automated. Under normal operation the system is in no need of human supervising or assistance. At the central terminal a computer controls and handles the collection cycles. The collection process is repeated two to five times a day depending on the amount of waste and the installed chute capacity (Envac AB, 2009).

The collection process varies in length depending on the size of the system. It can last for 15 to 20 minutes for small systems, 30 to 60 for medium systems and up to 2 to 3 hours for large systems (Envac AB, 2009). In between cycles the system is in a state of rest but this does not mean that waste cannot be emptied into the chutes at the local site.

Limitations:

- Bulky waste - *furniture, refrigerators, etc.*
- Flammable objects or substances
- Rigid objects - *Stones, iron scraps, etc.*
- Sponge-like objects - *objects that can swell and create* blockages
- Odorous articles - *feces, bodies of house pets and rats, etc.*
- Chemicals - *Acidic and alkaline solution, paint, adhesives, etc.*
- Highly moist waste.

(Envac AB, 2009)

Benefits - The Envac system aims to reduce the emissions of greenhouse gases through several measures. First it is enabled thanks to the reduced usage of collection trucks where gas emissions are avoided. With conventional waste management these trucks are forced to drive to each individual site for collection at which they are also required to lift and empty the waste collectors. This fairly unnecessary routine can be avoided when the waste is transported to central stations where it is collected only when the containers are filled and the collection process consists only of one lift. The Envac technology is also environmentally friendly due to its non-existent dependency of fossil fuels. The machinery uses less energy than conventional waste management systems and can run on electricity, which preferably can be extracted from renewable energy sources. (Envac AB, 2009)

Apart from the environmental benefits that the system ensures, Envac also brings various social benefits to the community in which it is installed. Trucks are deemed unnecessary to carry out the collection process, which leads to a decrease of noise and pollution throughout the streets of the society. With the elimination of collection by trucks there no need to make the residential area accessible to heavy vehicles. This contributes to a more efficient urban planning and more desirable residential area. In addition to this, the fact that all chutes are sealed and that the transport is carried out underground ensures that less odors associated with waste are eliminated.

Table 1 - Area needed for various types of the Envac system. (Envac AB, 2009)

No. of households	One waste fraction	Two waste fraction	Three waste fraction
8 500	150-200	350-400	500-600
6 000	100-130	200-250	300-400
< 3 000	50-75	100-150	180-230

2.3.3.2 Food disposer in sink

The other collection technique chosen for investigation is the food waste disposer. This is a system that grinds up the organic waste directly in the sink of the user. After the waste has been grinded into minute pieces, it is released into the regular sewage system of the residential area of the house. This enables the organic waste to be treated at a nearby waste water treatment plant. This procedure greatly increases the possibility to collect sludge for subsequent production of biogas. (Avfallskvarn AB, 2011)

History – It was originally the engineer John W. Hammes who built the garbage disposal system. Hammes later created the company InSinkErator and made the system available on the market in 1940. (Insinkerator, 2012) The system is installed in many of the homes in the United States and it is estimated that ninety million units have been installed during the last thirty years (Avfallskvarn AB, 2011). It is seen as a necessary kitchen appliance rather than a recycling tool in addition to making the regular kitchen duties more convenient.

Operation - An FDW can range in size and strength depending on the area of application. There are systems designed for industrial use and those designed for household use (Disperator AB, 2003). Domestic units usually range from 250 to 750 W in power (Insinkerator, 2012).

The unit uses a high torque electric motor that can be either inductive or have a commutator. Inductive motors rotate at 1 400 to 1 800 RPM and are characterized by low starting torques while commutator motors operate around 2 600 RPM and are usually noisier due to the higher speeds (Avfallskvarn AB, 2011). Systems with more power can operate at lower speeds while sustaining a high quality of grinding as well as leading to quieter operation.

It is often believed that the FDW works like a food processor with spinning blades that chop the material into smaller bits. Actually a FDW features a spinning turntable with impellers that force the waste outward. Around the turntable is a grind ring against which the waste is pushed. The grinding teeth of the grind ring grinds down the food until it is small enough to pass through the small openings of the ring (Bernstad et al., 2013). Some high-end units have a blade beneath the turntable used to chop up stringy waste that can cause blockages.

The system requires running water during operation to prevent blockages (Disperator AB, 2003). It is recommended that the water is of a fairly cold temperature in order to both help with the cooling of the process but also to prevent fats getting stuck in the pipes (Avfallskvarn AB, 2011).

The system can operate using two different methods, the continuous and the batch method (The Home Depot Inc., 2011). The continuous model operates with a continuous grinding process while a batch model is filled up and then grinds the content that has been loaded. A batch model is slightly more expensive but has the advantages of quieter and safer operation (Avfallskvarn AB, 2011). This model is recommended for households with children or where there is an increased risk for dropping objects into the grinder during operation. In the continuous system, waste can be continuously added to the grinder while in operation.

There are many different accessories that can be added to standard units to increase their performance and areas of use. There is a connector that can connect the disposer to the dishwasher making it possible to wash dishes with large amount of food on them without risk for blockages. Another attachable accessory is a sound isolator cover. It dampens noise and can be easily attached with rubber connectors that reduce the transmission of vibrations (The Home Depot Inc., 2011).

Benefits - The FDW has been proven to increase the waste sorting performance of individual households (Insinkerator, 2012). People usually lack motivation to properly separate their food waste from other types of waste, which can result in less desirable results. The FDW makes the process of sorting the waste several steps shorter and by that significantly easier. Installation of the FWD can decrease a household's waste left over to landfills by twenty percent (Avfallskvarn AB, 2011). This leads to fewer emissions of greenhouse gases and a more sustainable society where more waste is recycled. This may lead to an increasing amount of biogas produced at the water treatment plant to where the sewage water is transported. This is due to the fact that the organic waste is mixed up with the sludge and the total energy content of the separated substrate is increased, when food waste has a higher energy content than sewage (BC Farms, 2010).

Another benefit for the end-user is that the FDW is extremely simple to use and there is no need for a separate waste bin for organic disposals. Having a bin for organic waste is usually connected with fowl smells from the digestion process. With an FWD this problem is removed because the waste is processed and transported away directly (Insinkerator, 2012).

The negative side effects are not many and range from the excess water use that is required and the energy cost for operation. The increased water use is estimated to be around five to ten liters per day, which depending on the area can be more or less influential. The energy costs are also dependent on the local conditions but in a Swedish setting they amount to around three SEK per year (Avfallskvarn AB, 2011).

2.4 Production of biogas

This section aims to introduce the process of anaerobic digestion, where gas is recovered from the decomposition of organic mass. First, the chemistry behind the process is described and an in-depth look into the four different phases is undertaken. Following is an explanation of which sources of biomass are available for AD and the different advantages and disadvantages connected to each of them. The next section is of high relevance and includes the presentation of the techniques for AD and their characteristics. Last, is a look into the outputs of the process, including the rest products and their applications.

2.4.1 The chemistry of anaerobic digestion

AD is the process of using bacteria in an environment absent of oxygen in order to decompose organic material for the production of biogas. This process utilizes naturally occurring bacteria and has no need for artificial additives. The feedstock e.g. organic material is fed into a sealed digester-tank where the decomposition occurs for varying amounts of time. This digestion process is called residence time, and varies from ten days up to forty days depending on the type of feedstock and technique used (The Wales AD Centre, 2010). The resulting biogas consists of around thirty percent carbon dioxide and sixty percent methane along with other rest products. The process can be simplified into this generic chemical equation: (WTERT, 2009)

$$C_6H_{12}O_6 \rightarrow 3CO_2 + 3CH_4$$

Aside from the production of biogas, residues comprising digestate and wastewater are produced. The wastewater can easily be treated and fed back into the water system. The digestate is the remaining solid material that has not been broken down during the digestion process. Rich in minerals the digestate can also be treated for several minor toxins and then be used as fertilizer for farming purposes. (WTERT, 2009)

The anaerobic process can be divided into four stages. Although separate, the stages occur simultaneously and are deeply dependent on one another to function. Although the stages occur simultaneously, techniques exist where the stages are separated into different phases and are carried out in separate tanks (Severn Wye Energy Agency, 2012).

The first stage of the process is *hydrolysis*. In this stage water is added to the mixture in order to break down the chemical bonds of fats, carbohydrates and protein to form sugars, fatty acids and amino acids. The next stage begins where the products from the hydrolysis in the stage of *acidogenesis* are broken down. In this stage the sugars, fatty acids and amino acids are broken down into carbon dioxide, hydrogen, alcohols and organic acids including acetate. Some of these outputs can go directly to stage four but several alcohols and organic acids need further decomposition, for example propionate butyrate and ethanol. These substances need to go through the process of *acetogenesis* and be degraded into acetates before they can be uses as substrate for the methane-forming bacteria in stage four. In the final stage, called the *methanogenesis*, methanogenic bacteria produces methane which is the final product of the process (Severn Wye Energy Agency, 2012). The methane is however not the only constituent of the actual end product, the biogas comprises several other gaseous components.

The overall process of anaerobic digestion is a fairly sensitive process, which requires a pH ranging from 7.5 to 8. However, the acidity of the mixture is self-regulated through the natural production of calcium carbonate, which stabilizes the reaction. In order to prevent the process from becoming stagnant from lack of source material for the different stages, the mixture must be continuously stirred (Severn Wye Energy Agency, 2012).

2.4.2 Sources of organic substances

As mentioned in the section above, it is the choice of feedstock or input of organic material that affects the efficiency of the process. The key factor for biogas production is the level of putrescibility or the digestibility, which carries a direct correlation to the gas yield (Vandevivere et al., 2003). Sources of organic matter can range from city sewage waste to the rest products of large-scale food manufacturers to crop leftovers from farms.

The exception to all organic materials, which can be broken down, is wood waste. Woody materials contain the complex chemical compound lignin that is completely unaffected by the digestion process. However, lignin can be degraded either by the use of xylophalgeous anaerobes or high temperature pretreatment, such as pyrolysis (Severn Wye Energy Agency, 2012). However, this method is considered ineffective and costly.

Another naturally recurring type of waste is human excretion. This waste is collected through the sewage system and often treated on site at the water treatment plants (BC Farms, 2010). The equivalent waste collection for animal manure occurs at agricultural sites where a local digester processes the organic substance. However, both human and animal excretions do not withhold the greatest potential for biogas production simply due to that a living organism has already processed it. The animal or human body has extracted as much energy as possible from the organic material and there is therefore little energy left.

To optimize the production of biogas, producers often try to create a mixture of slurry with other materials with higher energy content (Gray et al., 2008). This dramatically increases the gas yield of the digester. For example a feedstock containing only cow manure can produce between 15 to 20 kW, but by adding 25 percent off-farm food wastes the gas yield can be increased to between 60 to 70 kW (BC Farms, 2010). This is illustrated in **Error! Reference source not found.**, which isplays the varying gas yields per ton feedstock. There are even producers that have a production of crops with the sole purpose of enabling their biogas production.

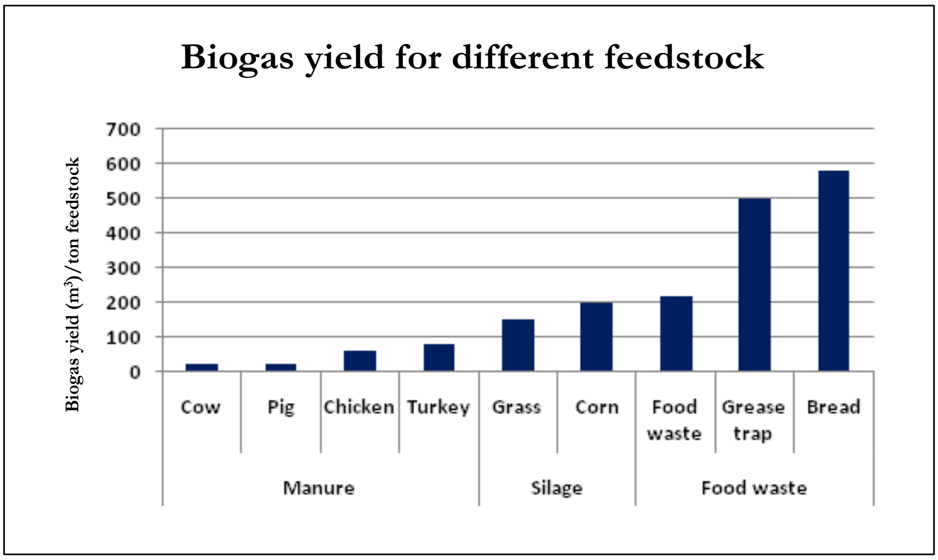


Figure 3 - Biogas yield for different feedstock. (BC Farms, 2010)

Another factor that must be taken into consideration when choosing the suitable feedstock is the moisture content of the feedstock. If a producer aims to maximize the organic material in the digest, water is unnecessary and contributes no added gas yield. However, the water and the moisture content contribute with other necessary advantages. As stated earlier, the feedstock should be stirred in order to increase the efficiency of the chemical reactions occurring in the digester. This procedure is necessary because the phases of the process are reliant on the corresponding outputs as well as the inputs. High moisture content simplifies this process because of the lubrication effect it provides. Having solely solid content in a digester would make it nearly impossible to mix without expending huge amounts of energy.

Another area where the moisture content is vital is the transport of the feedstock. Having high moisture content makes transport in pipes feasible for transferring the feedstock into and out of the digester and in some cases between digesters. This is in contrast to having a feedstock made up of only solids where energy intensive techniques, such as concrete pumps must be used to transport the material. Another aspect to consider when choosing appropriate input materials is the ratio of carbon content to nitrogen content. An excess of nitrogen can lead to ammonia inhibition of the digestion process. (Richards et al., 1991)

2.4.3 Processing techniques

Different techniques can be used to affect the gas yield of the process. These techniques differ in certain variables such as temperature, complexity, moisture content and residence time. In this following section the advantages and drawbacks of the different methods will be discussed.

Batch vs. Continuous - The digestion process can be designed to function using batch processes or through a continuous flow of material. These two techniques both have drawbacks and advantages that must be taken into consideration for each specific case.

In the batch process the reactor is loaded once and not unloaded until the end of the entire digestion process. This technique is similar to traditional landfill techniques but differs due to the higher temperature and continuous leachate recirculation process. This produces fifty to one hundred percent higher gas yields than in traditional landfills (Vandevivere et al., 2003). The batch process itself can then be split up into two categories of single batch and sequential batch.

For the single batch process all the material is stored in the digester until no more gas is produced. An organically rich leachate is produced during the process, which is collected and heated before being redistributed to the digester (WTERT, 2009). This method is used instead of mixing the feedstock to make sure that all the components needed in the different stages are always readily available.

Alternatively the leachate from a mature digester can be spread over a new batch until it has begun to produce its own rich leachate. This process is known as sequential batch because of the different stages the batch can find itself in. The three main stages are the new, mature and old stage. Once the fresh feedstock has started production of leachate it is considered to have reached the mature state. Here the leachate is recycled over itself like in the single batch process. When the production of biogas begins to slow the batch has reached the final stage and the leachate is used to set a new batch into motion. This more effective utilization of residence time means that more production of biogas is possible compared to the single batch technique (WTERT, 2009).

The demand for digesters with higher efficiencies is increasing due to availability of land being further limited. With land limitations becoming increasingly more essential the demand for even more effective digesters is high. Although batch techniques are simple and easy to implement, commercial plants most often use continuous flows of feedstock. Approximately ninety percent of all full-scale plants operating in Europe are continuous one-stage systems (Bouallagui et al., 2004). In a continuous system the feedstock is fed constantly, and simultaneously it is removed to create a continuous flow of the bio waste. The inflow may not in practice be continuous in the sense that the pumps are always operating; instead the pumping process may occur daily or more frequently (Wang et al., 2003). This system requires high internal fluidity both for inflows and outflows as well as for the mixing process, and it is therefore best suited for feedstock with low solid.

Mesophilic vs. Thermophilic - Another variable that has effect on the digestion process is the temperature at which the system operates. The temperature zones can be divided into two main groups, thermophilic and mesophilic. Thermophilic digestion occurs in the temperature range of fifty to sixty °C whilst mesophilic ranges from 30 to 40 °C (The Wales AD Centre, 2010). The two temperature zones depend on the different methanogens or microorganisms that are used for the digestion of the organic material. There have been experiments in colder conditions in both Bolivia and Alaska. In the Bolivian example the digestion process occurred naturally at ten °C but was slowed by a factor of three compared to a normal mesophilic reaction (Herrero, 2007). The Alaskan example used phychrophilies, harvested from a frozen mud lake, to produce methane with temperature conditions near 0 °C (Gupta, 2010). These examples illustrate that it biogas production is possible at other temperatures but most effective in the stated intervals.

Mesophile digesters outnumber the thermophile digester and are more tolerant of changes in the environmental conditions. Mesophilic reactions are therefore considered to be more stable. Thermophilic digesters are thereby more sensitive to faulty conditions such as temperature variations and excess amount of nitrogen. Nitrogen rich feedstock can result in inhibition of the digestion process in thermophilic processes (The Wales AD Centre, 2010).

Thermopilic systems result in faster reaction rates and therefore shorter retention times. As well as quicker reactions the process also extracts more energy from the biomass while simultaneously killing more pathogens in the process. Although a benefit, this greater pathogen kill rate is not always important. If the residues are pasteurized as part of the treatment process this benefit becomes insignificant. An aspect that needs to be taken into account is the energy necessary to heat the thermophilic reaction. Calculations should be done in each particular case to assess the energy balance and net benefit of using a thermophilic process.

Single vs. Multistage - The process of anaerobic digestion can vary in complexity in the production process. One of the simpler techniques is the single-phase digester. In this technique the four stages of digestion take place in one reactor simultaneously. These reactors have the advantage of being simple to operate and have a relatively low investment cost (WTERT, 2009). The retention time of this technique varies from 14 to 28 days (Verma, 2002) depending on the feedstock and temperature, which has been discussed in previous sections.

The digestion process can also be split into different stages to better utilize the space and energy of the system. This multistage process cleans and centrifuges the incoming pulp to separate the solids from the liquid (WTERT, 2009). The liquid is ready to go directly to the methane reactor because the organic material has already gone through the hydrolysis stage. The solid material is mixed with water once again in order to initiate the hydrolysis process. After two to four days this mixture is dewatered and the resulting liquid is ready to be fed into the second reactor where the methane is produced. The methane production takes around three days to complete which results in a total residence time of approximately seven days (WTERT, 2009).

Table 2 - Comparison between single-stage and multi-stage for an anaerobic digestion process. (WTERT, 2009)

Operation parameter	Single stage	Multistage	
	Digester	Hydrolysis	Methanization
Retention time	14-16	2-4	3
T (° C) Mesophilic	37	37	37
T (° C) Thermophilic	55	-	-
Biogas (m^3/Mg)	80-90	110-130	
Methane content (%)	60-65	30-50	65-75
Heating value (MJ/m^3)	22-25	22-25	

As can be seen in Table 2 - Comparison between single-stage and multi-stage for an anaerobic digestion process. The multistage process displays significantly better results than the single stage process. The table compares multi and single stage digestion processes by fixing variables that enables a more accurate display of their differences. The multistage process has twice the turnover as that of the single stage process making it much more space efficient for a required flow of bio waste. The biogas production is also greater in the multistage process with a forty percent higher biogas yield per ton of bio waste. The heating value is equivalent between the two mainly because of the low methane content in the gas produced during the hydrolysis stage. However, the biogas produced in the methanization stage of the multistage process has higher methane content than that of the gas produced in the single stage process. This means that due to the fact that the gases are separate, the methane rich gas can be used for enrichment purposes like transport fuels and the gas with low methane content can be used for more crude purposes like heating.

2.4.4 Usage of residues

Apart from the biogas produced, there are two other main products that are being generated in the AD process. After the digestion process is complete, a sludge-like mixture is left in the tank. When separated, either through a centrifuge or through a press, two products are left separated from the gas; a digestate and wastewater.

Depending on country-specific regulations, the direct use of digestate is regulated. In many countries the digestate is required to undergo the process of pasteurization before it is allowed for the use as fertilizer.

Digestate content differs depending on the source of feedstock used in the digestion process. The important nutrients present in digestate are nitrogen, phosphate and potash (WRAP, 2013). In food-based digestate eighty percent of the nitrogen present is readily available. This means that it could be used as a direct replacement to conventional nitrogen supplements. Animal slurry' digestate has a lower nitrogen content ranging from 45 to 60 percent. The anaerobic process will increase the amount of available nitrogen by about ten percent (WRAP, 2013). As for phosphate, around fifty percent will be readily available in the year of application. Phosphate is essential for living things and is often a limiting nutrient in the growth of crops.

Digestate is a great substitute to commercially sold fertilizer because these are often produced from fossil fueled processes and carries a significant carbon footprint (Severn Wye Energy Agency, 2012). The reliance on fossil fuel prices also means that the product is sensitive to price fluctuations.

The second residue constituting wastewater must be treated before being released out into the local water network. It may contain elevated levels of biochemical oxygen demand ("BOD") and chemical oxygen demand ("COD") resulting in algae growth etcetera. This is treated through oxidation where oxygen is passed through the water (Dosta et al., 2007).

The decomposing of organic and sewage waste through anaerobic digestion enables the production of raw biogas. When reaching a certain level of scale, the amount of biogas generated can subsequently be used as appropriate fuel in other transformation purposes. The next chapter of the literature study of this report explains the two main usage areas for the raw biogas in the Eco-City; biogas as fuel in the system of a CHP plant, followed by the upgrading of biogas in a refinery plant.

2.5 Transformation of biogas

After the production of raw biogas in the anaerobic process, focus is shifted to the application and utilizations of the resource. In this section two post-production techniques for biogas will be highlighted and investigated. The first is a Combined Heat and Power plan (CHP) where both heat and electricity are produced. Here the heat that is generated during the production of electricity is captured and distributed to different applications leaving little or no by-products. The other technology that will be considered is the upgrading of raw biogas where the biogas is refined to increase the methane concentration. The upgrading process is necessary to make biogas applicable for vehicle fuels and gas grid integrations. The section will also discuss other solutions that are considered plausible, though in less depth.

2.5.1 Combined-Heat-and-Power

2.5.1.1 Introduction to Combined-Heat-and-Power

Combined-Heat-and-Power ("CHP") is a technology that in a single constellation integrates the simultaneous production of both thermal and mechanical power. By being a specific form of distributed generation of energy, the CHP technology is a more efficient and customized form of energy production compared to central station generation (EPA, 2008). When serving to generate power or supply the heating or cooling needs of the consumer, the CHP technology is advantageous due to its ability to recover the waste heat that is simultaneously produced. The CHP technology utilizes the heat and therefore requires less fuel than traditional systems that have separate constellations for thermal and mechanical power generation. (Shipley et al., 2008).

The CHP system consists mainly of four parts; a prime mover, generator, heat recovery and electrical interconnection. However, when characterizing the most common types of CHP systems, there are two distinct systems. Firstly there is the CHP system that works with a gas turbine or a reciprocating engine with a heat recovery unit. It is displayed in Figure 4 with all its interconnecting parts. Water and the chosen fuel, most often natural gas or biogas, is the input for the system, and it can be seen that the fuel goes straight into being burned in the engine. The heat recovery unit captures heat from the exhaust stream of the combustion process. With the addition of a generator, transforming the power to electricity parallel with the steam from the heat recovery unit being transported for cooling or heating. The output of power can be distributed to the grid or to the actual site where the system is in use. (EPA, 2013)

Gas Turbine or Engine with Heat Recovery Unit

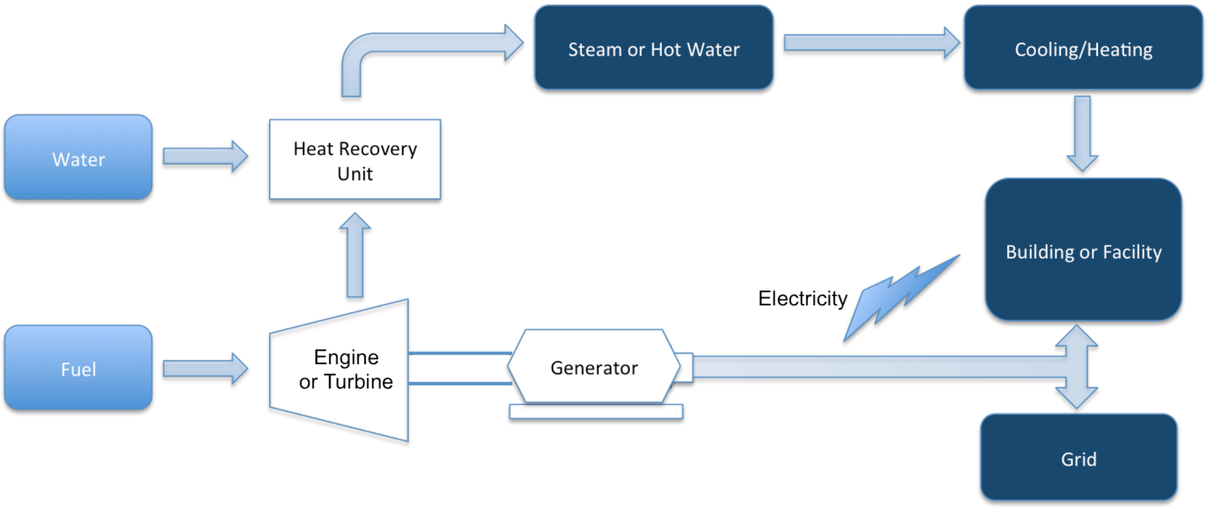


Figure 4 - Illustrating the system in which fuel is burned in an engine or gas turbine. (EPA, 2013)

The second CHP system commonly in use utilizes a steam boiler with a steam turbine. As can be seen in the illustration in Figure 5, the scenario is somewhat turned around, showing that here the electricity generation is the byproduct of the generation, whereas the previous illustration showed heat as the byproduct of the production of electricity. Fuel and water is inserted into a boiler and the initial step of this process occurs solely in the steam turbine. Both this and the previous systems are widely used, however, the constellation of the first system can be applied in many ways depending on which engine that is used in the prime mover. (EPA, 2008)

Steam boiler with Steam Turbine

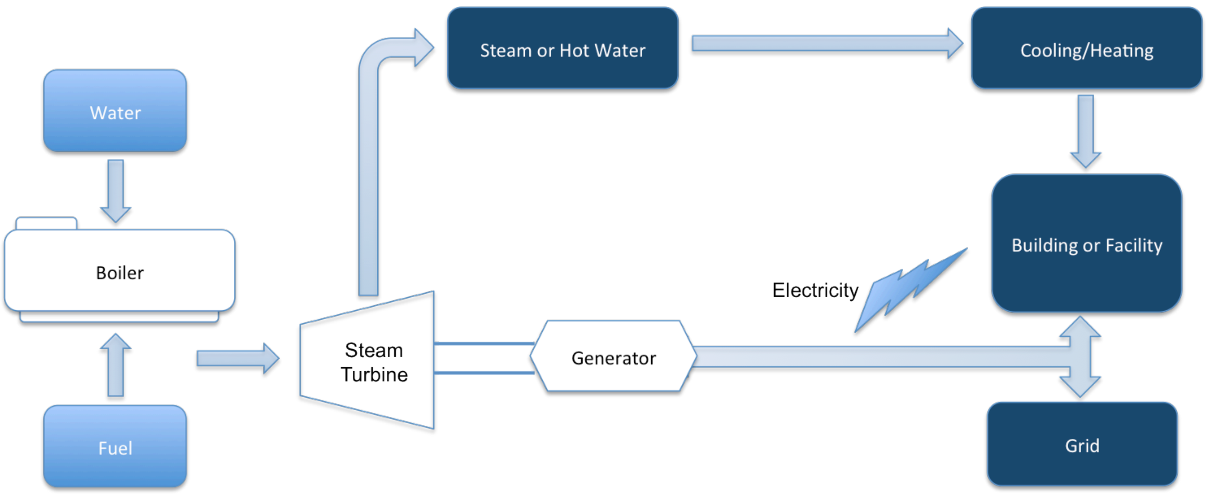


Figure 5 - Illustrating a CHP system with a steam boiler and a steam turbine. (EPA, 2013)

The prime mover is the most central component of the system and works as the heat engine for the generation of power. There are various sorts of heat engines in use for CHP, and certain advantages and characteristics will depend on which type of prime mover that is in use. (EPA, 2008) Next section of this chapter will elaborate which different types of engines that can be in use in a CHP system.

A significant quality of CHP is its ability to work with a wide array of fuels. The prime mover can burn natural gas, coal, oil or a number of more alternative fuels. Combining a CHP system with a renewable source of energy makes the technology superior in its ability to work without in a sustainable and environmentally friendly way. (EPA, 2008) When placing a CHP site close to industrial or agricultural processes, the biomass extraction can enable the CHP engine to run on alternative sources of fuels, called opportunity fuels. Opportunity fuels include black liquor that is a by-product from pulping processes, biomass that is collected in the form of wood waste, sawdust and other agricultural wastes. In addition to these fuels, there is also the possibility to produce biogas from residential and municipal organic food waste and sewage waste. By breaking down the organic matter, as described in section 2.4.1, biogas can be produced and this raw biogas can subsequently be used in the CHP engine. (EPA, 2013)

2.5.1.2 CHP systems

Since CHP belongs to the technologies collectively called distributed generation, it has the ability to be regarded as separate units that can be transported and placed in the location most suitable for its consumer. However, the CHP system can at the initially be defined by four types of systems; i) packaged CHP which is a complete package of the system, serving to be placed close to the client's electrical and heating systems; ii) Micro-CHP has the function of being a replacement to a site's small commercial scale boilers; iii) Custom-built CHP is the system that can more easily be designed completely after the site's specific conditions; and iv) Renewables CHP that is the alternative when only using opportunity fuels for the prime mover of the CHP system. (Department of Energy and Climate Change, 2013)

Due to the conditions of this report's set out objectives, the last type of the CHP systems will be the one relevant for observation. If the model of the chosen energy system for this report is to function, then the choice of CHP system is required to be able to run on biogas in addition to be properly scalable in dimensions for the use in the eco-city. When examining CHP technologies, the choice of engines in the prime mover is mainly the determinant of how the technology works. Therefore the following two prime movers will be presented, due to their ability to burn or boil raw biogas; the reciprocating engine and the gas turbine.

Reciprocating engine - The reciprocating engines with internal combustion are amongst the most frequently used technologies in use for CHP systems. The engine gains popularity due to both its scalability, it is used both for small-to-medium installations as well as on large-scale industrial sites as well as its capability to handle several different fuel sources. The engine is equipped with either a spark-ignition that generates power outputs of up to 5 MW or a compression-ignition that can generate as much as 15 MW of power (Shipley et al., 2008). The firstly-mentioned version only uses gaseous fuels for combustion, whereas the second option burns oil or oil-gas-mixtures. (DECC, 2013)

The reciprocating engine in the CHP-system generally burns natural gas, yet the use of landfill gas, propane or biogas is possible. Using a reciprocating engine in a CHP system, the spark-ignition is the version used for burning and with the use of a renewable gas such as biogas; the system can produce up to 5 MW of power while at the same time as keeping the process sustainable. (Shipley et al., 2008)

Gas turbine - Utilizing a gas turbine in the CHP system carries it advantages, with the most significant one being that its high-temperature exhaust makes it possible to generate process steam at very high temperatures (Shipley et al., 2008). The system initiates with the working gas being compressed in the compressor, fed with fuel and finally ignited. Following is the expansion of the high temperate, high-pressure combustion products through the turbines in order to generate shaft power. The compressor and the electrical generator then utilize the shaft power, and the cycle is then repeated continuously. (Zdaniuk, 2012)

Gas turbines use fuels such as natural gas, biogas, landfill gas and a set of different petroleum gases (Shipley et al., 2008). When used for CHP systems the main advantage is expressed as its capability for use in industrial process, due to that all of the waste heat is available at high temperatures. Not so advantageous however, is the fact that gas turbines have a significantly lower efficiency compared to reciprocating engines. The overall CHP efficiency of a system is defined for the gas turbine CHP system of around 75 percent. (Zdaniuk, 2012)

2.5.1.3 Efficiency of a CHP system

When compared to conventional power generation, CHP is predominantly more efficient. Separate heat-and-power production ("SHP") is less efficient due to its inability to use wasted thermal energy in a way to minimize the losses in production. When producing electricity and thermal power separately, the losses from each production are then put together, negatively affecting the efficiency level of the overall system. When combining the heat-and-power production as with CHP, the effective usage of waste heat from production enables the system to produce more electricity or useful thermal energy without increasing the initial fuel needed. The losses are smaller than for SHP and the system is more energy efficient from an overall energy system perspective. (Combined Heat and Power Partnership, 2011)

When defining efficiency levels for different CHP systems, the most common processes are to calculate the CHP efficiency with either the total system efficiency methodology, or the effective electricity efficiency methodology. For this report, the focus will be on presenting the relevant metrics and calculations necessary for the CHP system that will be used in the model. Therefore, this section will only highlight the informative version of CHP efficiency calculations, and section 3.7.3 will further present the calculations in use for the model of this report.

Total system efficiency - The initial and most straightforward algorithm in how to calculate a system's efficiency is simply to divide the sum of the thermal and electricity outputs with the input of fuel used. The total system efficiency methodology requires one to establish the quota between the outputs and the inputs, and it will show how efficient the system is in transforming and recovering fuel and energy in the system to generate useful thermal energy and electricity as outputs. The incorporated parameters are total fuel energy input Q_{FUEL}, net useful power output W_E, and net useful thermal output $\sum Q_{TH}$. This way the overall CHP system efficiency η_{CHP} can be calculated as follows. (Combined Heat and Power Partnership, 2011)

$$\eta_{CHP} = \frac{(W_E + \sum Q_{TH})}{Q_{FUEL}}$$

Eq. 1

The total fuel energy input means the total fuel used by the system multiplied with the heating value of the fuel of choice. Heating value will in Equation 2 be named ht. The equation for the total fuel energy input is the following:

$$Q_{FUEL} = \sum Q_{FUEL} * ht$$

Eq. 2

The heating value varies between fuels, and this can be displayed via a given set of examples; Natural gas has a heating value of 1020 Btu per cubic foot, coal has a heating value of 10 157 Btus per pound, and diesel fuel comprises a heating value of 138 000 Btu per gallon. (Combined Heat and Power Partnership, 2011) Btu stands for British Thermal unit and is defined as the thermal energy required to increase the temperature of 0,454 kg of water from 3,8 C^o to 4,4 C^o. (Wikipedia, 2013) For the objectives of this report, the fuel of interest for the CHP system is biogas, where the input of raw biogas from the anaerobic digestion process will be used as fuel. The heating value ht_{BIOGAS} of raw biogas can be calculated based on the parameter of methane-content in the gas, and is presented in Equation 3. (Astals & Mata, 2011)

$$ht_{BIOGAS} = \frac{35800}{\%CH_4} * 100 \qquad Btu$$

Eq. 3

Effective electricity efficiency - Calculating the effective electricity efficiency ε_{EE} is slightly different from the total system efficiency equation presented for the CHP efficiency, however a small addition of one parameter is necessary. As can be seen in Equation 4, α is added, and it stands for the efficiency of the traditional technology with which the useful thermal energy output would be produced as if the CHP system did not exist. (Combined Heat and Power Partnership, 2011)

$$\varepsilon_{EE} = \frac{W_E}{Q_{FUEL} - \sum(Q_{TH}/\alpha)}$$

Eq. 4

When exemplifying typical values for effective electricity efficiencies the combustion turbine-based CHP systems and the reciprocating engine-based CHP systems can be given. The firstly mentioned ranges from 51 to 60 percent efficiency while the second system has a significantly higher efficiency of 69 to 84 percent. The parameter α is typically fixed depending on which system is of use, and it is mainly 0,8 when the CHP system includes a boiler that burns natural gas, 0,83 for a coal-fired boiler and 0,75 for the boiler burning biogas. (Combined Heat and Power Partnership, 2011)

As a conclusion, CHP systems can be customized in several manners and with different integrated technologies, and depending on parameters such as choice of CHP system, prime mover, fuel type and heating value of fuel type, the efficiency of the systems may differ between them. The two methodologies presented are both useful, however under slightly different circumstances. The total system efficiency is valuable when a comparison of a CHP system and a traditional SHP system is performed. When the performance of a CHP system is compared to conventional power production technology, the effective electricity efficiency proves to be more useful.

When finally stating an example of realistic efficiency levels for a CHP system, the thermal efficiency will also be considered. In many CHP systems the assumption is often that the thermal efficiency is roughly double the electricity efficiency. (Malmqvist, 2013)

2.5.1.4 Advantages of CHP

Reasons for utilizing CHP systems in industrial, commercial and residential environments are several and they are seen in many different forms. A clear divide can be made between the actual technological advantages and those that are related to more external factors.

Compared to other conventional production sites of thermal power and those for electricity, efficiency is significantly higher for CHP, which works as a single integrated technology for the production of both heat and power. When using all the waste heat in production, CHP can increase its efficiency due to substantial savings of heat energy. Another technology-related advantage is the capability with CHP systems to adapt to the needs of the specific site in which it will operate. Depending on size, needed capacity or choice of fuel source, the CHP system can be customized and in most cases scaled to fit the sought applications of the customer's site. (EPA, 2008)

More external advantageous are mainly related to economical and environmental factors. A user of CHP in an industrial environment will come to gain from economical benefits due to reduced energy costs, because their need to use the central grid will decrease and the usage of heating or cooling can make then self-sufficient. Another economical security when using CHP is that the user might not be as vulnerable to volatile electricity prices and the availability of other supplies. Finally, another highly relevant advantage when incorporating CHP into an energy system that has a sustainability mission is that it should be environmentally friendly. CHP with the use of renewable sources, preferably biogas and biomass products generate significantly smaller emissions of carbon dioxide. (EPA, 2008)

2.5.1.5 Properties of large-scale CHP with biogas

The importance and relevance of using the CHP technology in different energy systems, infrastructures and sites is today significantly apparent. It is a widespread technology with many usage areas and it is fairly adaptable, due to its ability to be used on smaller sites as well as in industrial environments. It is however important for the objective of this report to make a difference between the CHP technology that suits small and medium-scale projects, to that of the large-scale biogas conversion plants with CHP. This section is therefor discussing the properties and features of large-scale CHP with biogas and its output in the form of electricity and thermal energy.

For large-scale biogas conversion plants it is namely co-generation plants that are of use. Co-generation is simply the function of using the thermal wasted heat recovered in the heat recovery station for the further production of electricity. Incorporating co-generation with a system based on gas turbines where the internal combustion process uses the input of biogas as a fuel. (Sacher et al., 2009) However, there are many alternatives depending on the preferences of the site. The gas engine using a reciprocating engine or a combined cycle power plant adapted for CHP is also of relevance. Some plants also use a steam turbine that uses the heating system as a condenser for the steam and the function of the steam turbine. A summarization is that several internal systems are applicable but with some consideration to the specific plant. When using a gas turbine with internal combustion for example, the mechanical energy is extracted due to the pressure that is given when the system changes the temperature of the gas. (Sacher et al., 2009)

Having an on-site CHP plant adjacent to the actual biogas production in the AD-tanks can differ significantly from having it off-site. The disadvantages of having the CHP system off-site are mainly the issues of transporting the biogas from the AD-tanks to the CHP plant. The risks of leakage and the combined transport costs of the process sums up to be a noteworthy economical disadvantage of the whole system. In addition to this, the plant loses the opportunity to use excess heat and some part of the electricity produced as supply to the AD-process. The operational demand of an AD-plant is called *parasitic load* when taken from the CHP process. It is approximately 10 to 20 percent of the electricity produced in the CHP plant that needs to go back to support the AD-process, and 20 percent for the heat respectively. (Enviros, 2011)

As already mentioned, the properties of CHP systems can differ substantially depending on several components and circumstances. With relevance to this report, the general properties of large-scale CHP will be displayed, and is approximately 35 percent of the energy content of the methane in the biogas that will substitute the electricity production and roughly 52 percent transforms to heat. (Enviros, 2011) These outputs have several functions, however the end-market for them is not always clearly obvious. It can be fairly difficult to find cost-effective choices of end-users of the heat produced, mainly due to the fact that it is not ideal to transport it to too distant locations. In addition to this, it may sometimes be hard to find high demand for heat on close proximity to the CHP plant. However the operational use of the heat in the AD-plant that can be placed close by is useful. (Enviros, 2011)

The electricity output is easier for establishing proper revenue streams. The electricity can be connected to the grid or via a private wire. Experiencing of selling electricity from an English CHP plant in Norfolk shows that when selling power one can price it for £40 to £55 and respectively for heat the price ranges £5 to £15. In this particular case it is showed that the heat has been useful to sell via the local heat market. (Enviros, 2011)

For a general case with a CHP plant converting biogas into useful power and thermal heat, the revenue generation depends largely on the fluctuations of the energy prices and the possibility of achieving some sort of subsidy or financial backing from the local government. (Enviros, 2011)

2.5.2 Refinery plant

Alongside the application for biogas as a fuel in a CHP system producing heat and electricity, there is also the possibility to upgrade the quality of the biogas for other purposes. A way of further incorporating biogas as an alternative energy source is to connect the biogas production to a refinery station where the biogas can be cleaned and refined in various ways. The output of this process is simply called biofuel or bio methane, considering the amount of methane being of majority. By combining the digestion process in the AD-tanks with the upgrading process, the efficiency level of the biogas reaches a whole new level. (Scandinavian Biogas, 2013) Replacing petrol, diesel and natural gas with upgraded biogas is a further step into making a society more sustainable, and the transport infrastructure in particular. (Scandinavian Biogas, 2013)

A necessary procedure for this processed biogas to be distributed is to connect the refinery station to the local network for injection and distribution of bio methane into new and existing pipelines. (SEAI, 2013) Having a grid connection at the refinery plant however requires that a small CHP unit is installed and that there is possibilities to further expand the distribution of the gas. In most cases the biogas can be transported through existing pipelines for natural gas. Asia amongst many other regions worldwide has old, yet functioning pipeline networks for the distribution of natural gas, which can be of adequate use when distributing biogas. (Scandinavian Biogas, 2013)

The purpose of cleaning the gas is mainly to remove unnecessary contents and particles, such as carbon dioxide, hydrogen sulphide, ammonia and water in addition to other trace components. The output is destined to have a methane content of above 95 percent of the volume of the gas. The function of this enables achieving a gas that has a higher calorific value, which can ensure longer distances for a car to drive. It must also show of sustained and regular quality as to obtain safe driving. The purified gas can also ensure its quality by not having any ice-clogging due to too high water content in addition to reduction of corrosion. (IEA, 2000) In the following section 2.5.2.1, the different techniques for cleaning and upgrading the original biogas from the AD-tanks will be explained.

2.5.2.1 Upgrading techniques

Carbon dioxide removal - The removal of carbon dioxide is of importance to both the increasing of the energy content and storage volumes of the fuel. The carbon dioxide present in raw biogas contains no energy value and therefore dilutes the energy value of the fuel. With a removal of the carbon dioxide particles, greater amounts of gas can be stored in a smaller volume. This is vital for the gas when used as a vehicle fuel due to the restricted storage volume in vehicles and directly correlates to their driving distances. (IEA, 2000)

Water scrubbing - Water scrubbing is a process that uses the higher solubility of carbon dioxide and hydrogen sulphide to remove the unwanted substances from the gas mixture. Because the carbon dioxide and hydrogen sulphide are soluble in water, the methane rises to the air and leaves the water mixture. This absorption process is purely physical, leaving particles and other contents in the water. (IEA, 2000)

The process is initiated with the incoming biogas being compressed to around 10 bar as is seen in Figure 6 (Kwofie & Ofori-Boateng, 2009). The raw biogas is then fed into a column of counter-flowing water, which is also pressurized to meet the incoming gas. The water is fed into the top of the absorption tower, while the gas is fed into the bottom. The refined gas exits through the top of the tower with a higher concentration of methane ranging from 90 percent to 95 percent. Finally the gas needs to be dried, removing any unwanted moisture. (IEA, 2000)

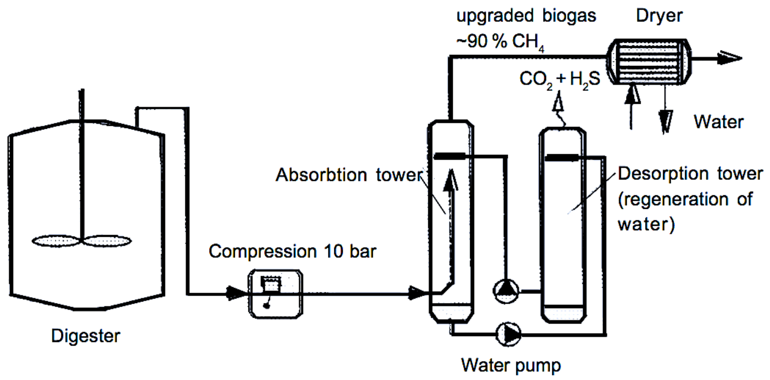


Figure 6 - Illustrating the water scrubbing process. (IEA, 2000)

This water scrubbing technique is simple and effective in the removal of both carbon dioxide and hydrogen sulphide. Although the recovery of the carbon dioxide is considered difficult because it has been absorbed into the water, the water can be depressurized and stripped of the contaminates. (Vijay, 2008) Problems may occur with high concentrations of hydrogen sulphide in the regeneration of the water since the water will soon thereafter be contaminated with elementary sulphur. (IEA, 2000)

Polyethylene glycol scrubbing - The process of the polyethylene glycol scrubbing is similar to that of water scrubbing but with a different medium. Instead of water, a solvent known as Selexol is used. This is a mixture of dimethyl ethers of polyethylene glycol in which carbon dioxide and hydrogen sulphide are more soluble. This results in a decreased amount of solvent and therefore decreased amount of pumping. The solvent also absorbs water and halogenated hydrocarbons, which are present in especially landfill gases. (IEA, 2000)

Carbon molecular sieves - Molecular sieves utilize the fact that different gases tend to be attracted to solid surfaces under high pressures. The process is also known as Pressure Swing Absorption ("PSA") due to the varying of pressure. The carbon sieves are produced from coke, rich in micro-pores, maximizing the surface area.

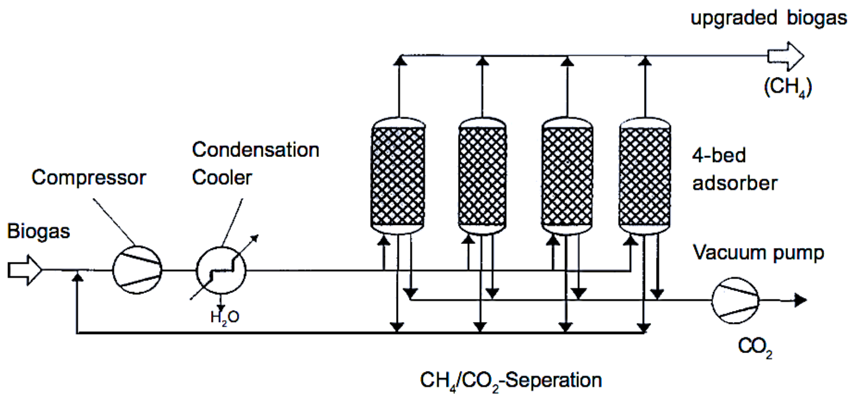


Figure 7 - Illustrating the process of using carbon molecular sieves. (IEA, 2000)

At different pressures and mesh sizes result in a selective absorption of the desired contents. A common system uses four absorber tanks as seen in Figure 7, acting under different pressures. The tanks try to utilize the pressures from earlier tanks in order to optimize energy efficiency. (IEA, 2000)

Hydrogen sulphide removal - Another substance present in raw biogas that needs to be removed is hydrogen sulphide. With the third largest concentration following methane and carbon dioxide, hydrogen sulphide is also highly reactive, especially under high pressures and temperatures. Therefore desulphurization is vital in preventing corrosion in pipes and machinery and is often carried out as early as possible in the process to minimize potential problems.

Iron oxide - A compound that reacts easily with hydrogen sulphide is iron oxide, which can therefore be used in the removal process. When exposed to each other they form the compound iron sulphide. This reaction is endothermic and requires a minimum of 12 °C in order to occur, although optimal temperatures lie between 20 and 50 °C.

After the sulphide has been bound to produce iron sulphides, they become oxidized with air. The iron oxide can be recycled and thereby used in the next cycle of the process. The number of cycles that the iron oxide can be reused depends on hydrogen sulphide concentration but it eventually has to be replaced.

The process features two reaction beds of iron oxide; one that is desulphurising the biogas and the other is exposed to air in order to force regeneration. The bed of iron oxide can consist of several materials including, steel wool covered with rust, iron oxide covered wood chips or iron oxide pellets. Wood chips have a higher surface to volume ratio than steel wool and can therefore bind more material. The low density of wood creates a superior surface to weight ratio to both iron oxide pellets and steel wool, nearly twenty grams of hydrogen sulphide per one hundred grams of iron oxide chips. The pellets are made of red mud, a residue from the production of aluminum. Iron oxide pellets feature the highest surface to volume ratio and are considered to be the most commonly used technology for larger plants such as water treatment facilities. (IEA, 2000)

2.5.2.2 Biogas an a vehicle fuel

When aiming to achieve a society will a smaller carbon footprint and an overall reduced negative impact on the environment, a transition towards upgraded biogas as vehicle fuel is a suitable choice. When comparing upgraded biogas to the conventional emissions of cars running on petrol, diesel or natural gas, it shows that the emissions are drastically reduced. Biofuel is considered carbon neutral and equal to a zero impact gas. (Scandinavian Biogas, 2013) An example showing this is that when a bus replaces its fuel of diesel to biogas the emissions of greenhouse gases are reduced by 96 percent. Equivalently for a car the reduction is 95 percent. (Scandinavian Biogas, 2013)

Unlike natural gas that has been widely used in so called Natural Gas Vehicles ("NGVs"), biogas is in no way considered as a fossil fuel (Scandinavian Biogas, 2013). When defining different vehicles that are suitable for using biogas as a fuel, there are a few different definitions. Light-duty vehicles are vehicles that can run on both gaseous fuels as well as liquid fuels such as diesel. Due to their dual capability, the name of bi-fuel vehicles is also used for this vehicle. When a vehicle is only capable of injecting bio methane as its fuel it is called a heavy-duty vehicle. (Rasi, 2009)

Vehicles that run on bio methane have both clear advantages as well as complications. The vehicles are considered of more complexity than regular vehicles and several versions are available due to being specially built. The vehicles are however perfectly optimized for the injection of bio methane and they can prove better efficiency. As newer versions appear on the market, the placement of the gas cylinders has improved and presently there are roughly fifty manufacturers worldwide that offer 250 modules for commuter, light and heavy-duty vehicles run on upgraded biogas (SEAI, 2013). The countries that have shown the most acceleration in using biogas as a vehicle fuel is mainly Sweden, Germany and Switzerland (SEAI, 2013), although the markets of Asia and South-America appears to be the fastest growing (Scandinavian Biogas, 2013).

The challenges of the usage of biogas in transport are mainly related to economic issues and the properties of methane gas. Firstly, the process of upgrading is fairly costly and it adds to the overall cost of producing biogas (Petersson & Wellinger, 2009). Secondly, the methane is considered significantly harmful if entering the atmosphere, (Rasi, 2009) and the risks of leakage are always present, depending on the quality of pipelines and vehicle modules. In addition to this, the features of gaseous fuels are different to those of liquid fuels, which can cause further risks. Gaseous fuels have higher ignition temperature but a higher lower flammability limit than liquid fuels. (Rasi, 2009) Finally the challenge of entering a market and an infrastructure for transport that has been adjusted to diesel cars for its entire existence can be complex. Thankfully the grid networks with natural gas functions works for biogas as well, and simplifies the procedure of distributing biogas to refueling stations. However, the industry for biogas vehicles and its stations is still in need of further development due to consumer unawareness, not enough refueling stations and high costs both in production and vehicle sales (Rydberg et al., 2010).

2.6 Relevant case-studies

A set of case studies is hereby brought forward to serve as useful tools in defining and forming the input values and dimensions of the different components in the model of the energy system in this report. The chapter first introduces the KTH project where food waste from restaurants on campus where digested to biogas and used as fuel in a micro-CHP plant. This example will highlight the necessity in feeding a CHP system enough fuel and thereby the sensitivity of the system to have adequate amount of substrate for digestion. The second example is from China, and serves to display how a farm in the city of Beijing uses a biogas process with a CHP system as a complement to their ordinary dairy handling. The farm has discovered how biogas production and wastewater treatment has turned out to be very useful for their need to handle their amount of their large-scale livestock dung and the water needed for cleaning it. The third example is necessary for showing how upgrading of biogas works in combination with an anaerobic digestion process for sewage water.

In addition to these case studies, a final section of this chapter will shortly present some examples of cost properties for the different plants and technologies that have been investigated in this report so far. These financial examples will be valuable in section 4.2, where an overview of the economic feasibility of the scenarios will be undertaken.

2.6.1 Small-scale project with biogas and micro-CHP

An example of a CHP system running on biogas can be displayed from the KTH campus experiment, where a micro-CHP technology was used to transform biogas from anaerobic digestion into heat and power. The idea was to collect the food waste from three of the four restaurants on campus and after the residence time of the organic waste, the biogas could be used as fuel in the prime mover of the micro-CHP. (Malmqvist, 2013) Micro-CHP is another one of the several CHP systems that are offered as customized versions of the original design and function of the CHP technology. There are a few versions available of what really defines a micro-CHP plant, however one definition prevailing is that the micro-generation unit has a maximum capacity below 50 kW of electricity and work according to the function of cogeneration where wasted thermal heat is reused. (Simader et al., 2006)

The KTH experiment borrowed a mobile biogas plant from SLU in Uppsala for the production of the biogas. (Malmqvist, 2013) SLU is the Swedish University of Agricultural Sciences and their ambition is to provide and execute high-quality research for a better co-existence between man and the environment, and provides research on different technologies that enables a better use of resources. (SLU, 2013)

The micro-CHP plant on KTH campus had a capacity of up to 30 kW of electricity with roughly the double in thermal energy. However, what this example shows is also how sensitive small-scale CHP plants can be. The chamber for the anaerobic digestion was 5 m^3, and it turned out to be more difficult than planned to collect the substrate needed for the process. The micro-CHP required more biogas than the mobile biogas plant could produce, due to a lack of organic waste.

The restaurants' provided waste was not enough and mixed up with waste that was non-organic. The organizers of the experiment at KTH managed to solve the problem by collecting old fruit from a local supermarket leading to that the micro-CHP could produce the electricity and thermal energy to its full capacity. (Malmqvist, 2013)

Micro-CHP generally has very high efficiencies, and it is in comparison to an in-house boiler, an effective alternative for providing space heating and warm water inn different buildings. The advantages of the technology is that it is environmentally friendly, energy-saving and it can help to reduce the electricity costs (Simader et al., 2006), however it is extremely sensitive to the amount of fuel it can get. The example above highlights the fact that the smaller the CHP plant, the more sensitive it is to shortages in fuel disposal. When introducing any CHP system into the model of the energy system in this report, the ambition will be to ensure a sufficient dimension of the plant in order to enable a continuous flow of electricity and thermal energy. The micro-CHP system of this example will not be relevant for the model, however it proves to be a reliable example when discussing overall CHP technology as a combination with biogas production.

2.6.2 Medium-scale farm project with biogas and CHP process

China has experienced a rapid increase of their large-scale livestock industry in recent year. The livestock is mainly based upon the pigs in national farms, but a growing amount of cattle farms is adding to the increase in Chinese livestock. The growth in this industry is however not only positive, and the owners of the pig and cattle farms are experiencing a worrying trouble in handling all the livestock dung that is growing proportionally to the farms growing. In addition to this, the need to have clean water for both the animals and the cleaning of the dung for other usages is also an apparent problem. (Fan et al., 2010)

There is however solutions for the problems, and as this example will display, the solution for a particular cattle farm in the Chinese Tong Zhou District of Beijing has been to find ways to use the dung for biogas production, cleaner energy and helpful fertilizer. Instead of simply scattering the dung around the farm, as many other small-scale Chinese farms have been found doing, this farm has created an effective energy system at their farm, parallel to their ordinary cattle business.

The farm has roughly 2 000 dairy cows present at their site, and each day they produce 30 tones of manure and 30 tones of wastewater. This equals up to 60 tones of useful substrate that can be used as substrate in the process of making biogas. Initially the substrate has to go thorough a pre-treatment process, where gravel, litter, hair and other residues need to be removed for a subsequent ideal anaerobic digestion can take place. This process is in many perspectives one of the most vital parts of the entire system, so to ensure the feed quality of the manure into the AD-tanks. At the Tong Zhou farm a circular hydrolysis tank is used for the 24-hour process where organic molecules will be broken down into molecular compounds. The pre-treatment process occurs at a temperature of roughly 30 degrees, where it may increase due to the actual digestion process of the manure. (Fan et al., 2010)

Following is the actual anaerobic digestion process. The AD-tanks keep the substrate inside for an approximate twenty days of residence time under where mesophilic fermentation takes place in combination with a real point of interest; the way they have chosen to keep the biogas stored. Unlike other AD systems, where biogas is directly fed out into pipes leaving the tanks, this farm has followed an original German example of keeping the biogas stored above the slurry. This is particularly advantageous due to less air leakages in the anaerobic tank and the gasholder. (Fan et al., 2010)

The storage possibilities of the AD-tank are the size of 1200 m^3 with a diameter of 16 meters and 6 meters of height. The tank is kept at 38 degrees and due to a pressure balance in the biogas storage of the tank; the biogas can subsequently be transported to the pipes. (Fan et al., 2010)

In the case of the cattle farm in Tong Zhou, the electricity production could begin shortly after the initial biogas operation was working stable, and it was enough to power to lighting, cooking and several other needs of the dairy farm. They had a CHP system that could make 1,5-2,0 kWh of electricity per 1 m^3 of biogas. According to their calculations this added up to an annual power output of 788 400 kWh. (Fan et al., 2010)

2.6.3 Large-scale upgrading of biogas from sewage waste

This case study is focusing on the value-chain of the Henriksdal water treatment plant in Sweden. The plant is especially unique due to its location of being interspersed into the mountain hill of Henriksdal and its size establishes it as one of Europe's largest sewage water treatment facilities. Since its foundation in 1941, the capacity has increased from 150 000 m^3 of sewage water per day to 250 000 m^3 per day in 2011. The whole site is 300 000 m^2 in size with tunnels combining to a length of 18 km. The treatment plant receives sewage water from roughly 750 000 persons (Stockholm Vatten AB, 2013). The input of sewage water is processed in various steps in order to separate the water for further filtering and the sludge for transport to the AD-tanks located at the plant. Finally the clean water is released into Saltsjön, biogas is produced and the residues of the AD process are used as fertilizers amongst other application areas. The biogas produced at the Henriksdal site is then transported to a close-by refinery, where it is upgraded to reach the quality of usable vehicle fuel. (Carlsson, 2013)

It was not until 2003 that the plant included a refinery for nearby upgrading of the biogas produced from the sludge. (Tendaj et al., 2013) The system that works today is an interconnected set of processes, where nearby residents' sewage water goes through the different steps and finally forms a biofuel that can be of value in a sustainable way of transport. The Henriksdal water treatment facility has however since the beginning of their business, kept developing efficient ways to clean the sewage water they receive each day. The initial step is when the water enters the site and the larger objects are removed. Following is the pre-sedimentation where the primary sludge is separated and sent to the AD-tanks. A further component of the process is the biological cleaning of the water, using microorganisms to remove smaller particles. The water is still very mixed up and is transported to large basins where the secondary sludge is sinking to the ground and then removed. Finally as a last part of the cleaning process, a filter ensures the output of clean water. (Carlsson, 2013) The energy of the water is used as district heating and cooling before being released out into Saltsjön. (Stockholm Vatten AB, 2013)

As the water treatment process is finished, the separated sludge can be transported to the on-site AD-tanks in which the anaerobic digestion process can initiate. The Henriksdal plant also accept other substrates, of which roughly 25 000 tons per year is fat from fat separators from all over Stockholm in addition to not more than 2 000 tons of organic food waste per year from Stockholm restaurants and market halls. This adds up to the sewage, which still comprise 85 percent of the total substrate entering the seven AD-tanks of the site. (Tendaj et al., 2013) At the Henriksdal site, the AD-tanks use the mesophilic process with a temperature ranging from 35 to 37 degrees Celsius with a constant stirring system.

The seven AD-tanks have a combined volume of 39 000 m^3, where the largest models contain 7000 m^3 and the smaller 5000 m^3. (Stockholm Vatten AB, 2013) Each year the output of biogas produced is 65000 MWh and it is Scandinavia Biogas that buys the majority of the biogas from the treatment facility for upgrading. Of all available cleaning techniques the company uses the water scrubbing technique, (Tendaj et al., 2013) to increase the level of methane from original 60 to 63 percent methane to an upgraded bio methane gas of 97 percent methane. (Stockholm Vatten AB, 2013)

The final step is to sell biogas for vehicle fuel to the buses of the southern part of Stockholm's central parts. The transport of the upgraded biogas is performed at a pressure of 4 bars inside the two km long pipes between the refinery site and the refueling station. When the gas arrives at the refueling station it is compressed in order to reach a pressure of 350 bar after which it can be distributed to the local community buses in the nearby area. (Tendaj et al., 2013)

The energy system of this case study is simply showing the benefits of interconnecting several components and processes to function together in creating valuable output from available input. If the production of biogas overpowers the need of Scandinavia Biogas, they can use it for their own production of heat and power and save on their own energy need and costs. (Carlsson, 2013)

2.6.4 Costs

This section will shortly mention the different cost properties connected to each one of the technologies and plants of the previous chapters. In order to establish if a certain construction of a plant is feasible, certain financial metrics need to be investigated. The relevant factors that will be displayed here are the operation and maintenance costs ("O&M") and the installations cost of each plant or technology.

Due to the character of this report, and the stated learning objectives in the initial chapter, this section will not be that elaborate as that of a proper financial analysis. The ambition is to ensure that a realistic comparison between scenarios can be performed, and to discuss in what cost ranges the different technologies and plants are located in. Therefore intricate parts that may be connected to an installation or long-time investment will not be disclosed in this section.

Table 3 - Shows the cost properties per m³ bio methane for two different plants, with both AD and upgrading process. (Krich, Augenstein, Batmale, Benemann, Rutledge, & Salour, 2005) The table has been modified from its original source format in order to display the relevant parts.

Facility	Methane (m3/day)	Estimated cost for AD ($/m3)		Estimated cost for Biogas Upgrading ($/m3)	
		Capital cost	O&M	Capital cost	O&M
Small AD plant	1300	0,11	0,02	0,11	0,18
Large AD plant	6800	0,09	0,02	0,06	0,13

Table 3 shows two different scenarios with a variation in the size of a plant, which holds both an anaerobic digestion and a refinery plant. The example is extracted from two dairy farms in Sweden, with manure from cows as substrate for their AD process. The raw biogas produced is then subsequently upgraded into bio methane in a refinery plant. The values however, can be used as comparatives for a regular AD process with bio methane production.

The one-time installation cost for the refinery station of the small plant equals to $500 000 when producing 4 745 000 m^3 of bio methane per year. (Krich et al., 2005)

These cost properties will in the subsequent discussion of section 4.2.1 be placed in context with economies of scale for bio methane production. As can be seen in Figure 8, the costs for bio methane production decrease significantly when the availability of raw biogas as fuel input increases. The graph shows a relation between production capacity and production cost per kWh in SEK, which in this report will be sued mainly to show the correlation between the two, rather then exact costs in SEK.

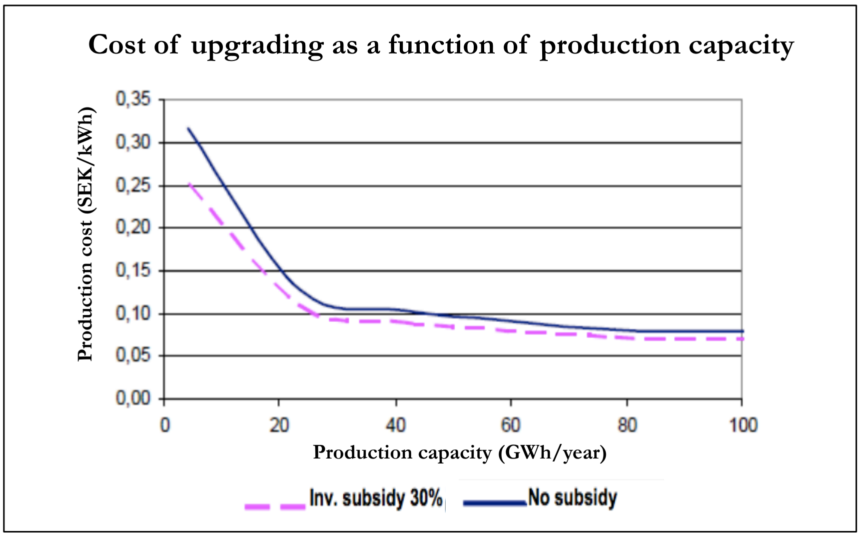


Figure 8- graph shows the relationship between bio methane production - scale and cost

When examining the cost properties of CHP installations the following metrics will function as a fairly reasonable benchmark for the power generation costs. (EPA, 2013)

Table 4 - Shows the operating assumptions for a general CHP system and its cost properties. (EPA, 2013) The table has been modified from its original source format in order to display the relevant parts.

CHP cost to generate power	
Operating assumptions	
CHP electric efficiency (%)	32
CHP power to heat ratio	0,7
Thermal utilization (%)	95
Incremental O&M ($/kWh)	**0,01**
Installed CHP System Cost ($/kWh)	**1200**

As can be seen in Table 4, the operating assumptions play a predominant role in what the financial cost output subsequently will turn out to be. For this plant, the electric efficiency is fairly general, assuming an approximate heat efficiency of 50 percent, and overall system efficiency of slightly over 80 percent. The incremental O&M costs are in this example slightly small, with a more significant number showing the installation cost. The example does not disclose any amortization or annual capital cost; neither does it include the fuel costs. This is mainly due to the character of the energy system of this report, with an integrated production of biogas and power, where there will not necessarily be any transaction costs between suppliers.

3 METHOD

3.1 Overall methodology

The initial methodology outlined for this project includes the following:

- A literature survey summarizing the different collection, production and transformation technologies relevant to the subject;
- A model of the energy system integrating biogas in the simulation program STELLA;
- Interviews with professionals and experts active within the subject;
- Studies of similar eco-city projects such as Hammarby Sjöstad, Sweden; and
- Analysis of the most efficient solution for biogas integration in the Sino-Swedish Eco city.

3.2 Assumptions

The initial assumptions drawn regarding the Sino Swedish Eco-City are necessary in order to create a sample of existing information that can prove a basis for further conceptualizing of plausible energy systems for the eco-city to be. Three main areas that need clarifying is i) the time frame, ii) dimensions and scale, and iii) population and usage behavior assumptions:

3.2.1 Time frame

The Eco-City is as of today not a finished project when looking at parameters such as actual city construction and fulfillment of all technologies. Neither is the city inhabited at the present stage. However, the actual construction of the city is to be executed shortly, and the planning phase is in many areas complete. In this report, the initial assumption with regards to time frame is mainly drawn in order to justify that suggestions brought forward in this report might already have been formed in the actual city project, or is simply not even included in the planning of the city. This report will assume that parameters such as geographic location, original key performance indicators and planned time frame for the city are constant, whilst undertaking further suggestions of city planning that regardless of time frame limitations still is viable for the purpose of this report.

3.2.2 Dimensions and scale

In the objectives brought forward for this report, it was suggested to analyze and form appropriate ways to integrate biogas production within the city structure of the Eco-City. By setting such an objective, it is crucial to highlight the assumptions taken when suggesting certain technologies and processes that are compatible with this objective. It will be assumed that the real dimensions of the Eco-City and the scale of its city structures can come to fit the ideas of plausible energy facilities. The area of the city is to be 2,4 square kilometers, and for this report it will be assumed that it is a proper dimension for both a small-scale anaerobic digestion plant in addition to a small-scale CHP plant and a refinery plant. Dimensions and scale will be further discussed in chapter 2 section 2.4, however more narrowed down to include the idea of more users connected to the system, and therefore more actual land.

3.2.3 Population and usage behavior assumptions

As formerly mentioned in the presentation of the Eco-City in chapter 2 section 2.2.3, the city area is projected to be a home for approximately 20 000 inhabitants (Fulco, 2011). When creating the suggestions and scenarios for this report, the assumption will be taken that the city will reach this goal of immigrating residents. The simulation program of STELLA will be used and in the calculations different population scenarios will obviously be investigated. The scenario will include an extremely low amount of population output, one regular low, one medium, one high and one extremely high. It is crucial to have both a low output as well as a high output scenario in order to shed light on the risk that the city will not be inhabited fully, or too much, and therefore the processes might not be economically viable.

In addition to the actual number of future inhabitants, some attention is to be given to the assumptions taken regarding the behavior of these inhabitants. The content of this report assumes that the future residents of the Sino-Swedish Eco-City will follow the given suggestions of recycling and waste management that will be present in their residential areas. When simulating models, available statistics of Chinese people's waste generation will be used. It will be assumed that the full population capacity of the Eco-City will follow the processes installed in their living areas that includes separating waste and disposing it as suggested. This area of usage behavior will be further discussed in section 4.2.3.

Further assumptions regarding this area are that of randomness and differences in the annual behavior of Chinese peoples' disposal of organic waste. An average value of how much organic waste each person in the city disposes of will be the base line, however a few variations will be assumed. Firstly, a built-in function of the STELLA simulative model will be used, randomizing the daily amount of organic waste. Secondly, consideration will be taken to several annual Chinese holidays, where organic waste is expected to increase. The actual assumption here is the percentages with which the waste disposal will increase during these holidays.

3.3 Limitations

Following the assumptions, the necessary limitations are presented. The time frame and boundaries of this report only allow so much information to be processed[3], and therefore a given set of limitations will highlight which areas that are not disclosed in this report. The following limitations that will be undertaken are related to the i) geographical boundaries, ii) choice of technologies, iii) availability of Chinese statistics, iv) energy system borders v) CHP systems:

3.3.1 Geographical boundaries

As mentioned in section 2.2.3, the Eco-City is destined for construction in the city area of Wuxi, in the city district of Taihu New District. This allocated area is in the middle of a vibrant city, where existing facilities, energy system and structures are already set in place. The limitations of this report are set to the actual borders surrounding the Eco-City, and further investigation of

[3] *The extent of this report is decided by the course MJ14X. The time allowance given is allocated over roughly four and a half months.*

how outer infrastructure may affect the eco-city will not be performed. It is obviously of great importance to research in how an eco-city can complement a city in various ways, however in order to exemplify how an eco-city can function individually, this will not be relevant. The boundaries of the model set in this report are solely based on the actual area size of the Sino-Swedish Eco-City. As mentioned in the assumptions above, the report will only examine what facilities and technologies can be used in the Eco-City, and this will be done without involvement of the nearby city areas.

3.3.2 Choice of technologies

These limitations refer to the proposed technologies in this report that may be used in the Eco-City. Regarding waste collection and waste management, the Envac system and the in-house FDW are presented as viable solutions to collect and separate different types of waste. Firstly, the Envac system is as of 2012 part of the city plan for the Eco-City (Envac AB, 2009), and it seems relevant to investigate further in this technology. As a competing solution, the in-house FDW has been chosen for investigation. The limitations are set here to exclude other technologies not fit in the scope. There may be further proven solutions that might fit the eco-city, however these are not to be included in the scope.

Furthermore, the choice of biogas production method for this report's energy system is the anaerobic digestion process. It is a proven method for extracting biogas from organic waste and the functionality of the anaerobic plant is suitable for the energy system. The limitations are set to this technology.

Finally, the limitations for the last part of the biogas value chain for the Eco-City are those for the transformation possibilities for the biogas. This report will investigate and evaluate the CHP plant and the refinery plant. The two technologies are chosen due to their suitable characters to this subject, and will both be included in the simulation model to some extent. However, the limitations are set to not include any further options in this area.

3.3.3 Availability of Chinese statistics

When executing different scenario simulations in the STELLA simulation program, a certain set of numerical values will be used. To the extent of the capability of the authors, the numbers for different parameters will be as realistic as possible, however the accuracy of the simulations will be limited by the findings of qualitative statistics for Chinese usage behavior, technology efficiencies and waste generation.

3.3.4 Energy system borders

For the transparency of this report, the borders of the chosen energy system will also be disclosed. The chosen energy system is set to include the waste generation and recycling processes of the eco-city's residents, the production of biogas and the transformation of the raw biogas. The energy system will not include the following:

- The eco-city's residents' choice of commodity use and food purchases that may affect the disposition of their waste generation. This also specifies the actual content of their food waste;
- The value chain of the combustible waste of the residents. The combustible waste is assumed to be separated and transported straight to a CHP plant, however this process will not be included in the scope of this report; and
- The final use of the output extracted from the transformation of biogas. Certain outcome such as electricity, heat and bio methane will be calculated in numbers of amounts, but there will be no detailed investigation of how this outcome can be used. Several suitable choices may be present, however the further use of the energy will be placed outside the scope and energy system of this report.
- Finally, the calculations and simulations on the sustainability level and the economical viability of the system will also *not* come to include the transports in between each part of the system. The transports can be neglected due to the areas short distances, and their inevitability in the process.

3.3.5 Presentation of the CHP system

The CHP technology is with its productive way of reusing wasted heat an efficient process in which heat and power can be produced. The CHP systems are many, and depending on which components are included in each system, the dimensions, efficiency levels and capacities differ. In this report the limitation regarding the CHP system allows the authors to not disclose all details of the wide array of different ways of composing a CHP system. These limitations enable this section to be focusing on the CHP systems that are relevant for fitting into this report's model. The objectives of this report does not state that a CHP plant should be either designed or numerously calculated on, therefore a general presentation of the technology is sufficient for the simulations in the model of this report.

3.4 Choice of case-studies

The choice of case studies is based on the need for displaying different scenarios where different components of the model of the energy system in this report are proven useful. The KTH campus example is showing how organic waste can be turned into biogas in an energy system where a CHP plant turns it into useful clean energy and heat. The example from China shows of several important factors and in particular the Chinese interest for renewable energy sources and energy-efficient technologies. In addition to this, the example also names the advantages of storing biogas inside the digestion tank of the biogas production, and also the structure of the system and its similarity to the model of this report. Finally, the last example is effective in showing the perks of using biogas from sewage water for upgrading of biogas, which can be used for environmentally friendly transport among other things.

3.5 The modeling process

Conceptual model - The modeling process began with creating a conceptual model illustrating initial layout of the biogas system. As mentioned earlier in the report the system was divided into three sections, the collection, production and transformation phases.

This was done to divide the modeling into more manageable parts into which the different technologies could be divided. It also gave an overview of what stocks and flows that would be used in the final model including where the eventual choices of technologies would be integrated. In the conceptual model these are shown with dashed connectors as can be seen in Figure 9. Any modeling problems of converting different materials and units presented themselves and could be addressed.

With the drawing of the conceptual model, the final outputs of biofuel, heat and electricity became absolute and more tangible. The inputs were not as clear as the outputs were after the conceptual model and revealed themselves further when the simulative model work began.

STELLA simulation- To start the building process of the simulative model a brief introduction period to the simulating program STELLA was needed. The ability to learn and familiar oneself with the logic behind the different stocks, flows and variables was possible. This presented some issues with the design of the model, which resulted in necessary changes to be made in the conceptual model.

Once the conceptual model could be incorporated in the STELLA program, the building of the simulative model could be initiated. The modeling process naturally followed the flow of the system, beginning with the collection phase. The water treatment plant sector and food waste sector were created with initially constant flows. Later the variables that controlled the flows were added to increase the complexity and control of the model.

The modeling process continued similarly for each of the phases; starting with a simpler structure to which more features were added to expand the model. A problem that was not seen from the start was all of the converting between the different forms of matter, from solids to liquids to gases. Questions like *"Should biogas be measured by mass or by volume and which one works best with the incoming flows?"* quickly arose. Therefore, at this point some additional information needed to be collected about the converting variables between the different materials and their forms.

Validation- When the logic and outputs of the model were working, the model needed to be tested and tweaked to give accurate results. Here the case studies of similar biogas systems were used to compare if our model gave similar figures. The Henriksdal treatment plant was one of the case studies used to compare the biogas production of the model. This case study was especially helpful in testing the biogas production from sewage. The population and sewage per person were entered to the specifications of Henriksdal with no additional food waste contribution. The resulting outputs were in the same range as the actual figures for the Henriksdal plant. When comparing what capacity the model generated for the Henriksdal plant with the actual capacity, a mere error of 1,2 percent was achieved. These results were sufficient to validate the quality of the model for the energy system of this report.

Model interface- Finally an interface was constructed for the model in order to increase usability for the user. The goal with the model was that an ordinary person would be able to understand the model and its outputs along with being able to change and play with it. The user should not have to go into the technical parts of the model to change simple variables and assumptions. Also the interface ensures that the user does not change and disrupt the workings of the actual model.

3.6 Conceptual model of the energy system

In this section, the conceptual model of the proposed energy system integrating biogas in the value chain is presented. The model of the energy system shows three divisions of relevant players; *residents* in the living areas of the eco-city, the *facility* of the AD plant and the *facility* of the CHP plant. The model also shows the three steps in which the biogas can be supplied, produced and subsequently transformed; the *collection* phase, the *production* phase and the *transformation* phase. This model is structured in order to show the original idea of how a suitable energy system integrating biogas production may look like for the Sino-Swedish Eco-City. This model will in combination with the simulative model presented further in Figure 9, support the overall goal of this report.

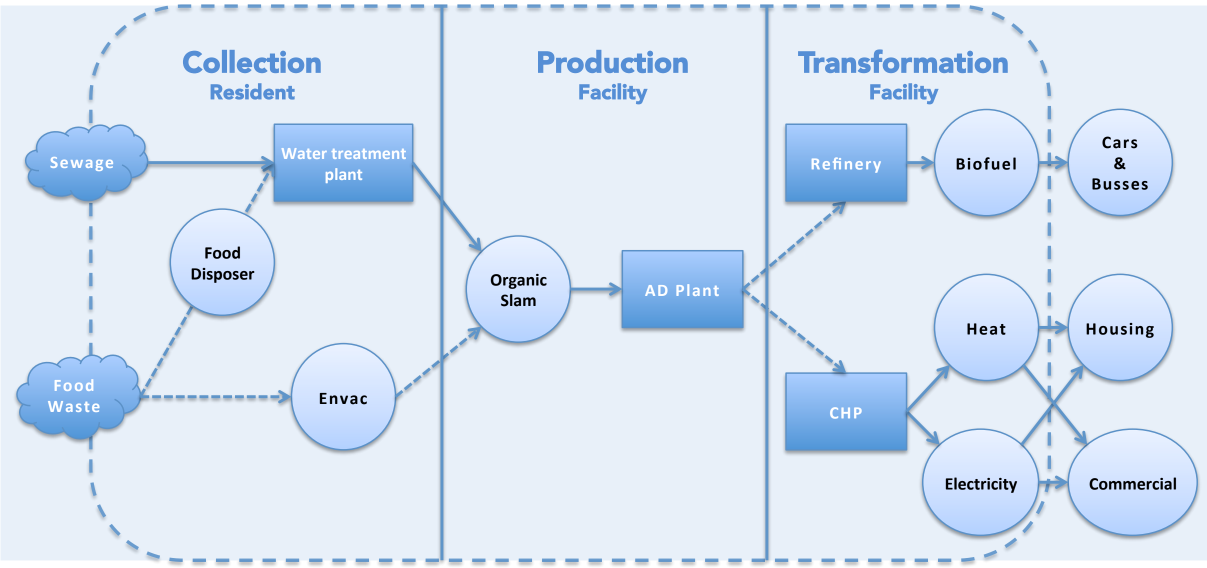


Figure 9 – Conceptual model illustrating the qualitative suggestion of how the energy system integrating biogas production in the Eco-City

3.7 Simulative model of the energy system

In this section, the simulative model of the energy system integrating biogas production in the Eco-City will be explained.

The chosen tool for achieving a model that will be sufficient to explain all the different inputs and parameters in the proposed energy system is the simulation program STELLA. The program shares the same philosophy regarding systems thinking that section 2.1.2 on systems dynamics explained. This will enable the usage of this program to be consistent with the overall approach to energy systems in this report. STELLA is an efficient tool for simulations that requires an overview of a more or less complex system, the organization of inputs and outputs in addition to serving as an enabler for students to change systems and observe how the system transforms over time (Isee Systems, 2013).

The following sub-sections are all relevant in explaining the structure and components of the simulative model of the energy system. The first three sections present the constants, variables and outputs of the model, followed by a thorough declaration of the entire model, supported with illustrations from the actual model built in STELLA. This section also includes all equations used in the modeling process. Following is the section describing all scenarios that will be tested in the model, with clarification of which variables and constants that are relevant for each scenario. Finally the modeling process of this report will be discussed, in addition to the last section that includes the sensitivity analysis of the model.

3.7.1 Parameters

Here all the parameters that are used in the model will be presented. First a set of constant parameters will be presented that will not be changed between the different scenarios. However, in the sensitivity analysis, these constant parameters will be increased and decreased as a percentage of their original value. This will show to what extent the parameters affect the outputs of the model.

Table 5 - Shows the definitions of the constants used in the modeling process.

Constant parameters	Symbol	Unit
Sewage waste	w_s	m^3/person/day
Density of organic waste	d_o	kg/m^3
Sludge content of sewage	s_s	$m^3_{sludge}/m^3_{sewage}$
AD efficiency for organic waste	η_o	$m^3_{biogas}/m^3_{organic}$
AD efficiency for sewage	η_s	$m^3_{biogas}/m^3_{sewage}$
Energy content per m^3 biogas	e_b	kW/m^3_{biogas}

Following is the presentation of the scenario parameters included in the model. These parameters are adjustable in order to examine different scenario simulations. All parameters will be determined or extracted on the basis of annual numbers if nothing else is stated. These are considered to be scenario parameters due to their capacity to be changed by the user in the interface of the STELLA model. However, they might not all be changed in the scenarios of this report.

Table 6 - Shows the definitions of the variables that may be changed due to certain scenarios in the modeling.

Scenario parameters	Symbol	Unit
Population	P	persons
Organic waste per person	w_o	kg/day
Variation	V	Distribution factor
AD residence time	R	days
Refinery efficiency	η_{ref}	$Output_{methane}/Input_{biogas}$
Heat production efficiency	$\eta_{chp\text{-}heat}$	kW_{heat}/kW_{biogas}
Electrical production efficiency	$\eta_{chp\text{-}el}$	kW_{el}/kW_{biogas}
Biogas distribution to CHP	B_{CHP}	%
Biogas distribution to refinery	B_{ref}	%
Methane leakage factor	M_{loss}	%

3.7.2 Outputs

This table shows the relevant final outputs in addition to outputs of the different sections of the model. Firstly there is the outcome of prospected waste generation for the eco-city as a whole on an annual basis. Following is the output from the processes at the anaerobic digestion plant. Lastly, the final outcome of actual amount of electricity, heat and bio methane is defined.

Table 7 - Shows the definitions of outputs from the model.

Output (annual basis)	Symbol	Unit
Amount of organic waste in the city	W_o	kg/year
Amount of sewage waste in the city	W_s	m^3/year
Amount of raw biogas produced	B_{raw}	m^3/year
Amount of electricity from CHP plant	I_{chp}	kWh/year
Amount of heat from CHP-plant	H_{chp}	kWh/year
Amount of upgraded biogas	$B_{refined}$	m^3/year

3.7.3 Walkthrough of model

In this section the model of the energy system will be explained. A description and a more detailed view of each sector will be presented. The section will follow the natural flow of the model in order to increase the understanding of how the sectors are linked and how they interact with each other. As seen in **Error! Reference source not found.**[4] the model is divided into five ectors.

A certain notification is necessary to shortly explain. The model will run for a period of time of 385 days, generating certain outputs. These outputs are in all tables referred to as annual outputs, even if the model runs for 385 days. This dissimilation is explained with the fact that the AD tanks have twenty days of residence time, and therefore it takes twenty days before the first

[4] *For a more superior resolution of the model please see appendix C*

amount of raw biogas is produced. In order to create a model that gives the correct accumulated annual amount of the outputs, it was then deemed necessary to include the twenty initial startup days in the time period of 365 days. This is also mentioned in the discussion of the model is the subsequent chapter.

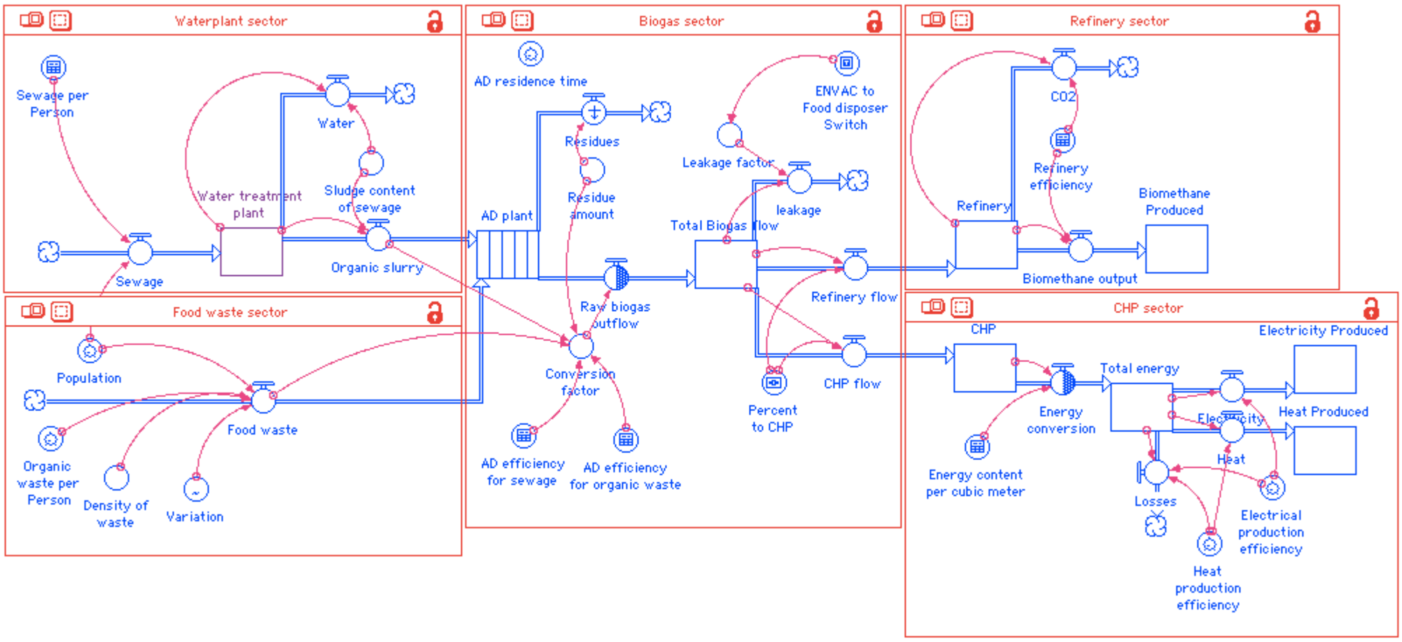


Figure 10 - STELLA image of all sections of the entire model

3.7.3.1 Food waste sector

The food waste sector simulates the amount of food waste that is produced and collected in the Eco-City. This amount of food waste is represented in the form of a flow. As seen in **Error! Reference source not found.**, this flow is named *Food waste* with the dimensions in m^3 of food waste per day.

The flow is calculated from three variables that the user is able to input and one variable that has already been set (*Variation*). All these variables (*Population, Organic waste per person, Density of waste and Variation)* can be seen in the model in **Error! Reference source not found.** and are used in Equation 5:

$$Food\ waste = (Random(90,110)/100) * P * w_o * d_o * V$$

Eq. 5

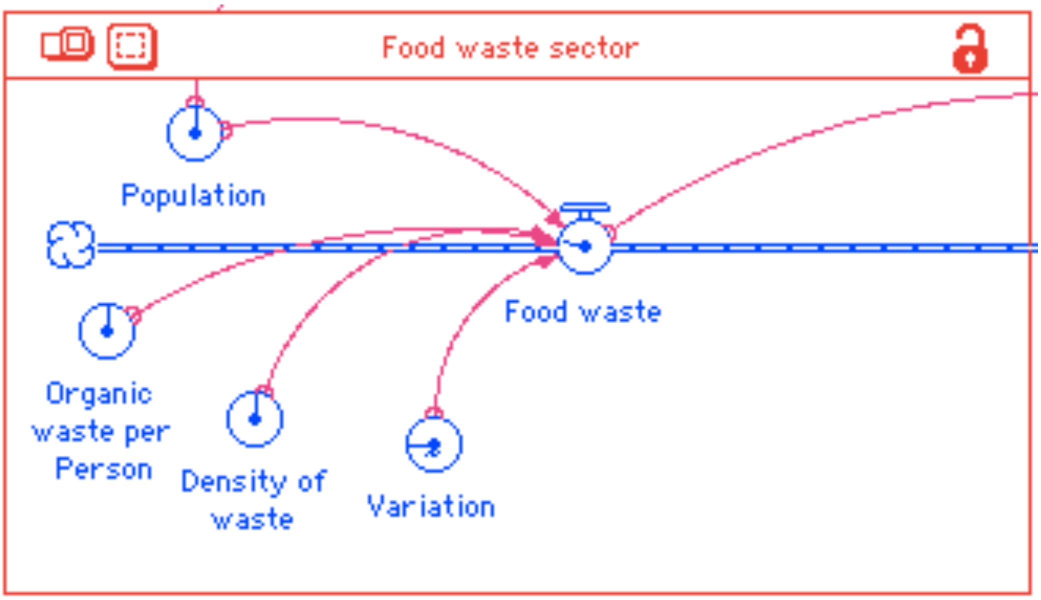


Figure 11 - STELLA image showing the food waste sector

The density of the waste is used as a converter because the amount of organic waste a resident accumulates is mostly measured in kg rather than m^3. However it is necessary for the flow of *Food waste* to be in m^3 because the inflows into the AD plant need to be of the same units.

The Random function is a built-in function in the STELLA software that randomizes an integer in the given interval (*90,110*). This integer is then divided by 100 in order to scale down the factor to the right proportions.

The *Variation* variable is a distribution factor that affects the average distribution of *Organic waste per person*. It takes in account the spikes in food consumption during Chinese holidays, which affects the amount of food waste produced. This was added to make the model more realistic and test the systems ability to handle spikes in waste production. These Chinese holidays can be seen in Appendix A.

3.7.3.2 Water plant sector

In this sector the amount of organic material extracted from the sewage water is computed. This sector features three flows, first the *Sewage* inflow into the treatment plant and then the two outflows of *Organic slurry* and *Water*. All of these flows are measured in cubic meters. The sewage flow uses the variables *Population* and *Sewage per person* to calculate the inflow of sewage:

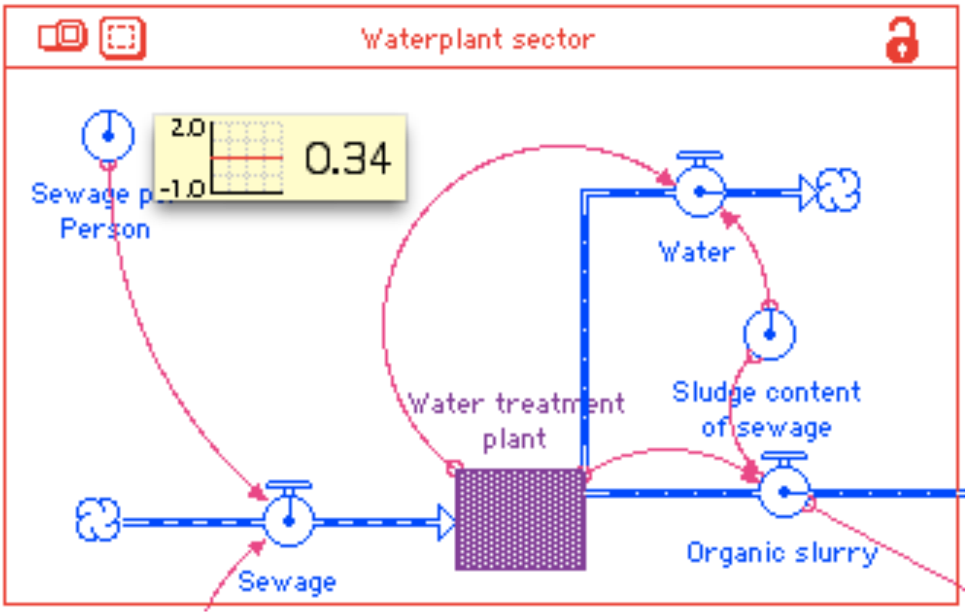


Figure 12 - STELLA image showing the waterplant sector.

$$Sewage = P * w_s$$

Eq. 6

After the sewage has entered the water plant, which is represented with the use of a stock, the *Sludge content of sewage* dictates how much organic material is extracted. The remaining substance in the treatment plant is considered to be clean water, represented with the flow *Water*. Equation 7 shows the amount of organic slurry.

$$Organic\ slurry = Water\ treatment\ plant * s_s$$

Eq. 7

3.7.3.3 Biogas sector

The biogas sector is where the flows of *Sewage* and *Food waste* are converted into raw biogas. First the flows enter the *AD plant* that is represented with a conveyor belt stock. This conveyor belt works just like an actual conveyor belt, the inflowing material is placed at the beginning of the belt and is then transported to the outflow of the *AD plant*. The time the conveyor belt takes to transport the material is used to symbolize the residence time of the actual AD plant. The occupancy time on the conveyor belt is controlled with the variable *AD residence time*. This tool best models the chosen technology for the energy system, a continuous feeding system. There are no batches of feedstock entering the digester and the inputs and outputs remain relatively constant. To symbolize the residues left over from the digestion process a loss factor is introduced, *Residue amount*. This controls the loss flow that is seen in **Error! Reference source not found.** as *Residues*.

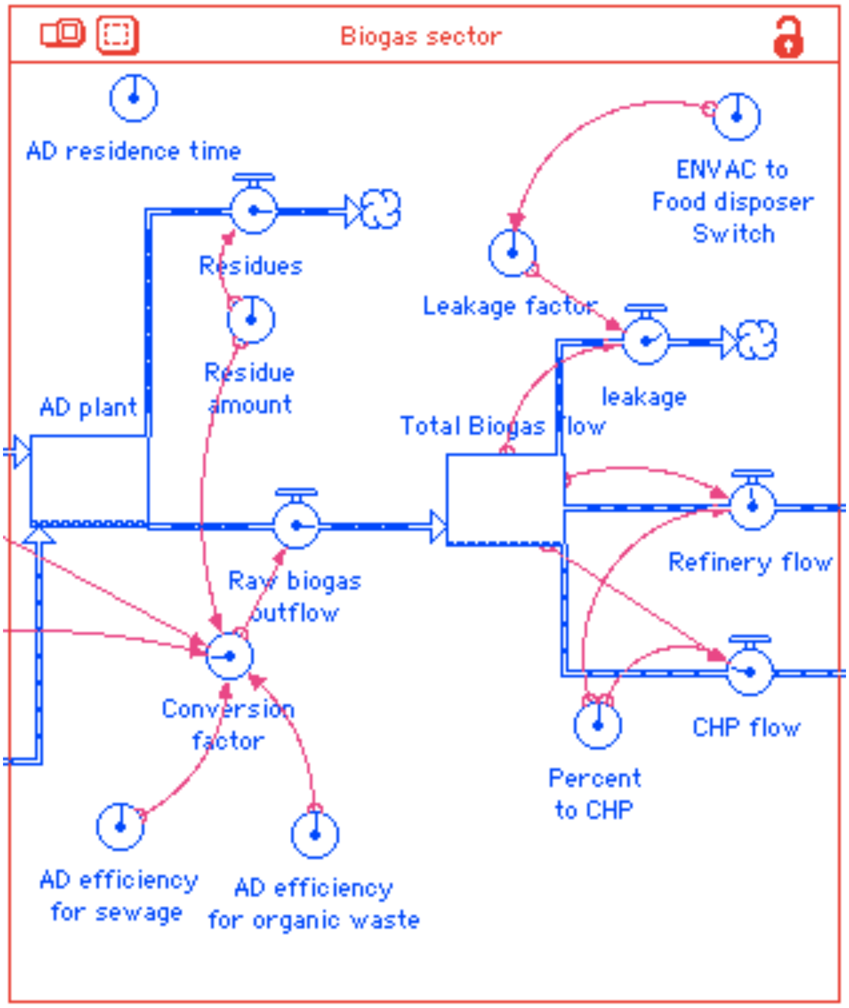


Figure 13 - STELLA image showing the biogas sector.

The final output of the *AD plant* is illustrated in the flow *Raw biogas outflow*. This uses a conversion factor to calculate the volume of gas output that the semi-solid input into the *AD plant* has produced. The conversion factor takes into account the distribution of food waste and slurry inflows to then use efficiency factors for the two to compute the amount of biogas that is produced. The *Residue amount* is also used to cancel out the effects of the residue losses for the calculation.

$$CF = \left(\left(\eta_o * \frac{Food\ waste}{Total\ inflow}\right) + \left(\eta_s * \frac{Organic\ slurry}{Total\ inflow}\right)\right) / Residue\ amount$$

Eq. 8

Once the *Raw biogas flow* has been calculated the flow is emptied into a stock named *Total Biogas flow*. This stock was introduced so that one would be able to analyze and graph the total output of raw biogas. Here a *leakage factor* is introduced for the leakage of methane. A switch on the interface that switches between the ENVAC system and the FDW system controls the magnitude for this factor. Unwanted AD processes is more common in the sewage system and therefore the *leakage factor* is greater for the Food disposer system.

After the leakage has been calculated, the flow of biogas is split up into two flows leading to either the refinery plant or the CHP plant. This distribution of flows can be controlled in the interface of the model with a slider that controls the variable *Percent to CHP*. This works with the logic that what is not sent to the *CHP flow* is instead sent to the *Refinery flow*.

3.7.3.4 Refinery Sector

In this sector the raw biogas that has been chosen for upgrading is sent. The flow enters the stock defined as *Refinery*. A variable named *Refinery efficiency* controls the amount of bio methane produced and the amount of rest product, carbon dioxide. This efficiency of the refinery depends to a great deal on the methane concentration in the incoming raw biogas. The model has been designed to only illustrate the carbon dioxide rest product because of the insignificant amount of other substances for the purposes of this model.

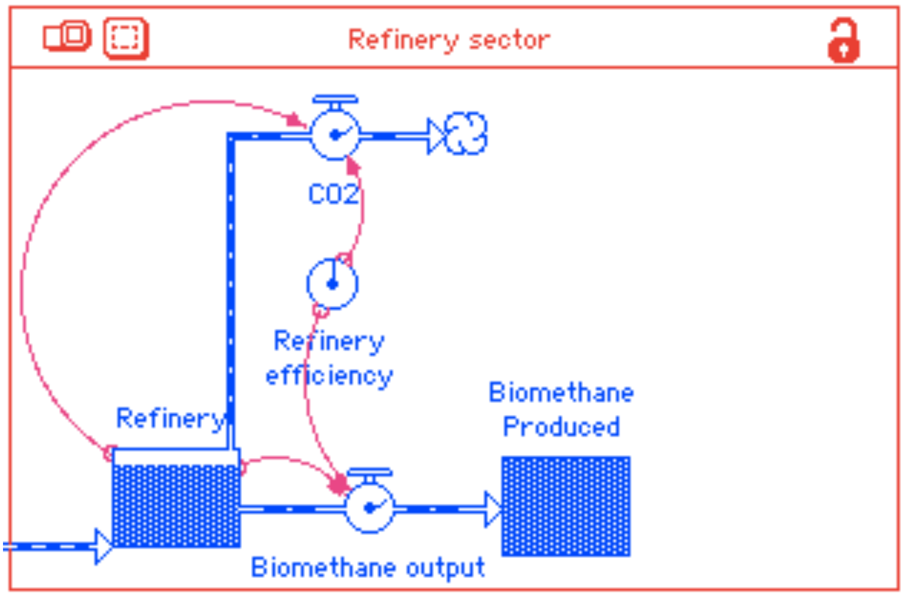


Figure 14 - STELLA image showing the refinery section.

The flow that carries the biogas output is featured in the model as *Biogas output*. It empties out into a collection stock that keeps track of the total cumulative amount of biogas, seen in the model as *Bio methane produced*. As the model has a runtime of 385 days this represents the annual biogas potential for the system, including the twenty first days of start-up time. Equation 9 is used to dictate the *Biogas output is:*

$$B_{refined} = \eta_{ref} * Refinery$$

Eq. 9

3.7.3.5 CHP Sector

The alternative to the refinery plant is the CHP-plant. In this sector the amount of electricity and heat produced from the combustion of the raw biogas in the CHP plant is simulated.

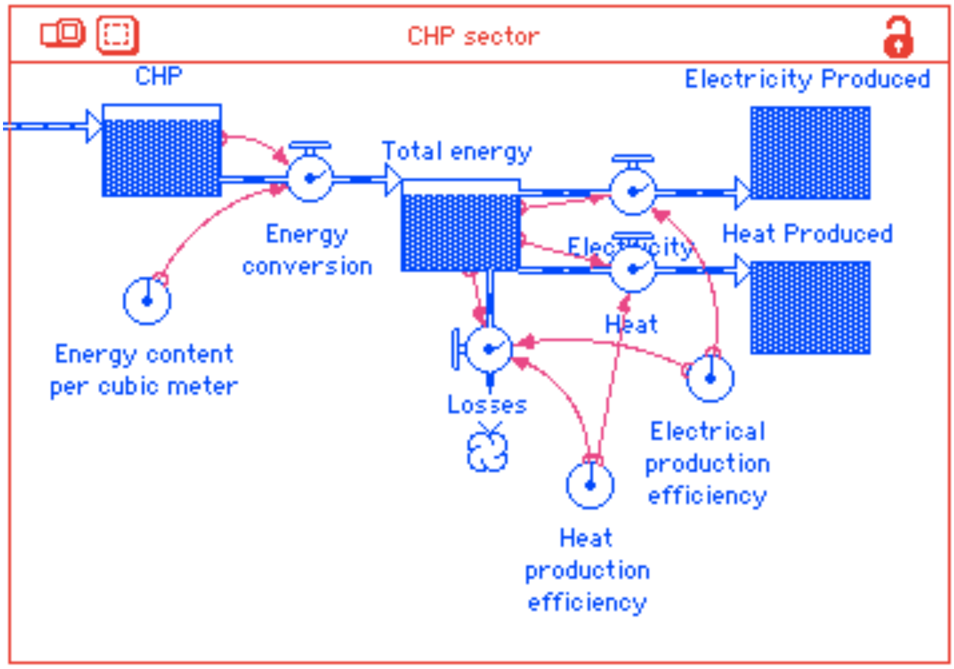


Figure 15 - STELLA image showing the CHP sector.

Initially the flow of biogas, *CHP flow,* enters the stock *CHP*. In order to calculate the amount of electricity and heat, the biogas is at first converted into energy. This is done with an energy content variable, *Energy content per cubic meter,* which is multiplied with the volume of biogas.

$$Energy\ conversion = e_b * CHP$$

Eq. 10

After the conversion, the flow collects into the stock *Total energy*. From here the energy is either converted into electricity or heat, with a flow for system losses. These flows of *Electricity* and *Heat* are controlled with their respective efficiency factor, *Electrical production efficiency* and *Heat production efficiency*.

$$I = \eta_e * Total\ energy$$

Eq. 11

$$H = \eta_h * Total\ energy$$

Eq. 12

The loss flow is controlled by the *Electricity* and *Heat* flows, emptying the energy that has not been captured in the form of heat or electricity. These losses consist mostly of heat losses that could not be captured into a viable energy transporter. As in the previous sector the flows run out into two collection stocks, *Electricity Produced* and *Heat Produced.*

3.7.3.6 Interface

To further involve the user and simplify manipulation of the model an interface to the model is included. The interface is built up of two main pages that make the model descriptive and adaptive. The first page contains the results and technology choices available. As seen in Figure

16[5], buttons for *Start, Stop* and *Pause* are located on this page, which control the runs of the simulation. The results displayed here are the amounts of bio methane, electricity and heat together with the estimated capacity need for the AD plant. Apart from the final outputs displayed, a graph presents the flows to the two transformation plants along with the total raw biogas production. This graph was included to show the user how their choice of technology directly affected the model.

The variables that the user is able to adjust on this initial page are the distributions of biogas flows to the respective plants and the choice of either the ENVAC or the FDW technology. The distribution of biogas flows is controlled by a slider, which sets the percentage of biogas that flows to the CHP plant. The choice between ENVAC and FWD is simply a switch that is moved to either solution.

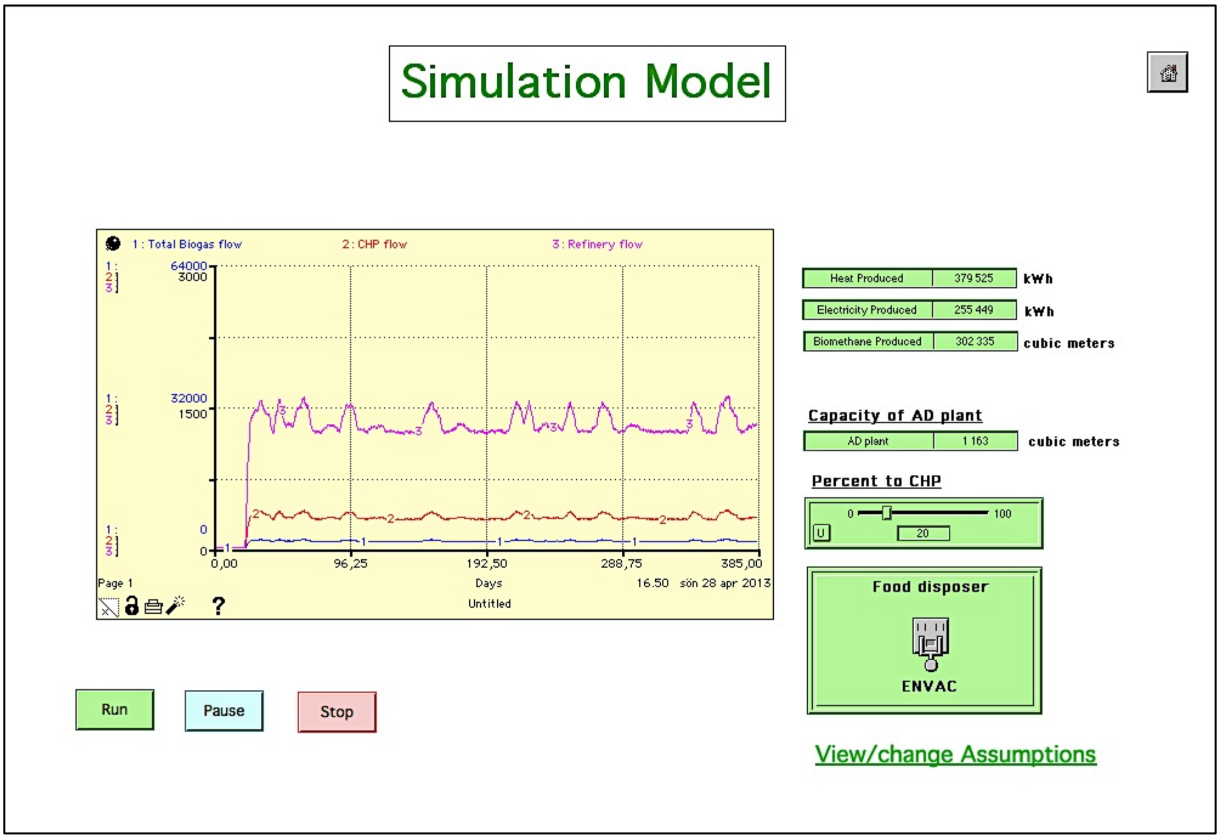


Figure 16 - STELLA image showing the interface of the model.

Figure 17[6] shows the second part of the interface comprising the assumptions and variables page, where variables and constants can be changed and viewed for each run of the model. The variables can be adjusted by the user with the help of the knobs that can alter the variables within a specific range. These are then divided into three categories to make the usage easier. Other variables and constants are listed in the tables to the right. These can be altered when the user clicks on the number and changes. This less apparent way of changing the variables is used

[5] *For a more superior resolution of the model please see appendix D*
[6] *For a more superior resolution of the model please see appendix E*

because these figures do not necessarily need to be changed in the aspect of the energy system of this report.

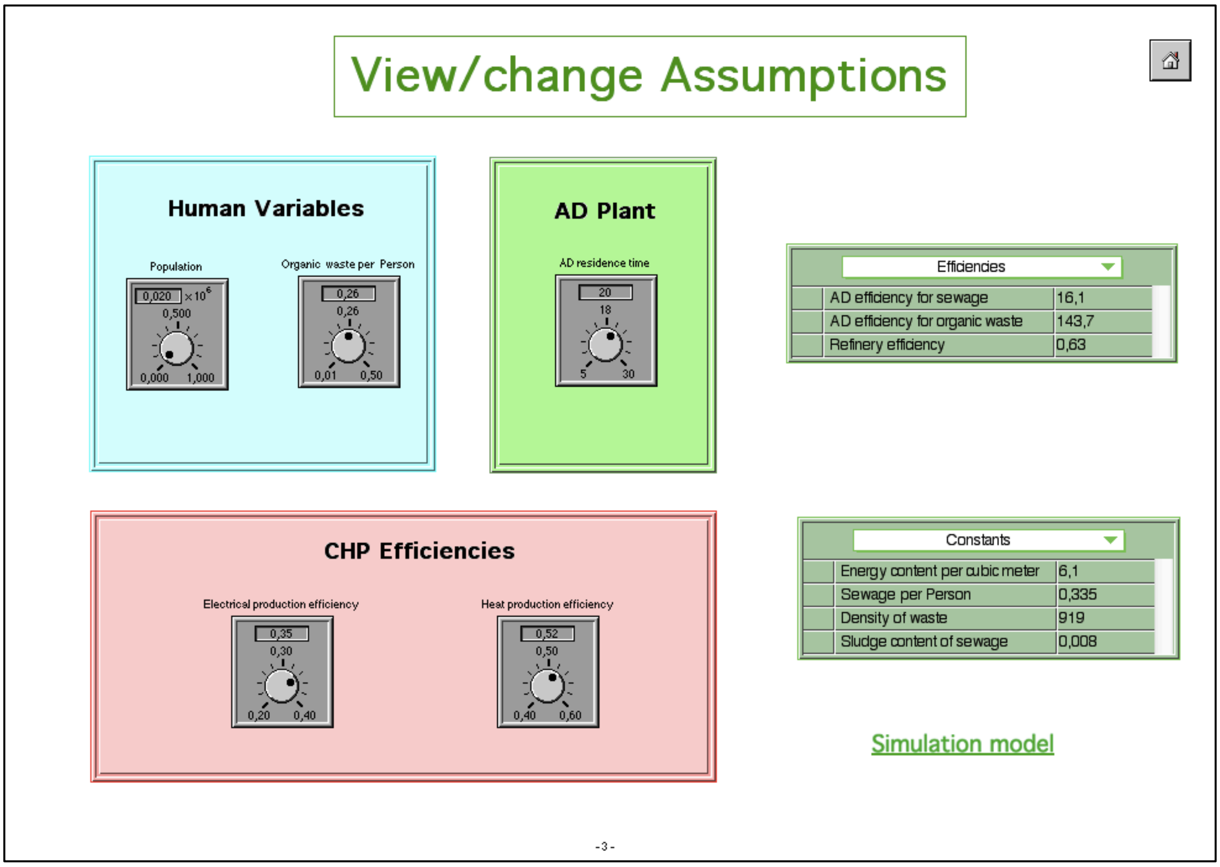


Figure 17 - STELLA image showing the View/change Assumptions screen of the program.

3.7.4 Scenarios

As part of the method for this report, a given set of scenarios will be investigated. The scenarios are based on all or a few of the given variables, however they will be tweaked in different ways in order to highlight different scenarios in order to clarify if the model is proved both sustainable and economically viable. Table 8 shows the constants that will remain unchanged throughout all scenarios of the modeling. All simulations will be run based on the use of the Envac collection technology, except scenario E, where the FDW will be included and tested. This will enable a more even comparison between other changes in variables, if all is based on just one technology.

Table 8 - Constants that will remain unchanged during the scenario modeling.

Constant	Symbol	Value	Unit	Reference
Sewage waste	w_s	0,335	m^3/person/day	(Stockholm Vatten AB, 2013)
Density of organic waste	d_o	919	kg/m^3	(Roberts, 2010)
Sludge content of sewage	s_s	0,008	$m^3_{sludge}/m^3_{sewage}$	(Stockholm Vatten AB, 2013)
AD efficiency for organic waste	η_o	143,7	$m^3_{biogas}/m^3_{organic}$	(Banks, 2009)
AD efficiency for sewage	η_s	16,1	$m^3_{biogas}/m^3_{sewage}$	(Stockholm Vatten AB, 2013)
Energy content per m^3 biogas	e_b	6,1	kW/m^3_{biogas}	(Banks, 2009)

Below is the description of all scenarios undertaken, each combined with a table showing the variables included in the model; some changed specifically for each scenario, some constant:

A. Integrated solution – This scenario combines the advantages of both the CHP technology and the upgrading of the biogas. When only using a CHP solution in combination with an AD-tank, ten percent of the electricity produced and twenty percent of the heat extracted is needed for keeping the AD process running. (Enviros, 2011) For this scenario the CHP system will only exist as to support the operation of the AD-tank, therefore twenty percent of the biogas will be allocated to an on-site CHP solution in order to extract the sufficient amount of electricity and heat to keep the mesophilic AD process running. The remaining biogas will be upgraded to vehicle fuel. Excess of electricity from the CHP process can be distributed in a local grid or to the refinery process. Table 9 shows the included variables for scenario A.

Table 9 - Shows the included variables for scenario A

Variables	Symbol	Value	Unit	Reference
Population	P	20 000	persons	(Fulco, 2011)
Average organic waste	w_o	0,26	kg/person	(Eggleston et al., 2006)
AD residence time	R	20	days	(Carlsson, 2013)
Refinery efficiency	η_r	0,63[7]	$Output_{methane}/Input_{biogas}$	(Stockholm Vatten AB, 2013)
Heat production efficiency	$\eta_{chp\text{-}heat}$	0,52	kW_{heat}/kW_{biogas}	(Enviros, 2011)
Electrical production efficiency	$\eta_{chp\text{-}el}$	0,35	kW_{el}/kW_{biogas}	(Enviros, 2011)
Biogas distribution to CHP	B_{CHP}	20	%	N.A.
Biogas distribution to refinery	B_{ref}	80	%	N.A.
Methane loss factor	M_{loss}	2,4	%	(Jonerholm & Lundborg, 2012)

The majority of the values for the variables of scenario A will be used in the following five scenarios, if nothing else is disclosed.

B. All CHP production scenario – This scenario is simply necessary in order to display how the production turns out when all of the raw biogas is used for heat and electricity production in a CHP-plant near the AD-plant. This scenario uses the same input data as scenario A, however with 100 percent distribution of biogas to the CHP unit.

C. All refinery production scenario – This scenario is fairly similar to scenario A. Both scenarios share the same input data, except the distribution between CHP and refinery is not 20/80, it is for this scenario 100 percent of the biogas allocated to the refinery plant. It will be assumed that the AD process is supported by an external electricity source. This way, the total amount of biofuel can be extracted and further calculations on how many vehicles that may be supplied with biofuel can be executed.

[7] *A benchmark based on the output of upgraded biogas in relation to input of raw biogas, from given reference.*

D. Population scenarios – The Sino-Swedish Eco-city is projected to house 20 000 inhabitants, according to early projections of the eco-city. (Fulco, 2011) This scenario will display the differences in output of bio methane, heat and electricity, depending on how the amount of inhabitants will turn out. The model will run with different inputs of the population amount, each generating two results; one with only CHP production and one with only bio methane production.[8] The remaining variables are identical to that of scenario A.

Table 10 - Shows scenarios with different levels of population for the eco-city.

Scenario	Population	% change
B.1 Low extreme	15 000	-25%
B.2 Low	18 000	-10%
B.3 Medium	20 000	0%
B.4 High	22 000	10%
B.5 High extreme	25 000	25%

E. FWD scenario – Since all previous scenarios are based on a system in the eco-city using only the Envac system for waste collection, this scenario highlights the mid-system outputs of raw biogas, using the food waste disposer system. The model will be adjusted as to include a slightly larger loss factor in the transport process between the residential areas to the central sites for the AD process. The equation for this loss factor M_{loss} is shown in section 3.7.3.3 Biogas sector, and is for this scenario 3,1 percent. All other relevant variables will be identical to that of scenario A.

F. Envac scenario – In order to achieve equal comparisons between technologies, this scenario will display the amount of raw biogas produced, using only Envac installations for the entire population. All other relevant variables will be identical to that of scenario A.

3.7.5 Sensitivity analysis

In this section a sensitivity analysis will be performed in order to establish if the set constants have a major or minor impact on the end result of the model. The defined constants will be increased with 10 percent and decreased with 10 percent and the model will be running with these new values. All results will be documented and the percentage increase or decrease in end result will be presented.

[8] *Meaning one run with 100 percent biogas distribution to CHP production and one run with 100 percent distribution to the refinery plant.*

Table 11 - Sensitivity analysis displaying how changes in constant values affect the outputs of bio methane, heat and electricity.

SENSITIVITY ANALYSIS	INPUT				OUTPUT			
Constants	-10%	Regular	10%	Unit	-10%	Regular	10%	Unit
w_s	0,302	0,335	0,369	m^3/person/day	-5,3%	378265	5,0%	m^3 bio methane
d_o	827	919	1011	kg/m^3	5,4%	377550	-4,3%	m^3 bio methane
s_s	0,0072	0,0080	0,0088	$m^3_{sludge}/m^3_{sewage}$	-5,1%	377675	5,2%	m^3 bio methane
η_o	129	144	158	$m^3_{biogas}/m^3_{organic}$	-3,4%	377908	3,5%	m^3 bio methane
η_s	14,5	16,1	17,7	$m^3_{biogas}/m^3_{sewage}$	-5,3%	378433	5,0%	m^3 bio methane
e_b	5,49	6,10	6,71	kW/m^3_{biogas}	-10,0%	1898	9,9%	MWh heat
					-9,9%	1276	10,2%	MWh electricity

When examining the results of the sensitivity analysis, some constants seem to have greater impact on the end-result than others. The dark grey colored rows of Table 11 show how a 10 percent increase or decrease in the constant of energy content per m^3 of biogas can result in changes in the output of heat and electricity equivalent to approximately the same percentage size. The majority of the remaining variables have been colored with light grey due to their slightly smaller impact on end-result when changed with 10 percent up or down. The changes in bio methane production simply changed with roughly 5 percent change on both sides of original value. Noticeable is that when tweaking the density factor d_s with 10 percent up and down, the output results showed inverted correlation. This is because of the model being built on the volume of the sources of organic material being put into the AD tanks, and not their actual mass.

Summarizing this discussion and the table showing the sensitivity analysis, it can be said that the model is fairly robust, however a few changes in the constants for the model, may have a slight impact on the end-result. These results in addition to the validation of the model shown in section 0, it can be stated that the model seems fit to generate reliable data for the purposes of this report.

4 RESULTS AND DISCUSSION

4.1 Results from scenario testing

In this section the results from the model will be presented in the order that the scenarios have been presented in section 3.7.4. Graphs and tables will be used to best illustrate the results together with an explanation of the figures. The discussion of each scenario will be held as the results are presented with an additional discussion following the presentation of the numerical results.

4.1.1 Integrated solution (A)

Figure 18 shows the accumulated production of bio methane on an annual basis. It is displaying the scenario in which 80 percent of all raw biogas produced in the AD process is dictated to the refinery plant. This equals 480 000 m^3 raw biogas per year that is sent to the refinery plant for upgrading. The relation between the amount of upgraded bio methane over time is linear, and the accumulated amount of bio methane is equal to 305 000 m^3 upgraded biogas. The small variations in the graph is due to both the randomizing function of the STELLA model in addition to the Chinese holidays[9] which may contribute to an increased amount of food waste, therefore increased the amount of produced raw biogas. These variations are displayed more clearly in Figure 20.

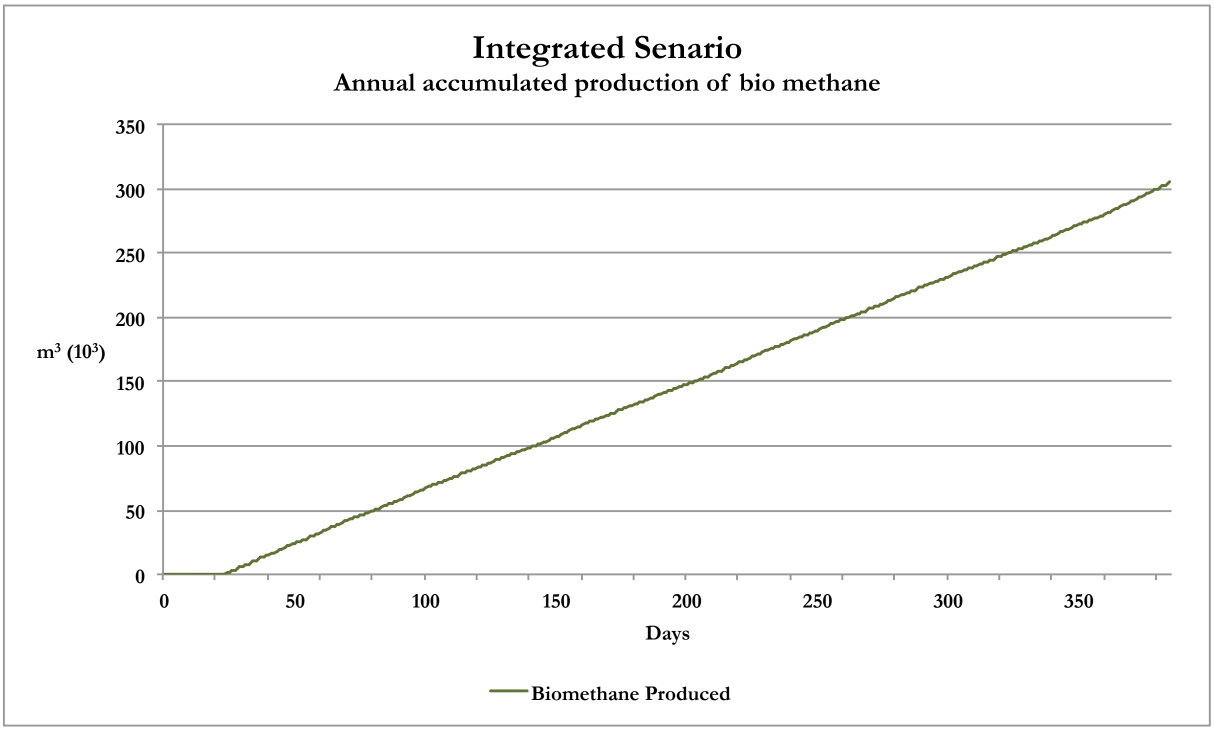


Figure 18 Integrated scenario- Annual accumulated production of bio methane

[9] *See appendix A for all Chinese holidays.*

An observation that can be made is that during the first twenty days, the production of bio methane is non-existent in this graph. The technical answer to this is that the residence time needed for the biogas production in the AD-tanks is twenty days (See 2.4 Production of biogas for more on the AD process); therefore the production of bio methane cannot commence until on the 21st day. For this reason the model is designed to run not for 365 days, but 385 days. This gives an accurate number for a normative year's production of bio methane, whilst still showing the start-up time for a process like this.

A comparison can be made to put this result into perspective by establishing how many vehicles that can run on this amount of bio methane. The average Chinese vehicle in a city environment, travels 24 000 to 27 000 km per year. (Wang et al., 2006) A benchmark on a biofuel-driven medium-sized car from 2009 can be given using 6,4 Nm^3 per 100 km. This information in combination with given results from this scenario testing, shows that using a 20/80 distribution of raw biogas between the CHP plant and the refinery plant, enables 200 of the bench-mark cars to drive on biogas as vehicle fuel per year.

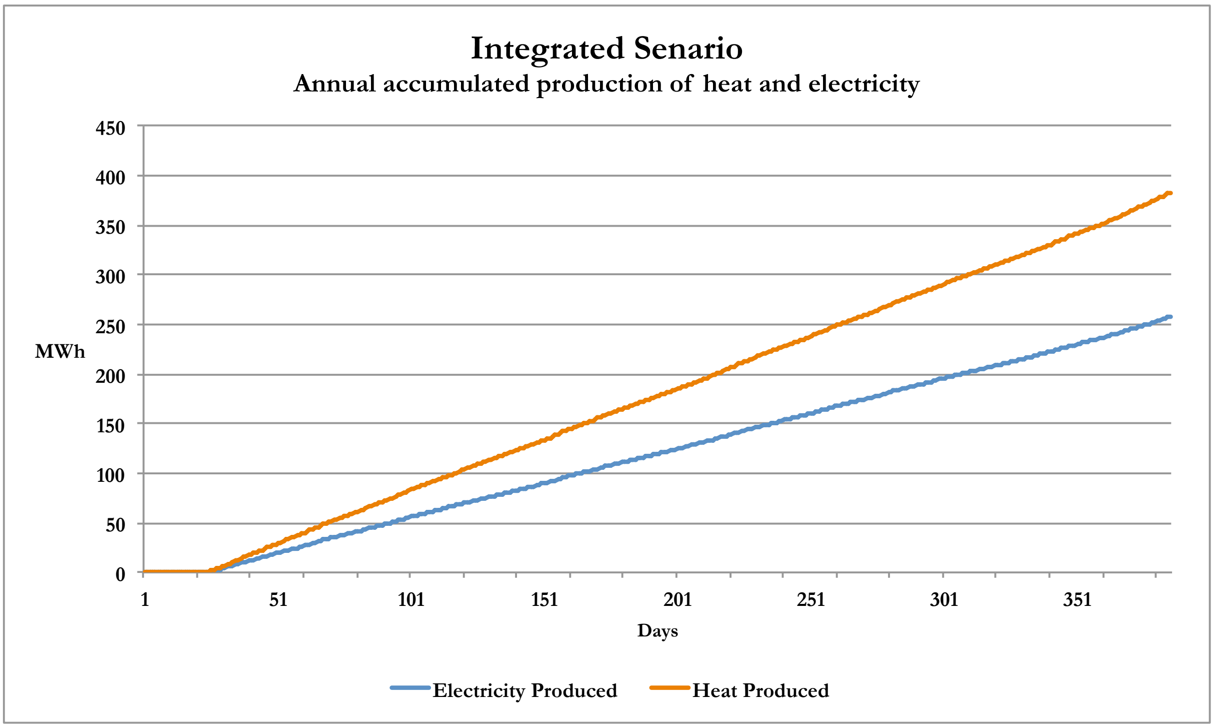


Figure 19 Integrated scenario- Annual accumulated production of heat and electricity

Figure 19 displays the graph over annual production of heat and electricity over time. This is the production generated according to scenario A, where only 20 percent of the raw biogas produced will be allocated to the CHP plant. The line showing the accumulated heat production from the CHP plant results in an annual production equal to 383 MWh and the value for the electricity with the same conditions is 258 MWh. As mentioned earlier in the description of this scenario, the idea is based on only using CHP for supporting the AD process in order to allocate the remaining raw biogas for the production of bio methane. That kind of support equals 20 percent of the total heat potential and 10 percent of the total electricity potential of the all-CHP scenario.

(Enviros, 2011) According to the results that are presented in scenario B, this kind of support would equal to 380 MWh of heat and 130 MWh of electricity. A comparison can then be made with the actual output of this scenario, which shows the same amount of heat being produced and twice the amount of electricity needed.

This scenario entailed 20 percent usage of biogas, leaving the AD parasitic load with enough heat and 50 percent of produced electricity as excess electricity, due to an only 10 percent need. As a proposition, the remaining 128 MWh of electricity can then be used as a further integration factor to the entire system, by being connected to the electricity distribution for the refinery. The benefits of this is the possibility of energy and cost savings for the refinery plant, due to its character of being both costly with a high energy demand.

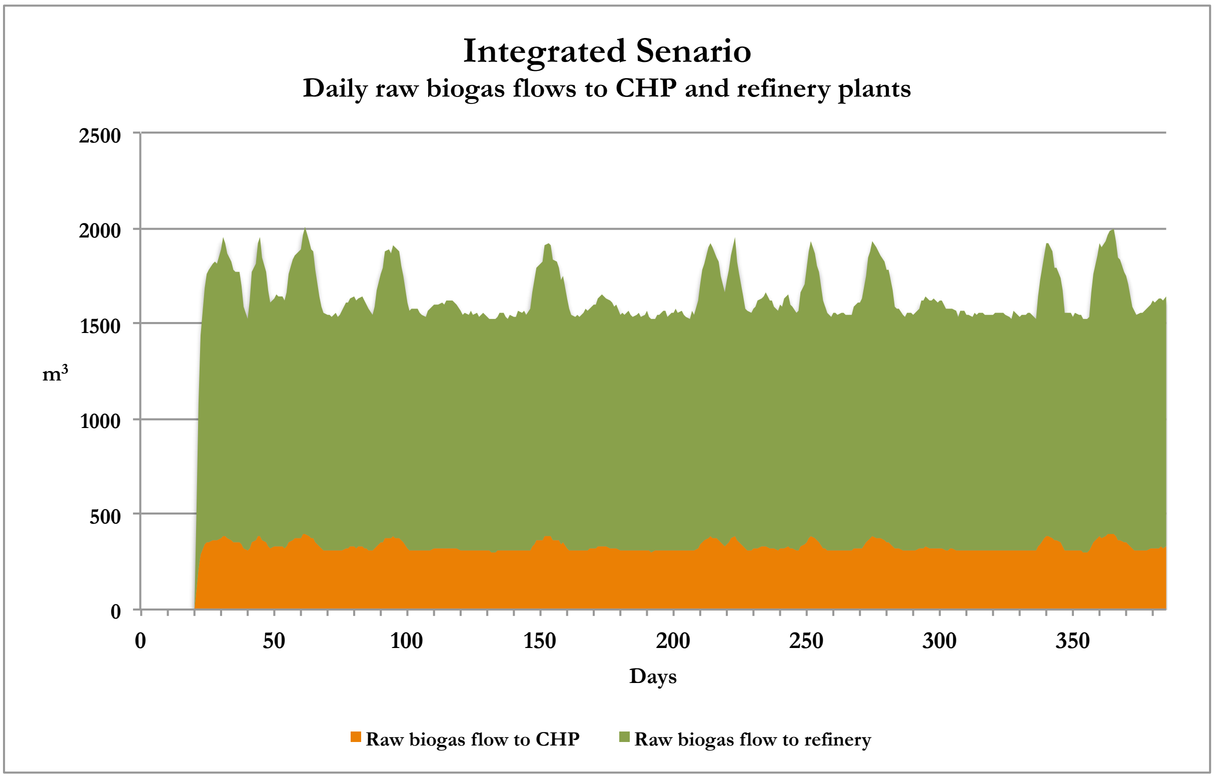


Figure 20 Integrated scenario- Daily raw biogas flows to the CHP and refinery plants

Figure 20 shows a stacked graph of the daily flows of raw biogas for scenario A. The time frame is set to 385 days in order to display both the start-up period for the system of 20 days in addition to the ability to show an accumulated annual capacity. The graph shows a 20 percent distribution of raw biogas to the CHP plant for each day, and an 80 percent distribution to the refinery plant. This integrated scenario also shows the complete production of raw biogas for each day of the time period, due to the stacked character of the graph.

The results show of a total biogas production in the system of 603 000 m^3 distributed as 121 m^3 to the CHP plant and 482 m^3 to the refinery plant. Noticeable in this graph are the spikes in the production throughout the year. These are apparent in both outputs, however the dimensions of the flows make these spikes more distinct in the refinery flows. The spikes are due to the fact that at these dates various Chinese holidays take place, leading to an increase in food consumption and therefore an increase in the amount of organic waste. These differences should be acknowledged as an affecting variable that should be taken into consideration when establishing different equipment and dimensions of the system. An example can be given for the size and capacity of the AD tanks; they should be capable of handling not only the average amount of organic waste and sludge, but also handle the days with an excessive amount of substrate.

4.1.2 All CHP production (B)

Seen in Figure 21 the accumulated productions of heat and electricity are over the period of a year. The annual outputs accumulate to 1280 MWh of electricity and 1900 MWh of heat. This distribution is due to the electrical and heat efficiencies of the CHP plant, 35 percent and 52 percent respectively.

$$\frac{1280}{1900} = \frac{35\%}{52\%} = 0{,}67$$

Eq. 13

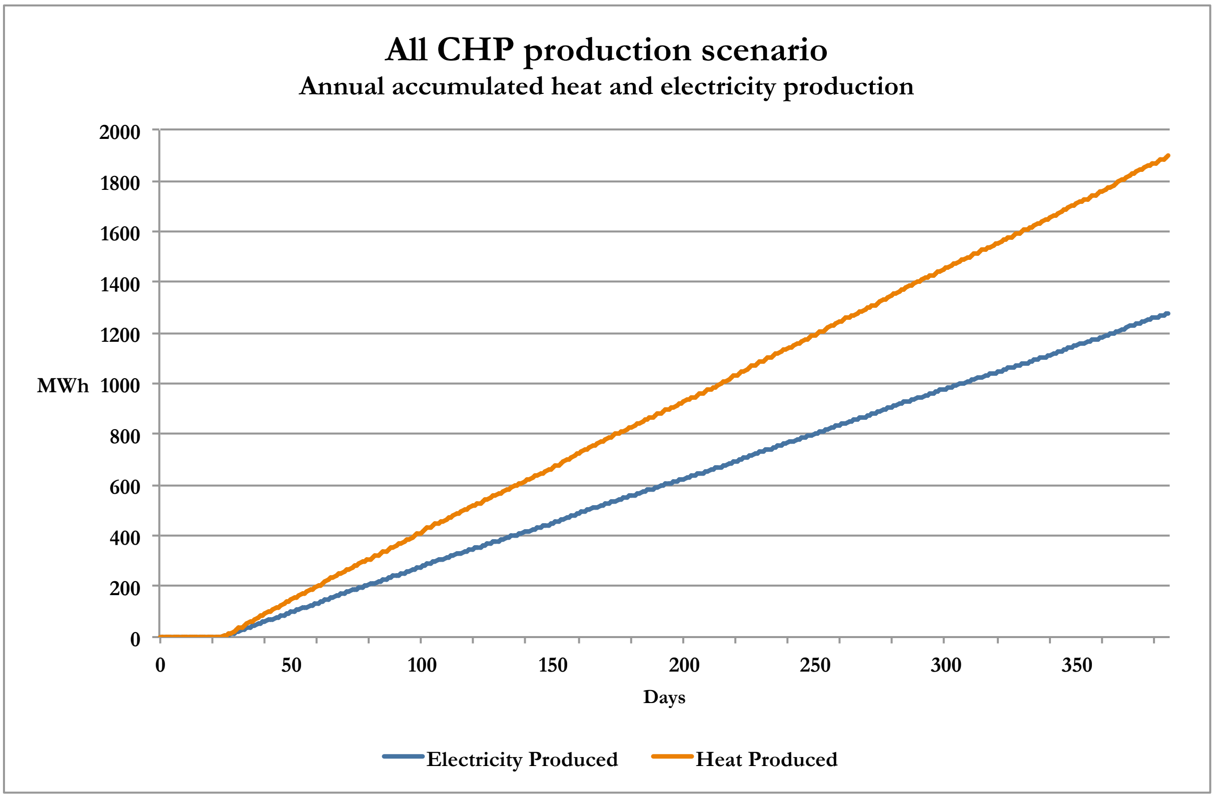


Figure 21 All CHP production scenario- Annual accumulated heat and electricity production

The electrical production per day is equal to 3,5 MWh. This can be compared to the average domestic use of electricity per electrified household of a country with a similar average living standard to the Wuxi eco-city. The reason that the average electrical use in China is not used is because of the higher living standards that the eco-city will have compared to China as a whole.

Germany would be an interesting comparison since they have similar climate conditions and energy demands. The domestic electrical usage per electrified household in Germany is 9,6 kWh compared to China's which is 3,7 kWh. This results to that, with German standards, the electricity produced could meet the energy demands of approximately 360 households (Shrink That Footprint Ltd, 2013). If the Chinese figure is used the electricity can supply 950 households. This can in turn be can be compared to the projected amount of households for the eco-city which is 7400, satisfying 5 percent of the cities domestic energy demand with German standards and 13 percent with Chinese standards. This figure of 5 percent can be seen as relatively low and the use of biogas for the production of electricity can be questioned. On the other hand the figures can be seen to China as a whole, if all of China integrated similar systems of organic waste collection and sludge separation 13 percent of the country's domestic energy demand could be satisfied.

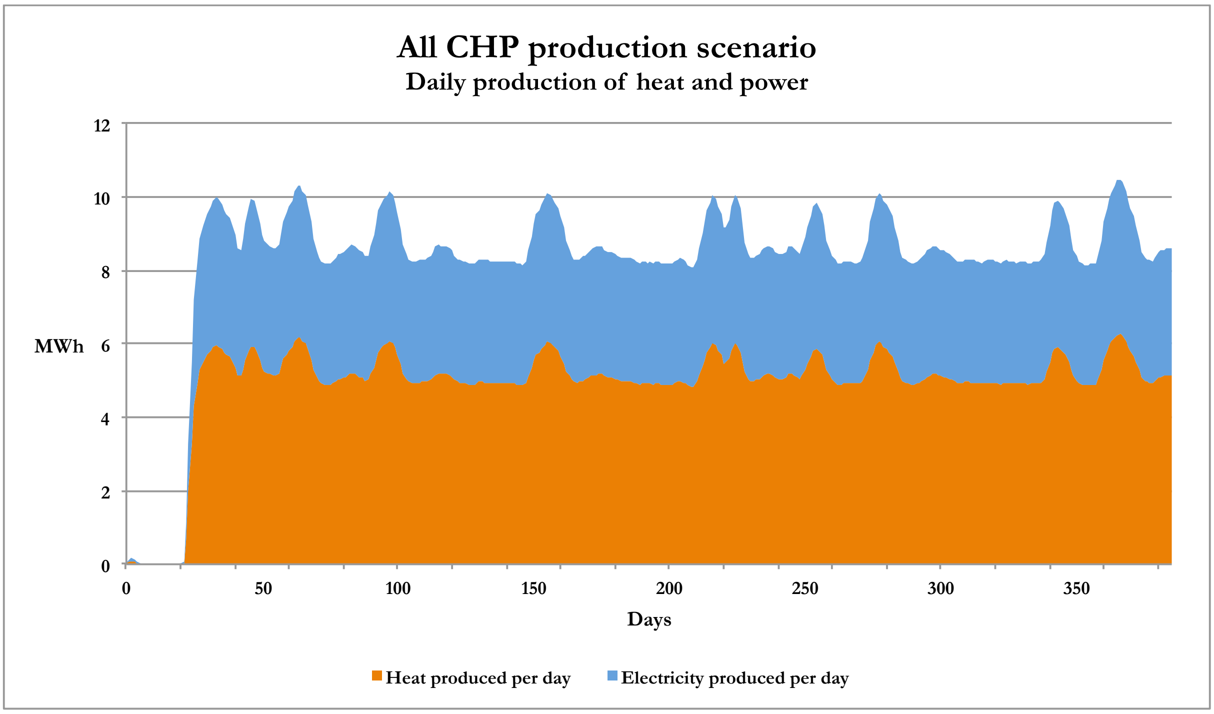


Figure 22 All CHP production scenario- Daily production of heat and power

The stacked graph in Figure 22 illustrates the daily production of heat and electricity from the CHP plant. The average production of heat after the start up phase equates to 5,2 MWh per day with highs at 6,2 MWh and lows at 4,8 MWh. The electrical production as mentioned above averages at 3,5 MWh with highs at 4,2 MWh and lows at 3,2 MWh. These differences are due to the spikes in biogas production that have been explained earlier. However the spikes in production for the CHP plant are only a result of how our model is built. Theoretically biogas could be stored and burned at a later time enabling the heat and power production to be tailored to the energy demands. This is an advantage that many other renewable energy sources lack. For example wind and solar power production is dictated by outside factors, such as wind conditions and hours of sunshine.

4.1.3 All refinery production (C)

Figure 23 shows a line graph displaying the annual production of bio methane in 10^3 m^3 accumulated over 385 days, including the first twenty days of start-up time for the AD process. The graph shows the scenario of allocating 100 percent of available raw biogas from the AD tanks to the refinery plant. Adding each day's production sums up to an accumulated annual production of 380 000 m^3 of bio methane, equivalent to roughly 60 percent output of the input of raw biogas in the refinery plant.

Figure 24 displays the all-refinery scenario with a production of bio methane based on 100 percent of the biogas produced in the AD process. The stacked graph shows the daily production of bio methane over time, including the twenty days of start-up time. The average daily output of bio methane equates to 1030 m^3. Observed variations are as previously mentioned in scenario A, a variation in the eating habits of the Chinese people, due to the events of holidays displayed in appendix A.

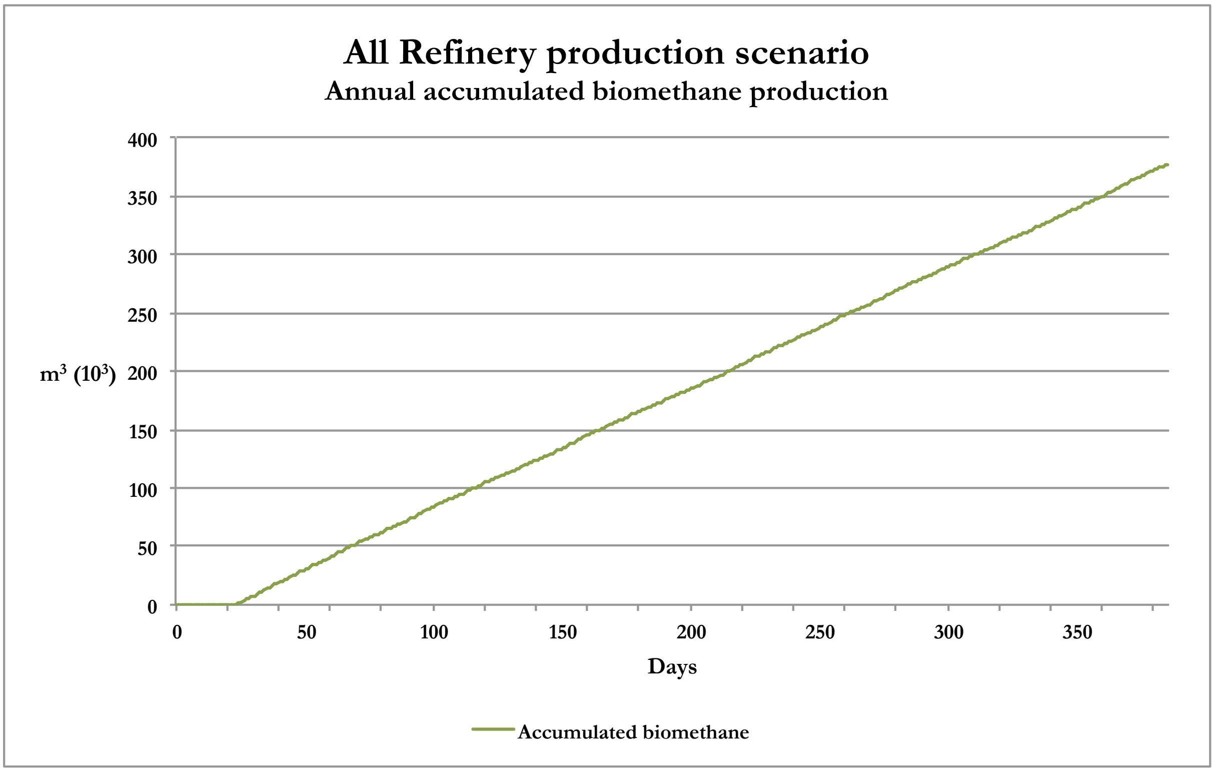


Figure 23 All refinery production scenario- Annual accumulated bio methane production

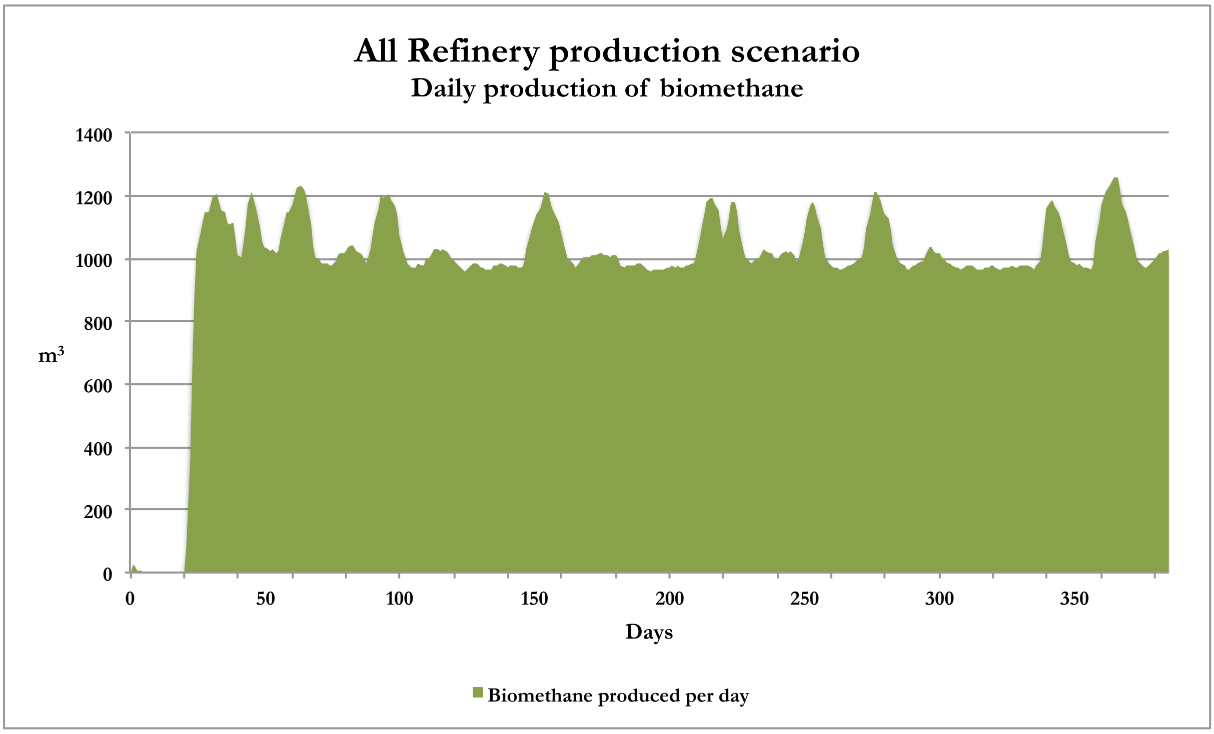


Figure 24 All refinery production scenario- Daily production of bio methane

This scenario shows the full capacity of bio methane production for this energy system. Using the same constants for a vehicle's consumption of biofuel and average transport length per year as mentioned in scenario A, the accumulated amount of bio methane in this scenario suffices to supply roughly 250 biofuel driven cars per year. This result shows of a considerably low flow of bio methane for the eco-city that will hold 20 000 inhabitants, in addition to achieving possible goals of public transport that may run on green fuel. Therefore the proposition in combination with these results for this all-refinery scenario is that the produced bio methane may be mixed up with the more available source of natural gas. Natural gas and bio methane share equal characteristics and the possibility to blend them for the use of vehicles is a solution that can meet the standards of the eco-city in some sense. An example of suitable distribution can be extracted from the environmentally forward country of Germany. Their recent progress in increasing bio methane percentage in natural gas mixtures has gone from 6 percent to 15 percent. (Müller, 2013)

The Wuxi Sino-Swedish Eco-City is projected to apply transport possibilities that enable and to some extent, ensure, a 20, 35, 45 percent allocation between walking/bicycling, public bus transport and cars respectively. (Wuxi Taihu New Town Eco-City, 2012) These numbers in addition to average statistics for the size of China's car-driven population[10], an example suitable for this scenario can be given. If roughly 3 000 inhabitants of the Sino-Swedish Eco-City will own a vehicle, and the sought goal is that the bio methane of the energy system should be used as an environmentally friendly vehicle-fuel, then the contribution of natural gas is required for and the percent of bio methane in the mixture would represent 8 percent.

[10] *As calculated based on 2011 statistics with 78 million car vehicles in China, (Tencer, 2011) and a Chinese population of 1,34 billion people (Wikipedia, 2013).*

4.1.4 Comparison of scenarios A, B and C

Figure 27 shows a comparison between the three previous scenarios. The bars display the amount of annual energy production in MWh, where bio methane has been converted from actual volume of bio methane to the energy content of the gas. The purple bars show the total amount of energy from the different energy outputs of the three scenarios with no consideration to the quality or applicability of the energy forms.

The main noticeable factor of this graph is the impact of the losses existent when a CHP production is included. For the all-CHP scenario the losses equal 13 percent of the total energy content of the raw biogas. For the integrated scenario the losses connected to the CHP production only affect the 20 percent of the raw biogas, meaning a total energy loss in the integrated scenario of 2,6 percent. However, worth noting is that even though the refinery seems to have no energy losses it does require a higher energy demand in its production process which in some aspect favors the choice of CHP production. This matter is further discussed in the section 4.2 Additional discussion.

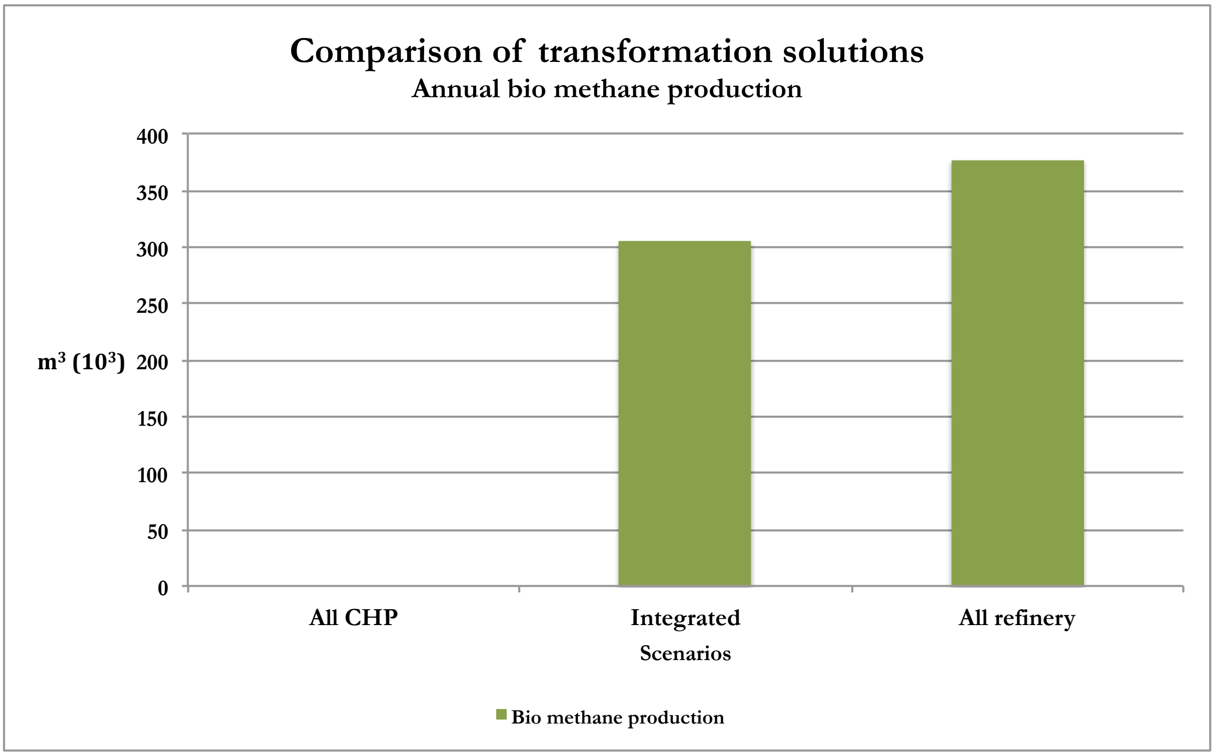


Figure 25 Comparison of transformation solutions- Annual bio methane production

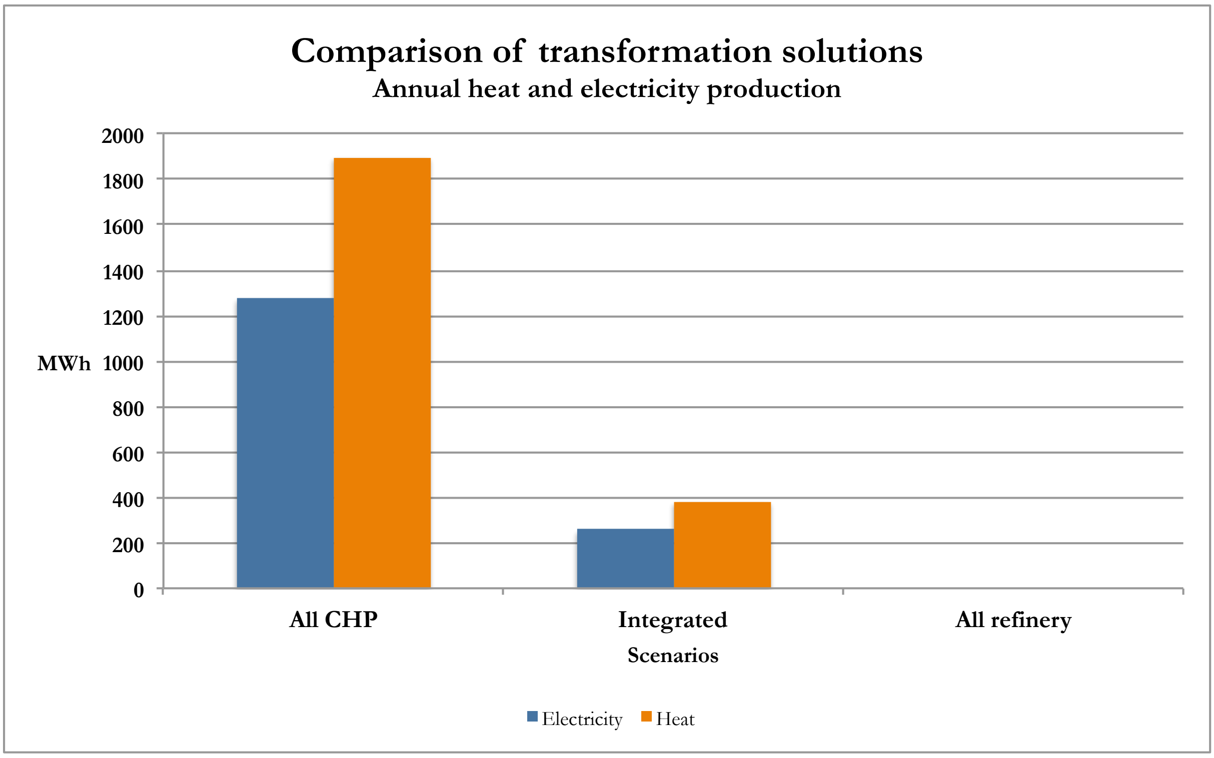


Figure 26 Comparison of transformation solutions- Annual heat and electricity production

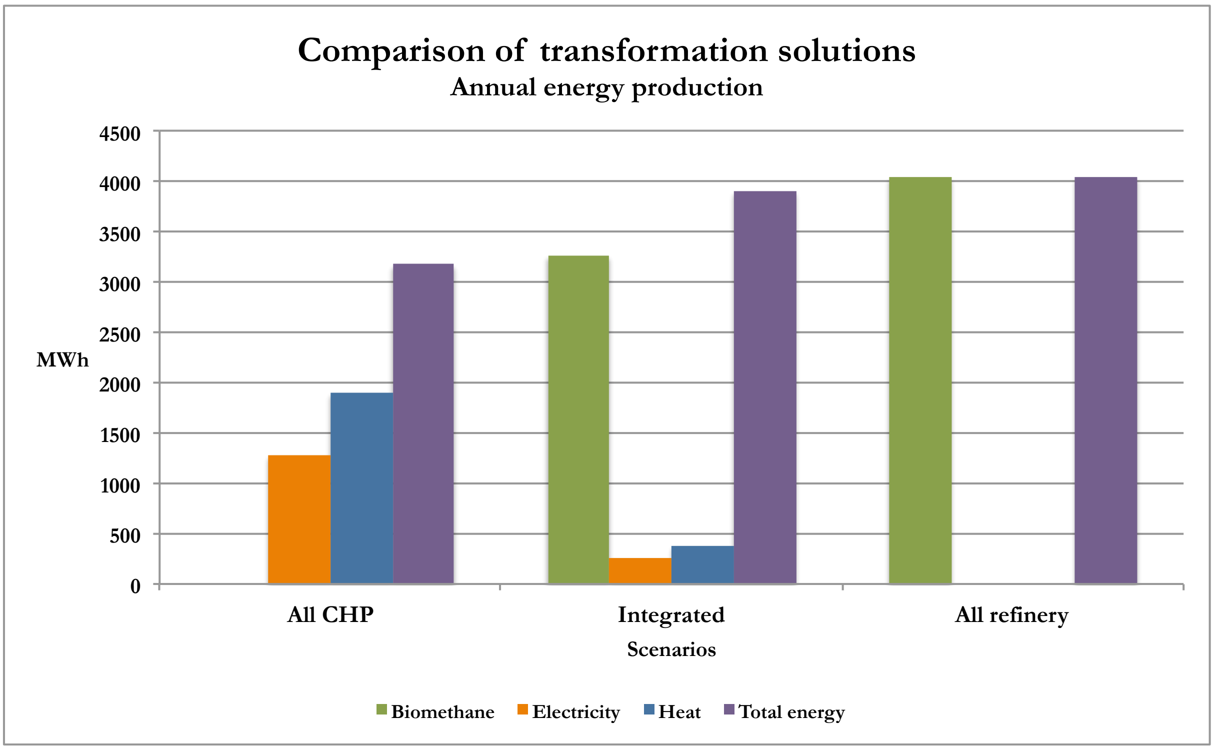


Figure 27 Comparison of transformation solutions- Annual energy production

Table 12- Usage areas for bio methane and electricity for the seperate scenarios

Scenario	No of cars with biofuel annually	No of households supported annually
Integrated	200	72
All CHP	0	360
All refinery	250	0

The summary of the usage areas for the different outputs is displayed in Table 12. Here the watts of power and cubic meters of biogas are converted into units that are more tangible and easier to grasp. Assumptions have been made surrounding the energy usage per household, fuel consumption and annual driving distances. The calculations behind these assumptions are discussed in earlier sections. Interesting comparisons can be made between the value of satisfying the demand of 360 households electricity needs and producing fuel for 250 gas driven cars. The need for environmentally friendly transport fuels can be considered to be larger because of the difficulty in creating clean mobile forms of energy that can be utilized by vehicles on the road today. More renewable options for the production electricity exist, for example wind, solar and hydropower. However on the other hand, in order to create any value for the society cars with biogas systems must exist.

4.1.5 Population (D)

Figure 28 displays the annual bio methane production for the five different population scenarios when only the refinery is used. While Figure 29 displays the same five scenarios, run with only CHP production creating heat and electricity as outputs. The estimated population for the Sino-Swedish Eco-city is 20 000 residents which is represented in the medium scenario in Figure 30, producing 378 thousand m^3 of biogas. The scenarios investigated are 10 and 25 percent increase and decrease from the scenario with 20 000 residents.

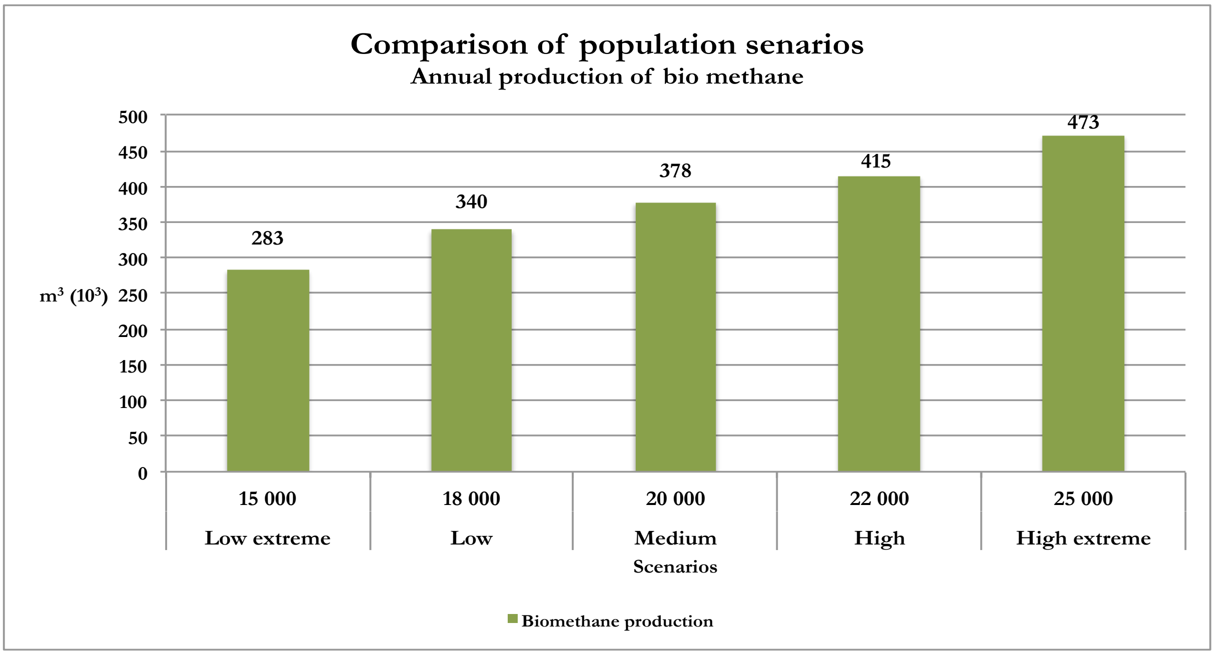


Figure 28 Comparison of population scenarios- Annual production of bio methane

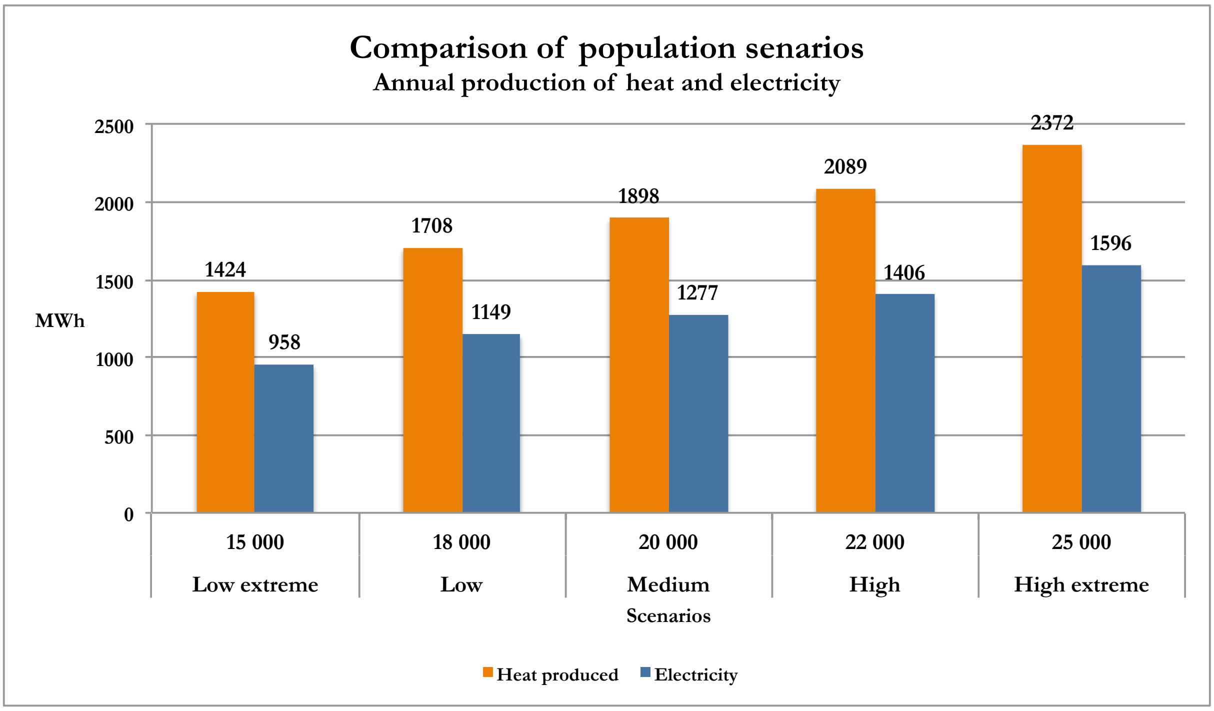


Figure 29 Comparison of population scenarios- Annual production of heat and electricity

When the bio methane production is examined one sees that the increase in the population factor is linearly connected to the increase in gas production. This is illustrated if the increase between the medium and high scenarios is compared to the increase between the high and high extreme. The calculation illustrates that every additional person in the eco-city adds 19 m^3 of bio methane production.

$$\frac{473-415}{25\,000-22\,000} \approx \frac{415-378}{22\,000-20\,000} \approx 19\ {m^3}/{new\ person}$$

Eq. 14

These figures for scenarios can be vital in the economic calculations and profitability scenarios for different occupancy rates. For example if the eco-city does not attract enough residents to fill the area, how will this affect the biogas production and thereby the revenues created. Similar equations can be done for the heat and the electricity production, and they are displayed in Equation 15 and Equation 16.

$$Heat\ production\ increase\ per\ person = 64\ {kWh}/{person}$$

Eq. 15

$$Electrical\ production\ increase\ per\ person = 94\ {kWh}/{person}$$

Eq. 16

4.1.6 Comparison of Envac and FDW (E and F)

In this section the result for the technology choice between the Envac and food disposer are presented and discussed. The two technologies differ in their transportation of food waste to the digestion plant.

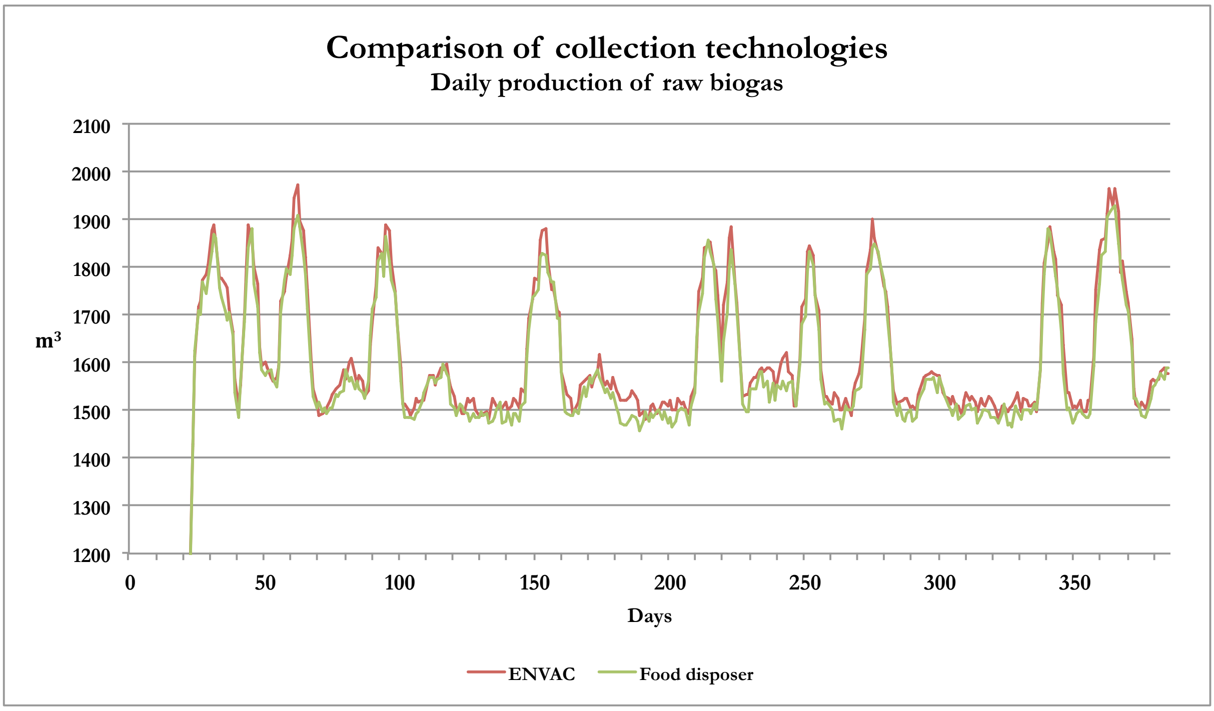


Figure 30 Comparison of collection technologies- Daily production of raw biogas

In Figure 30 the daily productions of raw biogas are compared. The y-axis has been altered to more clearly show the differences between the two technologies. The graph shows that the red line representing the Envac system is positioned higher than the food disposer (green line) for the majority of the time. When the averages are compared this observation is further backed up. The Envac average equates to 1523 m^3 per day and the food disposer scenario average equates to 1504 m^3 per day.

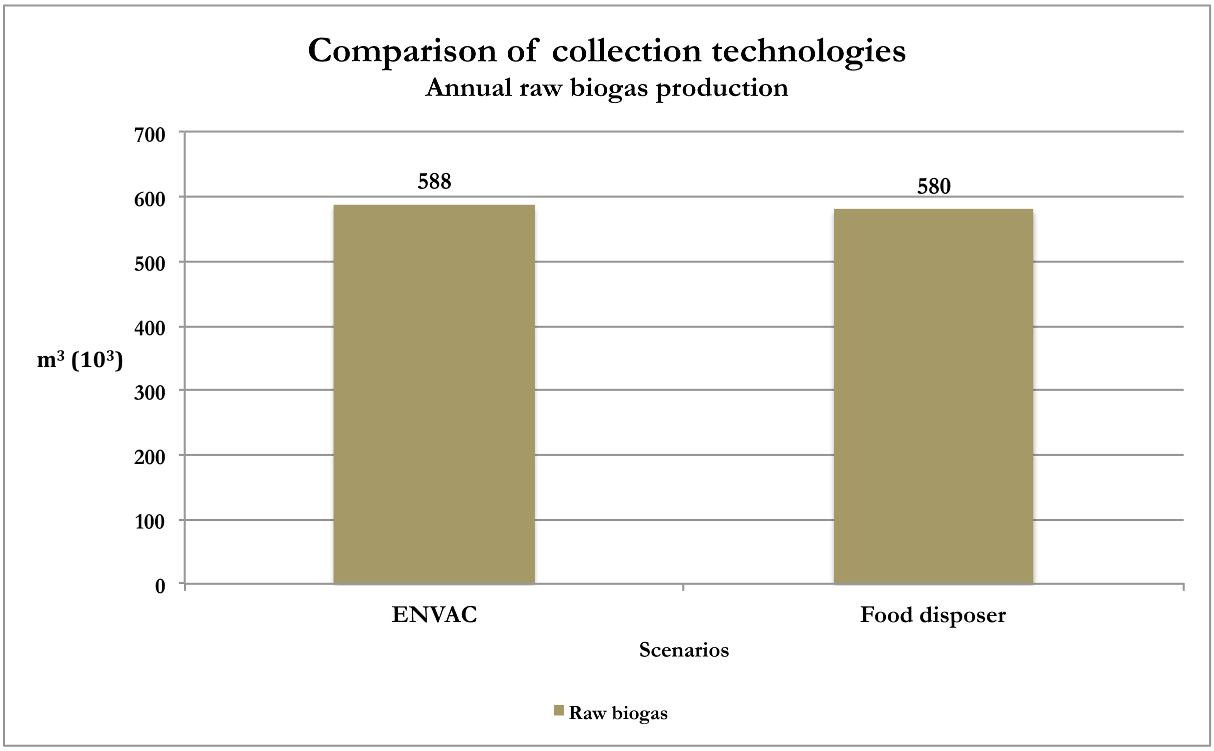


Figure 31 Comparison of collection technologies- Annual raw biogas production

When the daily flows are totaled to equal the annual production of raw biogas, the bars seen in Figure 31 are created. These show the total volumes of gas produced over the period of a year. The Envac solution totals to a production of 588 000 m^3 while the food disposer solution produces 580 000 m^3 of raw biogas. This is an 8 000 m^3 difference or a 1,4 percent difference in production.

These differences arise due to losses of methane that occur in the sewage system. In the sewage system anaerobic environments can occur leading to an anaerobic digestion of the organic material. The organic waste is also broken down in ordinary aerobic digestion, which leads to energy losses in the form of heat. This loss for water plant centered anaerobic digestion totals to a 3,1 percent methane loss in the system. The Envac system is however not free from these losses either. These environments for anaerobic digestion occur there as well but to smaller extent. The methane loss factor for solid waste collection averages to about 1,7 percent. (Jonerholm & Lundborg, 2012)

In the model these percentages are weighted to the flows of sewage and food waste. The sewage flow always has 3,1 percent loss and the food waste flow has a 3,1 percent loss when using the food disposer system and a 1,7 percent loss with the Envac system.

While the Envac system has a lower methane loss it also has a greater energy usage during the waste collection process. Even though it has a much smaller energy demand than traditional collection processes such as garbage trucks, it still requires energy for the running of fans in the vacuum creation process. The food waste disposer utilizes the flow of sewage for transport and minimizes the energy used for transport to minute amounts. These energy demands come from the grinding process when the food is chopped up into minute pieces as well as the increased separation load at the water treatment plant.

However the most decisive factor in the choice of waste collection does not come from the model or any energy demands but rather from the made decisions of the Sino-Swedish Eco-city's project-leaders. They have already decided on the use of an Envac system as the main collection technology for the city. Orders have been made and a plan for the area is already underway. (Wuxi Taihu New Town Eco-City, 2012)

4.2 Additional discussion

4.2.1 Economic feasibility and comparison

In this section the economic properties of the different technologies will be discussed and compared. The basis for the following discussion is on the tables disclosed in section 2.6.4, and proportional costs for each scenario will be discussed.

Table 13 - Shows the separate costs for O&M and installation and the total cost for each one of the A, B, and C scenario.

Scenario	Electricity (kWh)	Bio methane (m3)	Biogas (m3)	O&M costs ($/year)	Installation cost ($)	Total cost 1st year ($)
Integrated scenario	130 000	305 000	600 000	69 100	399 080	**468 180**
All-CHP scenario	1 280 000		600 000	25 700	226 080	**251 780**
All-refinery scenario		380 000	600 000	81 300	462 400	**543 700**

The three tables of Appendix B show the reorganized versions of the tables in section 2.6.4, where the given costs for O&M and Installation for each plant that has been used and the annual overall costs for different levels of output have been calculated. The first table shows the costs for an AD plant, where the annual O&M costs and the one time installation costs show proportional relation to the size of the output of biogas in m^3 of the plant. The two following graphs have similar disposition, where the annual output of electricity in kWh affects the costs for a CHP plant, and annual output of bio methane in m^3 affect the costs for a refinery plant respectively.

These tables help to calculate the size of costs are related to the different scenarios discussed in previous section. By using the tables and creating factors such as the relationship between outputs of plant to annual O&M costs, it has been possible to establish which scenario that seems the most cost-effective.

Error! Reference source not found. displays the separate costs for the A, B and C scenario and he total cost for the first year, which year is equal to the whole amount of installation cost plus a one year O&M cost. It shows approximate numbers, they cannot be used with a perfect compatibility to the situation for the energy system conceptualized in the Sino-Swedish Eco-City. However, they prove a good case when comparing the scenarios and it can be seen that the all-refinery scenario is the most expensive, roughly 16 percent larger costs than that of integrated scenario and fully 116 percent more costly than only using CHP.

Using all biogas for CHP production is considered the most economic option due to its installation cost being almost half the size of the two other scenarios, and an annual O&M cost no bigger than $26 000. The refinery plant can be seen as fairly expensive for annual O&M and the installation cost turns out greater than using some raw biogas for a small-scale CHP in addition to the refinery as displayed in scenario A. However, **Error! Reference source not found.** shows only two financial cost parameters, and cannot fully represent the entire financial situation, where other factors play a significant part in the actual case. E.g. are the vast infrastructure costs for building the heat distribution networks needed when building a CHP plant on a new location.

One factor that is not included when comparing the alternatives is revenues. Both the integrated scenario and the all-CHP scenario produce electricity that is otherwise fairly simple to produce with other means but will always be in high demand. The refinery generates only upgraded biofuel, which is considered a valuable source of substantial revenues as the demand for biofuels increases. The Sino-Swedish Eco-City may choose to structure a transport system, which should as far as possible use upgraded biogas, and in this case the biofuel would be in high demand, regardless of costs. Electricity and heat are also valuable energy sources, however the alternatives to produce these are more due to other energy sources available such as wind, solar and waterpower respectively district heating for heat.

The O&M costs for the integrated scenario are roughly 170 percent larger than that of the all-CHP scenario, and 16 percent smaller than that of the refinery. These numbers may be subject for further discussion, outside the scope of this report. This is due to the difficulty of comparing results only based on one source of cost information. When interconnecting two different plants the costs would naturally increase more due to additional costs including larger construction needs, more personnel and infrastructure costs such as pipelines and transport.

Summarizing the discussion above, it can be stated that the all-refinery scenario is the most costly, when compared to the two other solutions. Running a CHP plant is considered economic feasible when only examining the options based on their expense status, however when adding more variables to the equation, the situation gets more complex. The Sino-Swedish Eco-city can choose to focus on production on bio methane only due to the revenue opportunities when selling the gas to central gas filling stations for cars and public transport of the city. Even if the output of both bio methane and of heat and power are all equally small-scale, the use of the outputs can differ. Bio methane can be mixed with a suitable percentage of natural gas and used as a fuel that emits less greenhouse gases than that of petrol and diesel. With CHP, the outputs in heat and power do not support a large amount of houses, and the outputs can be produced with other means.

However, in addition to this one should also consider economies of scale. The production of bio methane is very costly when only producing small amounts of biofuel, but as Figure 8 in section 2.6.4 shows, the production costs of producing bio methane decreases as the amount of fuel input for the refinery increases. For the amount that our model has shown to produce the figure shows a high cost per produced cubic meter. The clear scale hurdle seen in the graph is thereby not reached. If there would be a possibility to connect more residents, large supermarkets and restaurants to the collection process of organic waste, then the installation costs and O&M costs would not be significantly expensive when achieving more revenues from a larger output. The same goes with the CHP production of course but to a smaller extend. As explained in section 2.5.1**,** small-scale CHP plants are more common and readily available.

Finally, worth mentioning is the errors in the calculations of the costs that may contribute to an unfair presentation of the scenarios. The costs related to the refinery plant and the AD plant are extracted from a Swedish benchmark showing a similar energy system, and the CHP costs are based on a situation where fuel costs are not included. The calculations have been rounded off in order to be used more general, and should preferably only be used as a comparison in size and proportion to each other, rather than exact numbers.

4.2.2 Sustainability discussion

A large factor in the sustainability of a technology or system is its emissions of greenhouse gases. Biogas production uses renewable organic material as its production source. This means that all of the material that is used is part of the organic lifecycle making the process carbon neutral and renewable. Fossil fuels, contrary to this, are not included in this cycle and therefore add to the total amount of carbon dioxide and greenhouse gases.

If a comparison is made, one cubic meter of upgraded biogas is equal to 1,1 liters of petrol. (Baltic Biogas Bus, 2009) The carbon dioxide emissions per liter for petrol are 2,35 kg/liter. (EPA, 2012) With an approximate conversion of the produced bio methane to petrol, the annual bio methane production equates to 418 000 liters of petrol. With carbon dioxide emissions of 2.35 kg/liter the total emissions saved equal 980 tones of carbon dioxide.

The recycling and reuse of substances present in the organic material is vital to creating a sustainable society. When organic material is collected and sorted, it simplifies the recycling of needed substances. The residues from the process of anaerobic digestion can then be used as fertilizer for farming and soil enrichment. This means that these elements do not need to be artificially produced or extracted from other locations reducing costs as well as the environmental impact.

The digestion process of waste has been used in controlled environments for generations as a way of handling waste products. The digestion process reduces the unpleasant odors associated with waste products and thereby creating a more desirable environment for the inhabitants. This is also part of the sustainability of our society, especially as we continue to live in more compact areas with increasing populations.

Apart from environmental sustainability, biogas production is also economically sustainable. To be less dependent of outside energy supply means that the society is less vulnerable to increased energy prices. These increases in cost of energy are especially plausible in China where living standards are increasing and thereby the demand for energy. By creating energy from the society's waste product, the system tries to utilize all available resources to create value.

4.2.3 User behavior discussion

The results of this report are based on a number of assumptions regarding the Sino-Swedish Eco-City that has been incorporated in a simulative model in STELLA. The assumptions have been connected to factors such as the number of future inhabitants, how much waste they dispose of and availability of space for different technologies and plants. This process has led to a model that displays the potential and capacity for production of bio methane, electricity and heat respectively for the Sino-Swedish Eco-City. However, the model does not include any consideration to loss factors such as lacking recycling efforts from the citizens of the Eco-City.

The fact that all people may not fully separate their organic waste from their combustible waste would affect the model if it were to be included. The outputs of biogas would decrease if less amount of waste reached the AD plants. The effect of poor user behavior of the residents would also make a larger impact due to the risk that waste in the forms of plastic, metallic waste and other inorganic materials would reach the AD tanks.

Using the Envac system for the collection process of organic waste can be very useful due to its system of different disposal chutes for each house, where one chute is designated for combustibles, one for paper and the third chute solely for organic waste. However, the risk that people do not understand the system or that they simply do not understand *why* it is expected of them to throw waste after these recommendations, will always be present. The solution to this usage behavior complexity is outside the scope of this report, however, the main action to prevent poorly performed recycling would be to clearly inform the residents of the system. With the use of notes, flyers and "how-to" guides for the whole process, a majority of the outputs could be secured. Residents need also understand the sustainable agenda of the Eco-City and therefore feel more enthused to collect their organic waste and make sure it ends up in the green chute of their house.

The comparison with the food waste disposer would simply be that of the technology. FWD is in many aspects easier to use in every day life. People used to simply mixing their waste in the garbage bag, might more easily get used to the task of throwing the food waste straight into the grinder in their sink. The model of this report may show a better result when using the Envac system, due to the methane losses connected to the FWD, however when including the effects of usage behavior the result might look slightly different because of the dissimilar levels of simplicity in recycling for the two techniques.

Summarizing the discussion above is that it states that the differences related to usage simplicity of the two collection techniques are not included in the model, and if they would be, the result might look slightly different regarding outputs values. Proposed solutions in how to assure a proper waste collection amongst residents is mainly to focus on instructions and easy-to-understand guidelines for the chosen technique.

5 CONCLUSION

The conclusions of this report will come to define how the original learning objectives have been fulfilled and if the expectations on the energy system of this report have been satisfied. The research and modeling of this report and for the Sino-Swedish Eco-City in China, have lead to the conclusion that:

- The potential for biogas production of the Eco-City is of the capacity 600 000 m^3 raw biogas, which may be transformed into either 380 000 m^3 bio methane or 1 280 MWh electricity and 1 900 MWh heat;
- The appropriate energy system solution to achieve the stated results have been encompassed into a conceptual model including a collection technology, a production process, and a transformation method;

    - The collection technology of choice is the Envac technology, mainly due to that it is already in the process of being built into the infrastructure of the city;
    - The production process of choice is anaerobic digestion tanks, where the Eco-City's organic waste constitutes the substrate; and
    - The transformation method of choice is the CHP plant, due to its ability to function well in small-scale production of heat and electricity.

- Seen from a wider perspective with both a sustainable and economical agenda, the choice of transformation method would be to use the produced biogas for upgrading, due to its ability to satisfy the increasing need of renewable fuels for transport; and by that
- Choosing the integrated solution structure, being the optimal choice by creating a self-sufficient system where the anaerobic process and the refinery are supported by a small-scale CHP plant;
- The system boundaries of this report have led to an energy system only including the Eco-City, preventing the possibility that the energy system may work more efficiently when increasing the interconnectivity with the surrounding city area of Taihu New District and Wuxi; meaning that
- A wider perspective is needed when analyzing and designing energy system with these characteristics.

6 FUTURE WORK

The numerous possibilities in how to create an energy system of this character for the Sino-Swedish Eco-City have left the authors with several suggestions on how to convene with future work. The reasons for leaving these topics uninvestigated is mainly due to them being outside the predefined system boundaries and the limitations of this report.

- Investigate in further sources of feedstock in order to gather more substrate for the anaerobic digestion process, e.g. live-stock waste from surrounding farms, large-scale restaurant and supermarket waste and purpose-grown vegetation feedstock, all of which are located outside of the Eco-City's borders;
- Examine how the energy system of this report would manage to interconnect further users from the Wuxi city, both for the collection of more organic waste, but also for the possibility to expand the distribution network of biofuel, heat and electricity;
- Elaborate the economical discussion of this report with more complex financial calculations on the investment opportunities and future profits of the different plants and technologies of the energy system; and
- Consider including the end-use of the bio methane, heat and electricity within the system boundaries in order to establish which feasible ways the energy can be used in the Eco-City.

REFERENCES

Avfallskvarn AB. (2011 1-January). *Avfallskvarn AB.* Retrieved 2013 10-March from Om Avfallskvarnar - Historik: http://avfallskvarn.se/historik.html

Avfallskvarn AB. (2011 1-January). *Om Avfallskvarnar - Fördelar med avfallskvarn.* Retrieved 2013 10-March from Avfallskvarn: http://avfallskvarn.se/om_avfallskvarnar.html

Astals, S., & Mata, J. (2011). *Anaerobic Digestion: Break the ice.* University of Barcelona, Barcelona.

Baltic Biogas Bus. (2009). *About biogas.* Retrieved May 1, 2013, from www.balticbiogasbus.eu: http://www.balticbiogasbus.eu/web/about-biogas.aspx

Banks, C. (2009). *Optimising anaerobic digestion.* University of Southampton.

BC Farms. (2010 1-January). *Feedstock Energy.* Retrieved 2013 25-February from BC Farm Biogas: http://www.bcfarmbiogas.ca/Feedstockenergy/feedstock

Bernstad, A., Davidsson, Å., Tsai, J., Persson, E., Bissmont, M., & la Cour Jansen, J. (2013). Tank-Connected Food Waste Disposer Systems. *Waste Management , 33* (1), 193-203.

Bouallagui, H., Haouari, O., Touhami, Y., Cheikh, B. R., Marouani, L., & Hamdia, M. (2004). Effect of Temperature on the Performance of An Anaerobic Tubular Reactor Treating Fruit and Vegetable Waste. *Process Biochemistry , 39* (2), 143-214.

Carlsson, A. (2013, March 27). Henriksdals Avloppsreningsverk. (A. Julin, & J. Siewert Delle, Interviewers)

Cederquist, B. (2013 4-February). Architect and Project Leader at GlashusEtt. (A. Juhlin, & J. Siewert-Delle, Interviewers)

Cederquist, B. (2009). *Facts and Figures on Hammarby Sjöstad.* Stockholm: Exploateringskontoret.

Combined Heat and Power Partnership. (2011). *www.epa.gov.* Retrieved April 10, 2013, from www.epa.gov/chp:
http://www.arb.ca.gov/cc/ccei/presentations/CHPEfficiencyMetrics_EPA.pdf

European Commission. (2012 18-September). *Biodegradable Waste.* Retrieved 2013 16-March from European Commission: http://ec.europa.eu/environment/waste/compost/index.htm

European Parliament. (2008). *Directive 2008/98/EC of the European Parliament and of the Council.* European Parliament.

Ecocity Builders. (2011). *International Ecocity Framework and Standards.* Oakland, California: Ecocity Builders.

Eggleston, S., Buendia, L., Miwa, K., Ngara, T., & Tanabe, K. (2006). *IPCC Guidelines for National Greenhouse Gas Inventories.* Japan: Institute of Global Environmental Strategies.

Envac AB. (2013 16-March). *Vakuumsystemets Historia.* Retrieved 2013 16-March from Envac: http://www.envac.se/om_envac/sopsug_vakuumsystemets_historia

Envac AB. (2009 1-August). *Vakuumteknologi.* Retrieved 2013 16-March from Envac: http://www.envac.se/produkter_och_tjanster/var_teknik/vakuumteknologi

Envac AB. (2009 1-January). *Envac Group*. Retrieved 2013 17-March from Wuxi - Sino-Sweden Low Carbon Eco-City: http://www.envacgroup.com/references/asia_-_greater_china/wuxi-sino-sweden-low-carbon-eco-city

Envac AB. (2013 16-March). *Fakta och Siffror*. Retrieved 2013 16-March from Envac : http://www.envac.se/om_envac/fakta-och-siffror

Enviros. (2011). *Norfolk government*. Retrieved April 23, 2013, from www.norfolk.gov: http://www.norfolk.gov.uk/view/ncc088274

Engineering News. (2012 2-November). *New Assessment Looks at Global Urbanization*. (Engineering News) Retrieved 2013 5-March from Engineering News: http://www.engineeringnews.co.za/article/new-assessment-looks-at-global-urbanisation-2012-11-02

EPA. (2008, December). *United States Environmental Protection Agency*. Retrieved March 15, 2013, from http://www.epa.gov/chp: http://www.epa.gov/chp/documents/catalog_chptech_full.pdf

EPA. (2013). *United States Environmental Protection Agency*. Retrieved March 16, 2013, from www.epa.gov/chp: http://www.epa.gov/chp/basic/biomass.html

EPA. (2012). *Greenhouse Gas Emissions from a Typical Passenger Vehicle*. Retrieved April 25, 2013, from www.epa.gov: http://www.epa.gov/otaq/climate/documents/420f11041.pdf

DECC. (2013). *Department of Energy and Climate Change*. Retrieved March 16, 2013, from chp.decc.gov.uk: http://chp.decc.gov.uk/cms/chp-technology/

Department of Energy Technology KTH. (2012 20-September). *KTH*. Retrieved 2013 26-February from Wuxi Sino-Swedish Eco-City: http://www.kth.se/en/itm/inst/energiteknik/forskning/ett/projekt/wuxiecocity/project-description-1.338870

Disperator AB. (2003 1-January). *Avfallskvarn*. Retrieved 2013 9-March from Disperator: http://www.disperator.se/avfallskvarn.aspx

Dosta, J., Galí, A., Macé, S., & Mata-Álvarez, J. (2007). Modelling a Sequencing Batch Reactor to Treat the Supernatant From Anaerobic Digestion of the Organic Fraction of Municipal Solid Waste. *Journal of Chemical Technology & Biotechnology , 82* (2).

Fulco, M. (2011 16-December). Sustainable business bolsters Sino-Swedish ties. *China Daily Shanghai Bureau* .

Fan, X., Li, Z., Wang, T., Yin, F., & Jin, X. (2010). *Introduction to a large-scale biogas plant in a dairy farm*. University of Science and Technology Beijing, Department of Environmental Engineering, Beijing.

Fränne, L. (2007). *Hammarby Sjöstad - A Unique Environmental Project in Stockholm*. Stockholm: GlasHusEtt.

Gupta, S. (2010). Cold Climates No Bar to Biogas Production. *New Scientist , 208* (2785).

Government of Singapore. (2013 4-February). *Tianjin Eco-City: A Model for Sustainable Development*. Retrieved 2013 5-March from Tianjin Eco-City: A Model for Sustainable Development: http://www.tianjinecocity.gov.sg/index.htm

Gray, D., Peck, C., & Suto, P. (2008). *Anaerobic Digestion of Food Waste.* Environmental Protection Agency.

IEA. (2000, January 1). *Biogas Upgrading and Utilization.* Retrieved April 16, 2013, from iea-biogas.net: http://www.iea-biogas.net/_download/publi-task37/Biogas%20upgrading.pdf

Insinkerator. (2012 1-January). *Environmental Benefits.* Retrieved 2013 16-March from Insinkerator: http://www.insinkerator.co.uk/environmental-benefits

Isee Systems. (2013 1-January). *Isee Systems.* Retrieved 2013 17-March from Stella: Systems Thinking for Education and Research: http://www.iseesystems.com/softwares/Education/StellaSoftware.aspx

Hald, M. (2009). *Sustainable Urban Development and the Chinese Eco-City: Concepts, Strategies, Policies and Assessments.* Lysaker, Norway: Fridtjof Nansens Institute.

Herrero, M. J. (2007). Experiencia de Transferencia Tecnológica de Biodigestores Familiares en Bolivia. *Livestock Research for Rural Development , 19.*

Hoornweg, D., & Bhada-Tata, P. (2012). *What a Waste, Global Review of Solid Waste Management.* Washington D.C: The Worldbank.

Jonerholm, K., & Lundborg, H. (2012). *Methane losses in the biogas system.* Baltic Biogas Bus.

Kwofie, C., & Ofori-Boateng, E. (2009). Water Scrubbing: A Better Option for Biogas Purification for Effective Storage. *World Applied Sciences Journal* , 122-125.

Krich, K., Augenstein, D., Batmale, J., Benemann, J., Rutledge, B., & Salour, D. (2005). *Biomethane from Dairy Waste: A Sourcebook for the Production and Use of Renewable Natural Gas in California.* Western United Dairymen .

Müller, C. (2013, March 27). Biomethane takes off.

Malmqvist, A. (2013, March 26). Micro-CHP. (A. Julin, & J. Siewert Delle, Interviewers) Stockholm.

Meadows, D. H. (2008). *Thinking in Systems: A Primer.* Vermont: Chelsea Green Publishing.

Petersson, A., & Wellinger, A. (2009, October). *International Energy Agency.* Retrieved 04 24, 2013, from www.iea-biogas.net: http://www.iea-biogas.net/_download/publi-task37/upgrading_rz_low_final.pdf

Sacher, N., Ortiz, E. R., Gensch, R., & Spuhler, D. (2009). *Sustainable sanitation and water management.* Retrieved April 23, 2013, from www.sswm.info: http://www.sswm.info/category/implementation-tools/reuse-and-recharge/hardware/energy-products-sludge/biogas-electricit-0

Scandinavian Biogas. (2013). *Scandinavian Biogas.* Retrieved April 24, 2013, from www.scandinavianbiogas.se: http://www.scandinavianbiogas.se/index_why.php?option=displaypage&main=102&subid=102&show=190

Severn Wye Energy Agency. (2012). *Biogas Regions - An Introduction to Biogas and Anaerobic Digestion.* Severn Wye Energy Agency.

SEAI. (2013). *Sustainable Energy Authority of Ireland*. Retrieved April 24, 2013, from www.seai.ie: http://www.seai.ie/Publications/Renewables_Publications_/Bioenergy/Upgrading_Biogas_to_Biomethane.pdf

Simader R., G., Krawinkler, R., & Trnka, G. (2006, March 2). *Austrian Energy Agency*. Retrieved April 10, 2013, from Austrian Energy Agency: http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0CDIQFjAA&url=http%3A%2F%2Fwww.buildup.eu%2Fsystem%2Ffiles%2Fcontent%2FD8%2520Report%2520-%2520Micro%2520CHP%2520state%2520of%2520the%2520art_FINAL_JB.pdf&ei=L_VzUdjpJMGJ4ASGuIGQDw&usg=AFQjCNGO4cUcqr7JinX6TnfmiVFBznPAnA&bvm=bv.45512109,d.bGE

Shafqat, O. (2013 26-February). Research Engineer at KTH. (A. Juhlin, & J. Siewert-Delle, Interviewers)

Shipley, A., Hampson, A., Hedman, B., Garland, P., & Bautista, P. (2008). *Combined Heat and Power - Effective Energy Solutions for a Sustainable Future*. Oak Ridge National Laboratory.

SLU. (2013). *Swedish University of Agricultural Sciences*. Retrieved April 21, 2013, from Swedish University of Agricultural Sciences: www.slu.se

Smith, A., Brown, K., Ogilvie, S., Rushton, K., & Bates, J. (2001). *Waste Management Options and Climate Change*. Culham: AEA Technology.

SSTEC. (2011 1-January). *Sino-Singapore Tianjin Eco-City*. Retrieved 2013 7-March from About SSTEC: http://sstec.dashilan.cn/en/SinglePage.aspx?column_id=10304

Stockholm Vatten AB. (2013). *Stockholm Vatten AB*. Retrieved April 26, 2013, from www.stockholmvatten.se: http://www.stockholmvatten.se/commondata/infomaterial/Avlopp/henriksdal_webb.pdf

Stockholm Stad. (2013 2-January). *Stockholm Växer - på väg mot ett Stockholm i världsklass*. Retrieved 2013 25-February from Hammarby Sjöstad: http://bygg.stockholm.se/hammarbysjostad

Rydberg, T., Belhaj, M., Bolin, L., Lindblad, M., Sjödin, Å., & Wolf, C. (2010). *Market conditions for biogas vehicles* . Swedish Environmental Research Institute.

Rapoport, E., & Vernay, A. (2011). *Defining the Eco-City: A Discursive Approach*. Amsterdam: Management and Innovation for a Sustainable Built Environment.

Rasi, S. (2009). *Biogas Composition and Upgrading to Biomethane* . JYVÄSKYLÄ STUDIES IN BIOLOGICAL AND ENVIRONMENTAL SCIENCE 202 .

Richards, B. K., Cummings, R. J., White, T. E., & Jewell, W. J. (1991). Methods for Kinetic Analysis of Methane Fermentation in High Solids Biomass Digesters. *Biomass and Bioenergy , 1* (2), 65-73.

Roberts, M. (2010). *Alachua County Organics Recycling Facility Feasibility Study*.

Tendaj, M., Andersson, R., & Moberg, P.-O. (2013). *Stockholms Vatten*. Retrieved April 26, 2013, from www.stockholmvatten.se .

The Wales AD Centre. (2010 1-January). *Mesophilic and Thermophilic Systems*. Retrieved 2013 4-March from The Wales Centre of Excellence for Anaerobic Digestion: http://www.walesadcentre.org.uk/technologies/mesophilicandthermophilicsystems.aspx

The Climate Group. (2012). *Concensus and Cooperation for a Clean Revolution: China and Global Sustainable Development.* Beijing: The Climate Group.

The Home Depot Inc. (2011 1-January). *Garbage Disposals.* Retrieved 2013 5-March from The Home Depot: http://www.homedepot.com/webapp/catalog/servlet/ContentView?pn=Disposers_Accessories&storeId=10051&langId=-1&catalogId=10053

Themelis, N. (2010 1-January). *WTE In China.* Retrieved 2013 5-March from Waste Management World: http://www.waste-management-world.com/articles/print/volume-11/issue-4/Features/wte-in-china.html

U.S. Energy Information Administration. (2012 4-September). *U.S. Energy Information Administration - China.* Retrieved 2013 1-March from U.S. Energy Information Administration: http://www.eia.gov/countries/analysisbriefs/China/china.pdf

United Nations. (1997). *Glossary of Environment Statistics.* New York: UN: Department for Economic and Social Information and Policy Analysis.

Yanfeng, Q. (2011 20-May). Green Works. *China Daily Asia Weekly* , pp. 8-9.

Zdaniuk, G. (2012, January). *The Chartered Institution of Building Services Engineers.* Retrieved March 3, 2013, from www.cibse.org: http://www.cibse.org/content/documents/Groups/CHP/Datasheet%203%20-%20Gas%20Turbines.pdf

Wuxi Taihu New Town Eco-City. (2012). *Index system of Wuxi Taihu New Town Eco-City.*

Vandevivere, P., De Baere, L., & Verstraete, W. (2003). Types of Anaerobic Digesters for Solid Wastes. In J. Mata-Alvarez, *Biomethanization of the Organic Fraction of Municipal Solid Wastes* (pp. 111-137). London: IWA Publishing.

Wang, J. Y., Xu, H.-L., Zhang, H., & Tay, J.-H. (2003). Semi-Continuous Anaerobic Digestion of Food Waste Using a Hybrid Anaerobic Solid-Liquid Bioreactor. *Water Science and Technology , 48* (4), 169-174.

Wang, M., Huo, H., & . Johnson, L. (2006). *Projection of Chinese Motor Vehicle Growth, Oil Demand, and CO2 Emissions through 2050* . Argonne National Laboratory, Energy Systems Division , Beijing.

Verma, S. (2002). *Anaerobic Digestion of Biodegradable Organics in Municipal Solid Wastes.* Columbia: Department of Earth & Environmental Engineering, Henry Krumb School of Mines.

Vijay, V. K. (2008). *Biogas Purification Using Water Scrubbing Systems.* Centre for Rural Development Technology. New Delhi: Indian Institute of Technology.

Wikipedia. (2013, April 7). *Wikipedia.* Retrieved April 17, 2013, from Wikipedia: http://en.wikipedia.org/wiki/British_thermal_unit

Wikipedia. (2013, April 17). *Wikipedia.* Retrieved April 27, 2013, from Wikipedia: http://en.wikipedia.org/wiki/Traditional_Chinese_holidays

World Wide Fund for Nature. (2011). *Hållbar Energi - 100% Förnybart på Naturens Villkor.* World Wide Fund for Nature.

WRAP. (2013). *Using Quality Anaerobic Digestate to Benefit Crops.* Wrap.

WTERT. (2009 25-November). *Waste-to-Energy Research and Technology Council*. Retrieved 2013 1-March from Waste-to-Energy Research and Technology Council: http://www.wtert.eu/default.asp?Menue=13&ShowDok=17

APPENDICES

Appendix A

Chinese holidays for 2014	
Holiday	Date
Laba	27-jan
Spring (New Year)	31-jan
Lantern	14-feb
Azure Dragon	02-mar
Shangsi	02-apr
Qing Ming'	05-apr
Dragon Boat	02-jun
Double Seventh	02-aug
Ghost	10-aug
Mid-Autumn	08-sep
Double Ninth	02-oct
Water Lantern	06-dec
Winter	28-dec

Appendix B

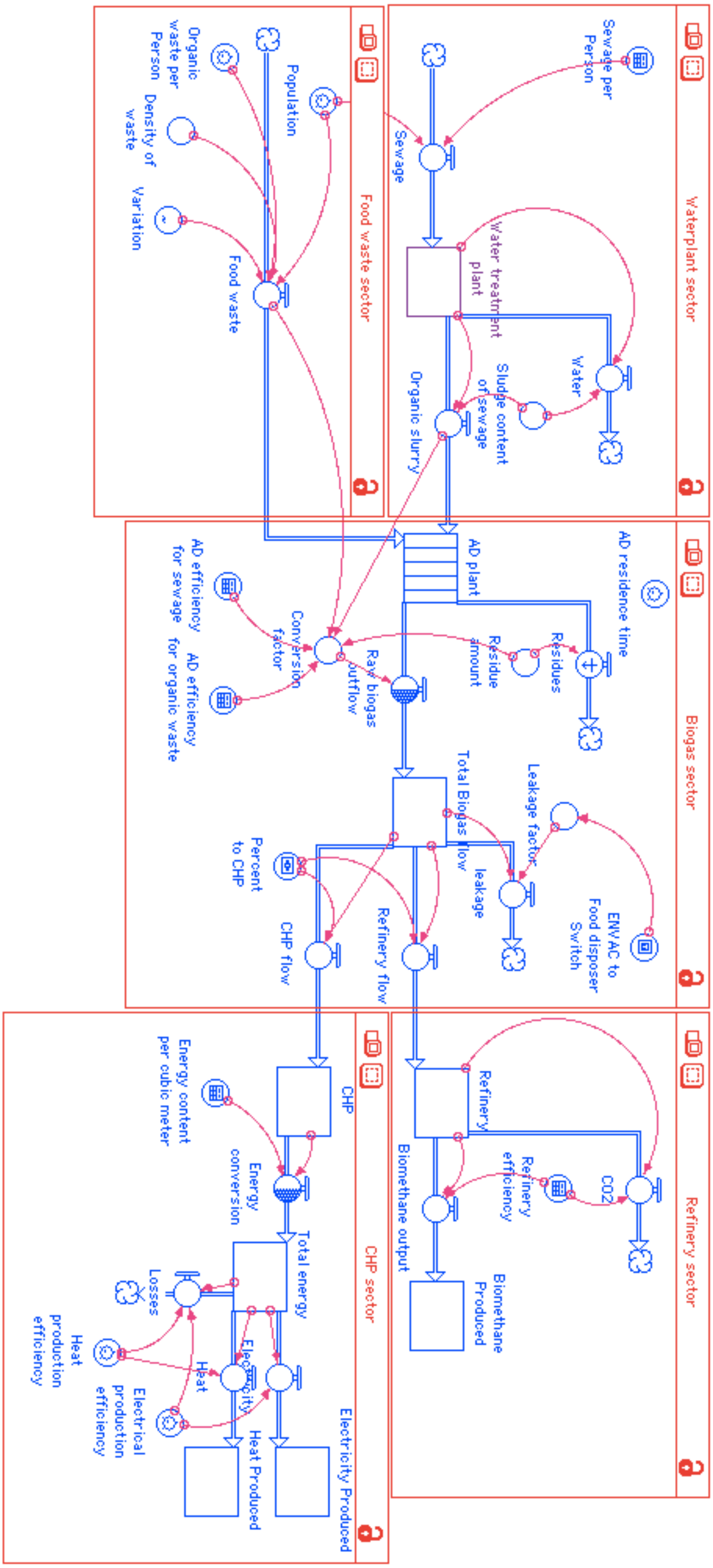
The tables below show the different costs for each specific plant.

COSTS FOR AN AD-PLANT		
Annual output of raw biogas (m3)	O&M Costs ($/year)	Installation cost ($)
100 000	2 000	11 000
200 000	4 000	22 000
500 000	11 000	44 000
700 000	15 000	61 000
1 000 000	21 000	88 000
1 300 000	28 000	114 000
1 500 000	32 000	131 000
2 000 000	42 000	175 000

COSTS FOR A CHP PLANT		
Annual output of electricity (MWh)	O&M Costs ($/year)	Installation cost ($)
500	5 000	68 000
750	7 500	103 000
1 000	10 000	137 000
1 250	12 500	171 000
1 500	15 000	205 000
2 000	20 000	274 000

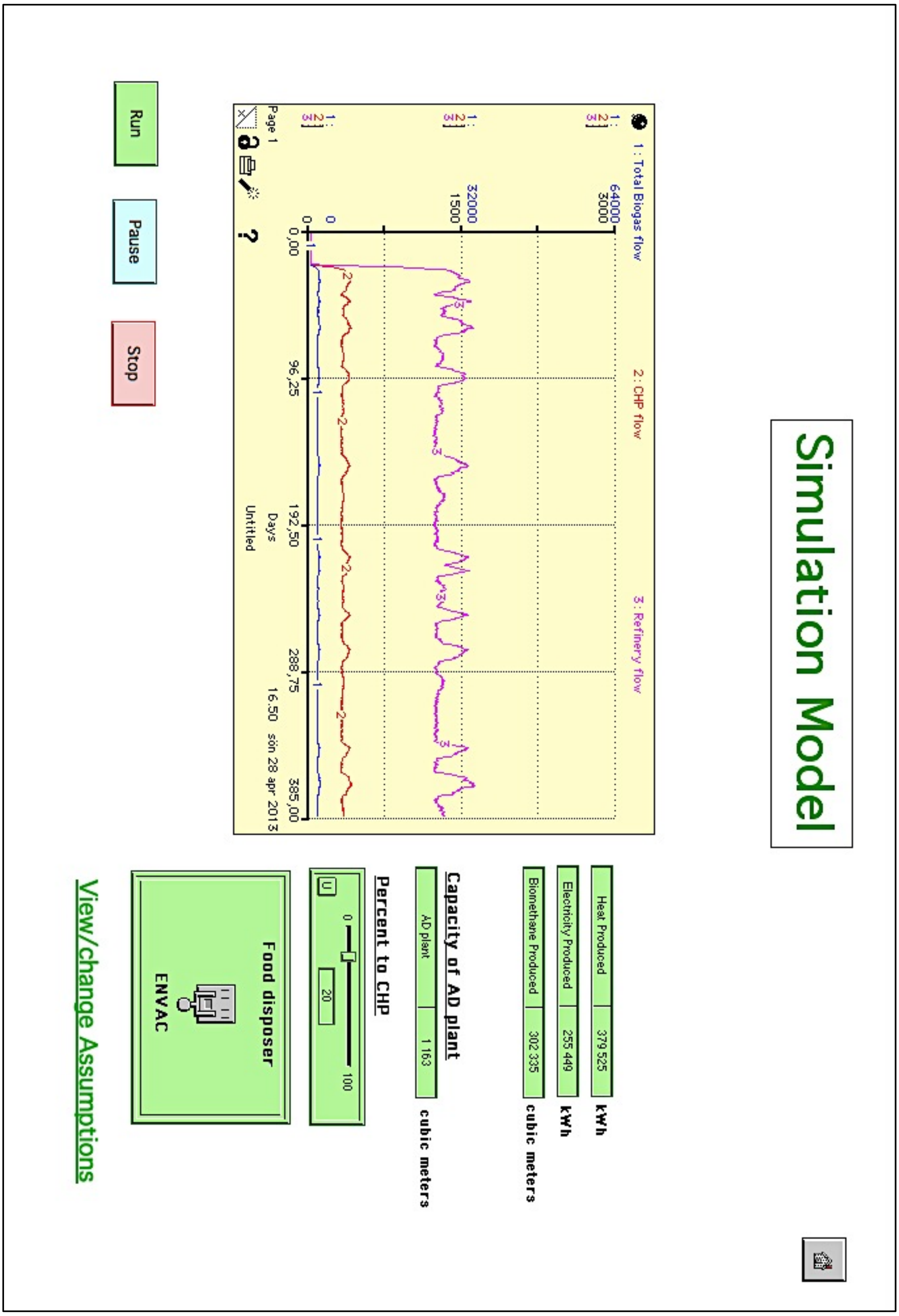
COSTS FOR A REFINERY PLANT		
Annual output of bio methane (m3)	O&M Costs ($/year)	Installation cost ($)
50 000	9 000	54 000
100 000	18 000	108 000
300 000	53 000	322 000
500 000	89 000	537 000
800 000	142 000	860 000
1 000 000	177 000	1 075 000

Appendix C

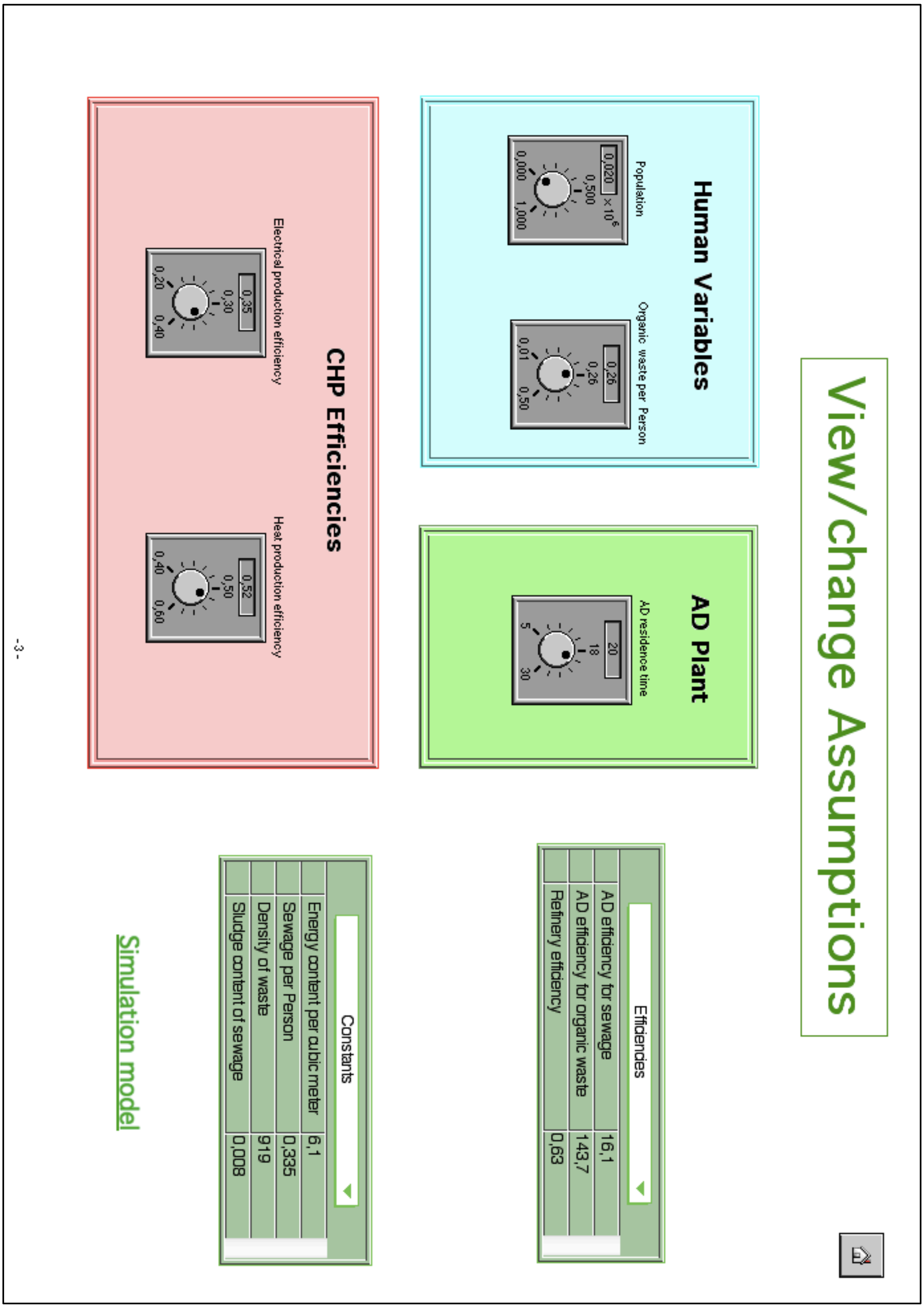


Waterplant sector
Sewage per Person
Sewage
Water treatment plant
Water
Sludge content of sewage
Organic slurry
Food waste sector
Population
Organic waste per Person
Density of waste
Variation
Food waste
Biogas sector
AD residence time
AD plant
Residues
Residue amount
Conversion factor
Raw biogas outflow
AD efficiency for sewage
AD efficiency for organic waste
Total Biogas flow
Leakage factor
leakage
ENVAC to Food disposer Switch
Percent to CHP
CHP flow
Refinery flow
Refinery sector
Refinery
CO2
Refinery efficiency
Biomethane output
Biomethane Produced
CHP sector
CHP
Energy content per cubic meter
Energy conversion
Total energy
Losses
Heat
Electricity
Heat production efficiency
Electrical production efficiency
Heat Produced
Electricity Produced

Appendix D


Simulation Model
1: Total Biogas flow
2: CHP flow
3: Refinery flow
64000
3000
32000
1500
0
0
0,00
96,25
192,50
288,75
385,00
Days
Page 1
Untitled
16.50 sön 28 apr 2013
Run
Pause
Stop
Heat Produced
379 525
kWh
Electricity Produced
255 449
kWh
Biomethane Produced
302 335
cubic meters
Capacity of AD plant
AD plant
1 163
cubic meters
Percent to CHP
0
20
100
Food disposer
ENVAC
View/change Assumptions

Appendix E



View/change Assumptions
Human Variables
Population
0,020 × 10^6
0,000
0,500
1,000
Organic waste per Person
0,26
0,01
0,26
0,50
AD Plant
AD residence time
20
5
18
30
CHP Efficiencies
Electrical production efficiency
0,35
0,20
0,30
0,40
Heat production efficiency
0,52
0,40
0,50
0,60
Efficiencies
AD efficiency for sewage 16,1
AD efficiency for organic waste 143,7
Refinery efficiency 0,63
Constants
Energy content per cubic meter 6,1
Sewage per Person 0,335
Density of waste 919
Sludge content of sewage 0,008
Simulation model
-3-