

# Storage of energy in biogas for dealing with fluctuations in renewable energy production

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## **Abstract**

A breaking point in the energy transition from fossil fuels to renewable energy sources is the inability of renewable energy to cover peak demands, wherein the amount of energy demanded is higher than the amount of renewable energy generated. Therefore the ability to deal with the fluctuations that occur in renewable energy supply and energy demand over the year was investigated for a system in which renewable energy is stored in biogas. A renewable energy storage system is proposed in which food and yard waste and an excess of solar and wind energy are converted and stored into biogas. A literature study is performed to compare different biomass and biogas storage techniques. The proposed system was further investigated within a case study of an office building in the Netherlands. The newsvendor model was used for determining the most profitable storage capacity of biomass and biogas within a single period. Thereafter, a model was developed for following biomass and biogas storage levels over the year. The results showed that according to newsvendor model, biogas and biomass storage capacities of respectively 2097 kWh and 261 kWh were needed for the system in the case study. However, following storage levels over the year showed that much larger storage capacities are needed to prevent energy shortages because of the large seasonal fluctuations of energy demand and renewable energy production. Therefore, it was concluded that the proposed system is not achievable on a small scale as investigated in the case study, but might be more beneficial on a large scale.

### **Keywords:**

Bio-energy      Renewable energy storage      Newsvendor model      Multi-period inventory

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# Nomenclature

$AD_{conv}$	Anaerobic digester conversion factor (kWh/kg)
$c$	Total system cost (€/kWh)
$CF$	Capacity factor of a power plant
$c_{inv}$	Investment cost (€/kWh)
$c_{inv,i}$	Investment cost in one cycle (€/kWh)
$c_o$	Overage cost (€/kWh)
$c_{opr}$	Operational cost (€/kWh)
$C_p$	Theoretical maximal daily capacity of a power plant (kWh/day)
$c_{p,w}$	Specific heat capacity of water (J/kg/K)
$c_{subs}$	Cost for delivering or producing the substrate (€/kWh)
$c_u$	Underage cost (€/kWh)
$D$	Energy demand (kWh/day)
$DC$	Digester capacity (tonnes/year)
$\eta_{elchem}$	Total efficiency of the electrochemical reactors
$\eta_{generator}$	Efficiency of the conversion of biogas in electricity within the generator
$\eta_{s,biogas}$	Biogas storage efficiency
$\eta_{s,biomass}$	Biomass storage efficiency
$E_{anae,dig}$	Energy demand of the digester for heating (kWh/day)
$E_{shortage,i}$	Energy shortage encountered in cycle $i$ (kWh)
$f_D$	In-stock probability for newsvendor model
$F_D$	In-stock probability corresponding with the lowest total cost
$I_{b,inv,i}$	Biogas inventory level at the beginning of cycle $i$ (kWh)
$I_{e,inv,i}$	Biogas inventory level at the end of cycle $i$ (kWh)
$I_{inv,i}$	Biogas inventory level during cycle $i$ (kWh)
$\mu_{D,biogas}$	Mean biogas demand (kWh/day)
$\mu_{D,biomass}$	Mean biomass demand (kWh/day)
$\mu_{DT}$	Mean total energy demand (kWh/day)
$\mu_{FYW}$	Mean food and yard waste supply (kWh/day)

$\mu_{WT+PV}$	Mean wind and solar energy supply (kWh/day)
$M_{b,inv,i}$	Biomass inventory level at the beginning of cycle $i$ (kWh)
$M_{e,inv,i}$	Biomass inventory level at the end of cycle $i$ (kWh)
$M_{inv,i}$	Biomass inventory level during cycle $i$ (kWh)
$p$	Total underage penalty (€/kWh)
$P$	Power output of a power plant (kWh)
$P_{biogas,i}$	New biogas production during cycle $i$ (kWh)
$p_{energy}$	Electricity price (€/kWh)
$p_{ncd}$	Not complied demand penalty (€/kWh)
$Q$	Order quantity or storage capacity (kWh)
$Q^*$	Optimal order quantity or storage level (kWh)
$Q_{biogas}$	Biogas storage capacity (kWh)
$Q_{biomass}$	Biomass storage capacity (kWh)
$Q_{biogas}^*$	Optimal storage capacity of biogas (kWh)
$Q_{biomass}^*$	Optimal storage capacity of biomass (kWh)
$R_{demand,i}$	Random electricity demand in cycle $i$ (kWh)
$R_{excess,i}$	Excess of wind and solar energy converted into biogas in cycle $i$ (kWh)
$R_{renewables,i}$	Random wind and solar energy production in cycle $i$ (kWh)
$R_{s,waste,i}$	Random waste supply in cycle $i$ (kg)
$R_{waste,i}$	Biogas production from random waste supply in cycle $i$ (kWh)
$\sigma_{D,biogas}$	Standard deviation of biogas demand (kWh)
$\sigma_{D,biomass}$	Standard deviation of biomass demand (kWh)
$\sigma_{DT}$	Total standard deviation of the energy demand (kWh)
$\sigma_{DT,long}$	Standard deviation of long-term fluctuations of the energy demand (kWh)
$\sigma_{DT,short}$	Standard deviation of short-term fluctuations of the energy demand (kWh)
$\sigma_{FYW}$	Total standard deviation of food and yard waste supply (kWh)
$\sigma_{FYW,long}$	Standard deviation of long-term fluctuations of waste supply (kWh)
$\sigma_{FYW,short}$	Standard deviation of short-term fluctuations of waste supply (kWh)
$\sigma_{WT+PV}$	Total standard deviation of wind and solar energy supply (kWh)

$\sigma_{WT+PV,long}$	Standard deviation of long-term fluctuations of WT + PV supply (kWh)
$\sigma_{WT+PV,short}$	Standard deviation of short-term fluctuations of WT + PV supply (kWh)
$S_{digester,i}$	Biomass supply to the digester in cycle $i$ (kWh)
$TC$	Total cost of a single-period system using newsvendor model (€)
$U_{biogas,i}$	Amount of biogas used to satisfy energy demand in cycle $i$ (kWh)
$v$	Salvage value (€/kWh)
$W_{biogas,i}$	System cost within cycle $i$ (€)
$W_{biogas,total}$	Total system cost for all simulated cycles (€)
$z$	Statistical value indicating number of standard deviations from the mean

# Chapter 1. Introduction

## 1.1. Background

Our carbon footprint keeps increasing and the effects of global warming are becoming more and more distinct. Therefore, there is an urgent need to decrease our dependence on fossil fuels and increase the production of sustainable energy from sources like photovoltaic cells and wind turbines. Also biomass is known as a good energy source for the substitution of fossil fuels (Gustavsson et al., 1995). However while the need for sustainable energy sources is rising, the fact that costs for renewable energy sources are still a lot higher than for fossil fuels is significantly stalling this energy transition process. Thus the production cost for renewable energy like energy from wind, solar, and biomass needs to be reduced (Fthenakis et al., 2009). An essential flaw of renewable energy from photovoltaic cells and wind power plants is their inability to cover peak demands, wherein the amount of energy demanded is higher than the amount of energy generated by these power plants. Also during periods with a lower demand, the excess amount of energy produced by photovoltaic cells and wind power plants has no use as it goes to the power grid and cannot be stored for later use. This process, in which the photovoltaic (PV) and wind turbine (WT) energy is directly transported to the consumer, is economically inefficient (Lewis, 2007). Thus it improves the economical sustainability of wind- and solar energy to store an excess of electricity for use during periods with too little energy production or peak demands.

One method to store electricity from wind and solar energy is within an electrical energy storage system (EESS) (Schneider et al., 2016). However, the battery wherein the energy is stored in the EESS undergoes self-discharge losses and the stored energy is difficult to transport. Another method of storing wind and solar energy is to store the electricity within biogas. An advantage of storage in biogas over storage in a battery is that there is less additional energy loss from the storage itself compared to the use of a battery. Other advantages are that biogas is more easily transported or that biogas can be used for other purposes like heating and chemical production. Because of the drawbacks of electricity storage in an EESS, this study will focus on investigating the storage of renewable energy within biogas.

### 1.1.1. Overage and underage cost

When storing the energy, two different sorts of cost are encountered: overage and underage costs. Overage cost is the cost for storage that exceeds the demand. Overage costs include production costs and storage costs for the excess of biogas produced. When these production costs  $c$  and the value for which the excess of energy is sold (salvage value)  $v$  are known, the overage costs can be calculated:

$$c_o = c - v \tag{1.1}$$

Underage cost is the cost for storage that cannot satisfy the demand. With known underage penalty  $p$  and production costs  $c$ , the underage costs can be calculated:

$$c_u = p - c \tag{1.2}$$

### 1.1.2. Newsvendor model

In order to maximize total profit of the stored energy, it is necessary to minimize the sum of both overage and underage cost. A model that minimizes the sum of overage and underage cost is called the newsvendor model.

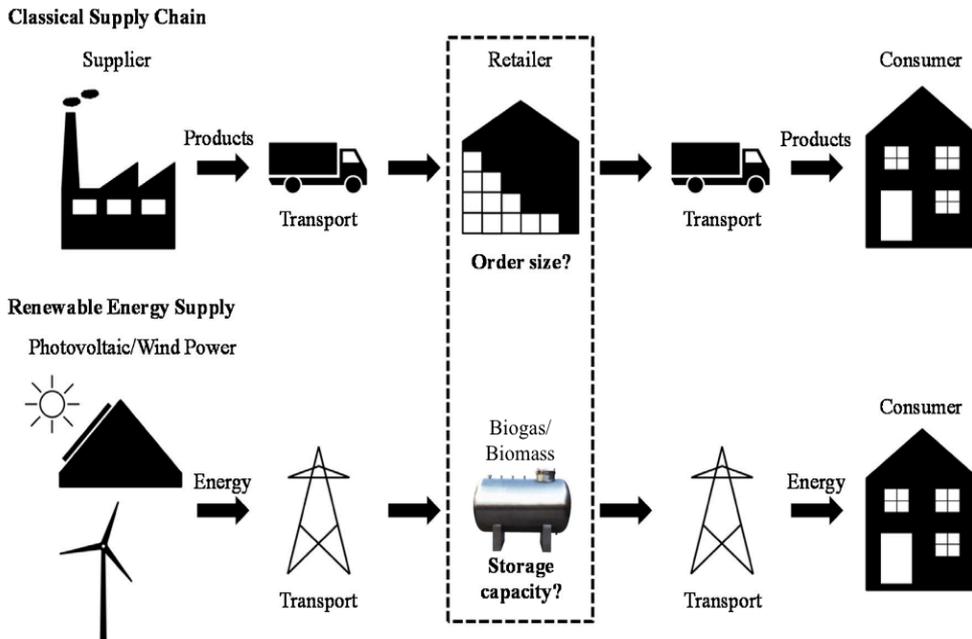
The newsvendor model (Schneider et al., 2016) describes the problem of a newspaper vendor who has to decide how many newspapers should be ordered in order to maximize selling profit. The order quantity  $Q$  is set to a fixed value, and the demand  $D$  is set to be uncertain. The total costs  $TC$  are minimized at the optimal order quantity  $Q^*$ :

$$TC = c_o \int_0^Q (Q - D) f_D dD + c_u \int_Q^\infty (D - Q) f_D dD \quad (1.3)$$

As can be seen in (1.3), the overage cost is multiplied with the chance that the demand is lower than the order quantity, and the underage cost is multiplied with the chance that the demand exceeds the order quantity. In this model,  $f_D$  is the in-stock probability or the probability that the order quantity is enough to satisfy the demand. The optimal in-stock probability  $F_D$  for which the sum of both overage and underage costs is minimal, is called the critical ratio and can be found with the critical fractile. The critical fractile is derived in Appendix A. The optimal order quantity  $Q^*$  can be derived from this critical fractile which will be further elaborated in this thesis.

$$F_D = \frac{c_u}{c_o + c_u} \quad (1.4)$$

There are a lot of analogies between the newsvendor model for the classical supply chain and for a renewable energy supply chain. Figure 1-1 shows that in order to change the model, the order size can be easily exchanged for the storage capacity of biogas or biomass.



**Figure 1-1: The analogies between the classical supply chain used in newsvendor model and the supply chain in a renewable energy supply show that it is possible to use newsvendor model for determining optimal biogas or biomass storage capacity. Changed from (Schneider et al., 2016)**

Because these two supply chains show a lot of similarities, newsvendor model can be used to determine optimal biogas or biomass storage capacity. However the problem with newsvendor model is that it is a single-period model, which means that it assumes the storage capacity to be empty at the end of each period. Therefore, when wanting to investigate in the biogas or biomass storage level over a longer period of time, modelling over multiple periods will have to be performed. This model will then have to include the re-use of a leftover of biomass or biogas from a previous period, in a next period.

## **1.2. Literature overview**

Currently no literature is available about the use of newsvendor model for optimizing storage of electricity in biogas. However, Schneider et al. (2016) have modelled electricity from wind and photovoltaic power plants for storage in a battery using the newsvendor model. The model used for this was a single-period model.

Götz et al. (2016) analysed the costs and conversion efficiency of a system in which renewable power is converted into biogas. This system uses electrolysis to convert the renewable power into hydrogen gas. Thereafter the hydrogen gas is converted into methane via methanation. This whole system has a total conversion efficiency of electricity into biogas of 55%. Methane can thus be produced using a sustainable and quite efficient pathway.

Matsuyama (2006) has altered the newsvendor model from a single-period model that assumes the stock to be empty at the end of each period into a multi-period model. Thereafter, Schmitt and Schnyder (2012) have altered the newsvendor model to one with supply uncertainty and a fixed demand together with the use of an additive yield. This additive yield covers the difference between the amount ordered by the newsvendor model and the amount that is actually supplied. The model of Schmitt and Schnyder (2012) is a single-period model, but can also be used for a multi-period planning horizon.

Østegaard (2012) has compared the impact of storage of electricity, heat and biogas on the integration of renewable energy. He concluded that although electricity storage gives significantly better integration of wind power than biogas storage, electricity storage also gives significantly higher costs than biogas storage. Hahn et al. (2014) have performed a cost analysis on biogas production for systems in which biogas is not stored at all, in which biogas is stored, and in which biogas is upgraded before storage. The cost parameters from this article can be used for making an estimation of the costs for the production of biogas.

### 1.3. The renewable energy storage system

The system that is investigated during this thesis is depicted in Figure 1-2. The proposed system contains production of wind and solar energy (WT + PV) that for a large part is directly transported to the consumer. However when this production exceeds consumer demand, the excess of solar and wind energy is converted into biogas within electrochemical reactors. Also food and yard waste is constantly supplied and converted into biogas within an anaerobic digester. This means that this storage system contains two main conversions: an excess of wind and solar energy converted into biogas via electrochemical reactions and supplied food and yard waste converted into biogas via anaerobic digestion.

In this supply chain, the anaerobic digester is constantly working which means that supplied food and yard waste is directly going into the digester. However because the digester has only limited capacity and the supply of food and yard waste is fluctuating, also storage of food and yard waste is needed for periods when the waste supply is higher than the digester capacity.

The electrochemical reactor is converting an excess of wind and solar energy into biogas. This biogas is stored for periods in which energy demand exceeds solar and wind power generation. Also the biogas produced from the anaerobic digester is not always immediately needed. So the biogas storage is used for both storage of biogas from the electrochemical reactor and the anaerobic digester.

Biogas is in this system first converted back into electricity in a generator before it is transported to the consumer. In this way the supply chain will be better adapted to future energy systems in which electricity will play a more prominent role than biogas (Bayod-Rújula, 2009). A part of the electricity from the generator is in this system used for providing heat to the digester.

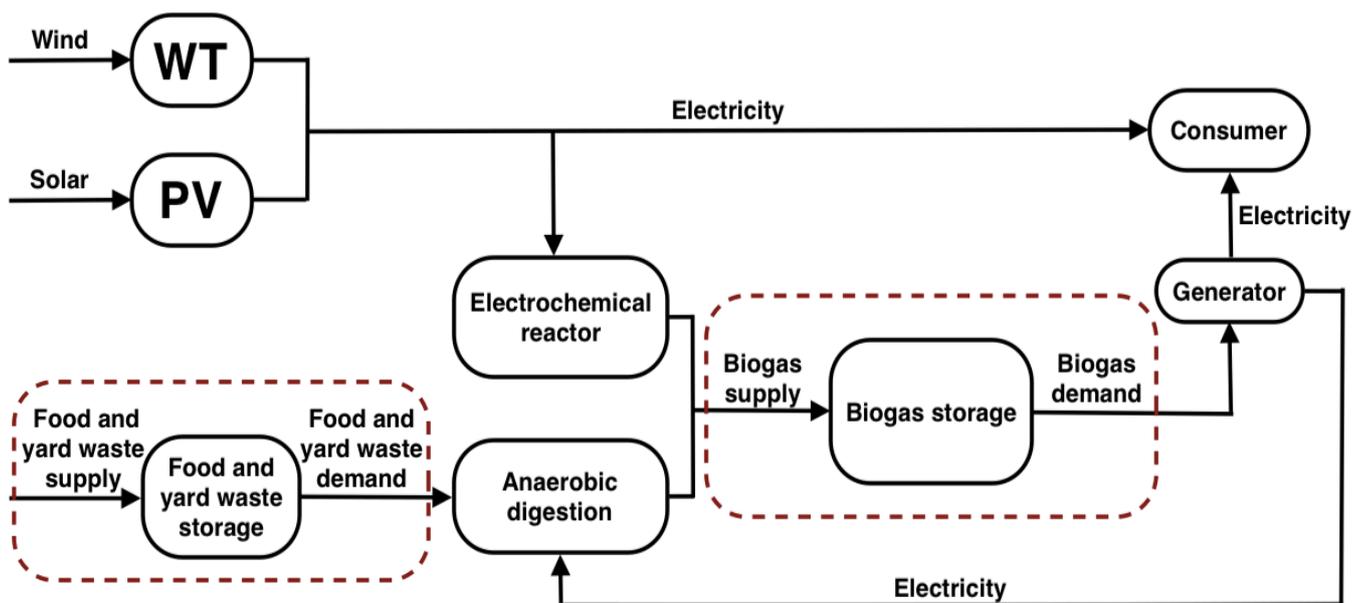


Figure 1-2: The energy storage system for combined power-to-gas and biomass-to-gas conversion

The system in Figure 1-2 allows storage of renewable energy in periods with high production and/or low demands, and use of this stored energy in periods with low production and/or high demands. However it is not known whether this storage system is able to cover renewable energy production shortages throughout the whole year.

#### **1.4. Objective and research questions**

The main objective of this thesis therefore is to validate whether the storage system for renewable energy in biogas (Figure 1-2) is able to deal with fluctuations of energy supply and energy demand over the year without additional energy shortages or extremely high costs. Therefore the main research question is:

*Is a system in which renewable energy is stored in biogas able to deal with the fluctuations that occur in energy supply and energy demand over the year?*

To enable answering this question, it is first necessary to investigate in different storage possibilities for both biomass and biogas. This includes a literature overview of the different storage losses, the investment costs and the operational costs that are encountered for different methods of storing biomass and biogas.

Secondly, investigation is needed to know how the newsvendor model can be used for determining the theoretically most profitable biomass and biogas storage capacity within the combined power-to-gas and biomass-to-gas supply chain shown in Figure 1-2. To enable use of the newsvendor model in the proposed system, it is first necessary to specify the overage and underage costs in the system.

Finally, a multi-period model has to be developed to enable investigating the biomass and biogas storage levels during the course of a year. For this, some literature research has to be performed for fluctuations and parameters that need to be included in the model. Also the total cost of the system and the energy shortages encountered during the year can be considered with the use of this model.

Therefore, the sub-questions are formulated as follows:

1. How do different biomass and biogas storage possibilities compare in terms of costs and storage losses?
2. How can the most profitable capacity of the biomass and biogas storage be determined within the combined power-to-gas and biomass-to-gas storage system?
3. How can the storage level of biomass and biogas be investigated within the combined power-to-gas and biomass-to-gas storage system?

## **1.5. Outline**

The remaining chapters in this thesis contain the following. Chapter 2 contains an evaluation of the costs, the losses and the achievability of different biomass and biogas storage options. In chapter 3, the use of the newsvendor model for determining the most profitable biomass and biogas storage capacity is demonstrated. Chapter 4 contains the development of a multi-period model and an analysis of the cost parameters and fluctuation data that are needed for the model. Subsequently in chapter 5, the models of chapter 3 and 4 are used within a case study for an office building in the Netherlands. In chapter 6, a general discussion on the work is performed. Finally in chapter 7, a conclusion is drawn based on the results of this thesis.

## Chapter 2. Biogas and biomass storage possibilities

Before looking at the optimal size of biogas and biomass storages, it is first good to evaluate between different storage options. Therefore, this chapter gives a short overview of the possibilities to store both biogas and biomass within the combined power-to-gas and biomass-to-biogas supply chain (Figure 1-2). This comparison is made by looking at the different storage options with their costs and storage losses.

### 2.1. Biogas storage options

There are multiple options for storing biogas, such as gas grid storage and compressed tank storage. Also belowground reservoir storage could be a good option for storing an excess of biogas because of the huge capacity of the storage.

#### 2.1.1. Gas grid storage

During gas grid storage, biogas is injected into the existing natural gas network. This gas network is already in use for the distribution of pumped up natural gas to the consumers, which means that the entire infrastructure is already present. Therefore the benefit of this kind of storage is that the investment costs are very low and the biogas is easily distributed to the consumer. However the storage capacity of gas grid storage will not be sufficient at large biogas production scale. Another disadvantage of gas grid storage is the fact that the methane content in the biogas sometimes needs to be increased in order to meet the required methane content for the gas grid. Therefore, gas grid storage is not the best option for storage of biogas in the storage system of Figure 1-2.

#### 2.1.2. Compressed tank storage

A more suitable biogas storage option is compressed tank storage. Large pressurized gas containers can directly be filled with biogas. The main cost for a compressed biogas tank is the cost for the compressor to bring the biogas to an appropriate pressure. Low-pressure biogas storage tanks are the least expensive, but when the biogas needs to be transported over long distances it is better to use more expensive high-pressure biogas storage. The investment cost for the pressure vessel is 20-200 €/m<sup>3</sup> dependent on the pressure that is needed in the storage vessel (Budzianowski & Brodacka, 2017). The pressure in the storage tank can range from low-pressurized biogas storages of about 6 bar (Kapdi et al., 2005) up to a maximum of about 345 bar (Krich, 2005). When a high pressure in the tank is needed, an expensive multi-stage compressor is necessary. This compressor is very energy intensive and has an investment cost of 600-6000 € per kW, dependent on what pressure is needed in the tank (Budzianowski & Brodacka, 2017). For a medium sized compressor of 85 kW with a biogas storage capacity of 2000 kWh, this would mean an investment of about 25-250 € per kWh of storage. The operational costs for a biogas storage are estimated at 0.058 €/kWh (Hahn et al., 2014). The losses of biogas during compressed tank storage are small: it can be stated that the biogas loss during storage has a maximum of 0.1% (Budzianowski & Brodacka, 2017).

### **2.1.3. Belowground reservoir storage**

The final option for biogas storage, belowground reservoir storage is a good option when it is necessary to supply energy for vast regions. This method makes use of depleted natural gas or oil reservoirs, which have a storage capacity of over 300 billion m<sup>3</sup>. These reservoirs can be adapted for biogas storage at a low cost because existing pipelines can be used for the distribution of biogas to the consumer and the geological structure of the reservoir is well known. Belowground reservoir storages are particularly suitable for dealing with large seasonal fluctuations in renewable energy production. The capital expenditures of the storage like design and infrastructure are estimated to be 0.55 €/m<sup>3</sup>. The operating expenditures like internal energy consumption, labour costs, maintenance and repair are estimated to be 0.013 €/m<sup>3</sup> of working capacity. The gas losses during storage consist only of low uncontrolled emissions (Budzianowski & Brodacka, 2017). However because these depleted natural gas reservoirs are not abundant, it is difficult to use this kind of storage for smaller supply systems like buildings or offices.

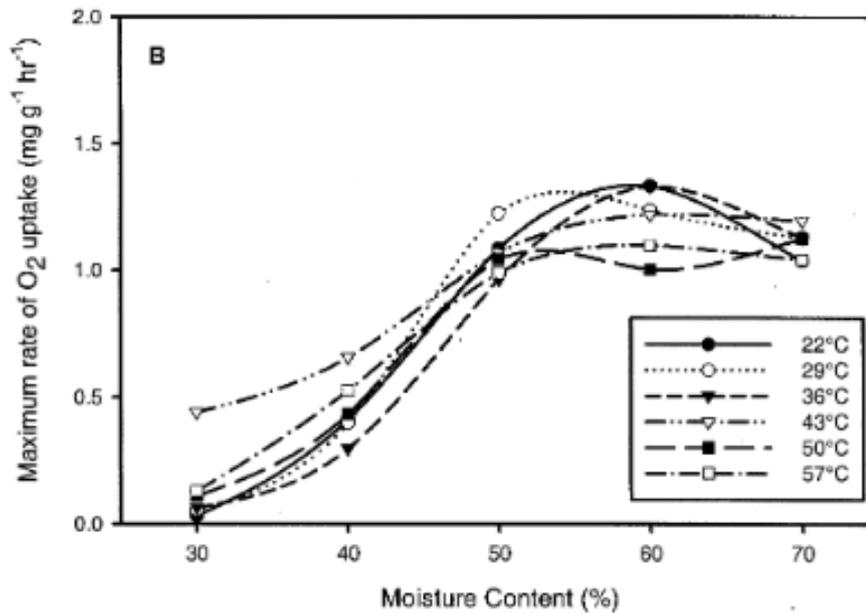
## **2.2. Biomass storage options**

When looking at the kind of biomass as a substrate in the system of Figure 1-2, it is also necessary to look at the sustainability of the biomass. The use of first generation biomasses like weed or maize silage would not be beneficial, because the substrate for the process would then compete with the food production. Therefore it is interesting to look at the use of food and yard waste as a substrate for the conversion of biomass to biogas. A great disadvantage of the storage of food and yard waste is the high moisture content, which could contribute to large storage losses. For this reason, also a possible pre-treatment of food and yard waste is investigated.

### **2.2.1. Storage of food and yard waste without pre-treatment**

Biomass storage loss depends greatly on the moisture content of the biomass. High moisture content of biomass gives high composting rates, which apart from causing loss of biomass, also increases mould formation and fire risk from elevated temperatures. The loss of dry weight during biomass storage means an equal loss of energy content of the biomass (Forest\_Research, 2016). The moisture content of food and yard waste was found to be about 60% (Saura-Mas & Lloret, 2007), but no literature was found about storage losses of food and yard waste.

A literature overview of Scholz (2005) did however conclude that storage of wood chips with a moisture content of 30% had a dry weight loss of 0.075% per day. To be able to translate this loss to a loss during storage of food and yard waste, a relation between the composting of biomass and the moisture content of biomass is needed. Liang et al. (2003) investigated this relationship in terms of oxygen uptake due to microbial activity during aerobic composting and concluded that composting occurs most at a moisture content of 60%. The values for the oxygen uptake rate were taken for a temperature of 29 °C (Figure 2-1). Now it can be seen that at a moisture content of 30%, the oxygen uptake rate is about 0.1 mg g<sup>-1</sup> h<sup>-1</sup>. At a moisture content of 60% (food and yard waste), the oxygen uptake rate is about 1.2 mg g<sup>-1</sup> h<sup>-1</sup> (Figure 2-1).



**Figure 2-1: Relating oxygen uptake rate as a measure for the amount of composting with the moisture content of biomass. The oxygen uptake rate at a moisture content of 30% is about 0.1 mg g<sup>-1</sup> h<sup>-1</sup> and at a moisture content of 60% about 1.2 mg g<sup>-1</sup> h<sup>-1</sup>. Source: (Liang et al., 2003)**

This means that the dry weight loss of food and yard waste will be about 12 times higher than the loss of wood chips with a moisture content of 30%. This gives a loss of about 0.9% per day. Thus storage of food and yard waste without pre-treatment would lead to a loss of 0.9% of dry weight and thus energy content per day.

The cost for the biomass storage itself is 18 €/m<sup>3</sup> (Rentizelas et al., 2009). However, because of the high increase in temperature in the storage tank due to the composting, it would be necessary to install a cooling system to decrease high fire risks. This cooling would be quite energy intensive. So storage of food and yard waste without pre-treatment would overall be very inefficient in energy use.

### 2.2.2. Storage of food and yard waste with pre-treatment

In order to dry the biomass and thus reduce the losses during storage, a pre-treatment of biomass is needed. Torrefaction is a pre-treatment that can be used for the purpose of drying biomass. The torrefaction process is performed at a temperature of 200-300°C, and decreases the moisture content and changes the chemical properties of the biomass to make it more suitable for combustion and gasification (Bergman & Kiel, 2005). The final product of the torrefaction resembles charcoal and storage losses of this product are negligible. The operational costs for the torrefaction of biomass with a moisture content of 40% are about 0.010 €/kWh (Svanberg et al., 2013). Because moisture content plays a large role in the operational costs, torrefaction of food and yard waste with a moisture content of 60% will have higher operational costs, assumed to be 0.015 €/kWh.

### 2.3. Numerical comparison between the storage options

To make a numerical comparison between the different storages, the investment cost  $c_{inv}$  and the operational cost  $c_{opr}$  can be compared for low-pressure biogas storage, high-pressure biogas storage, belowground reservoir storage, and torrefied food and yard waste storage.

The costs for low-pressure biogas storage can be calculated with the known cost parameters and the energy content of biogas: 6.4 kWh/m<sup>3</sup> (Cheng-qui et al., 1989). Note that the investment cost for the pressure vessel at low pressure is 20 €/m<sup>3</sup>:

$$c_{inv} = \frac{20 \text{ € m}^{-3}}{6.4 \text{ kWh m}^{-3}} = 3.125 \text{ € kWh}^{-1} \quad (2.1)$$

$$c_{opr} = 0.058 \text{ € kWh}^{-1} \quad (2.2)$$

The costs for high-pressure biogas storage can be calculated with known cost parameters and known pressure. Biogas is reported to have storage pressures of up to 345 bar (Krich, 2005). The energy density of biogas with this pressure is 345 \* 6.4 = 2208 kWh/m<sup>3</sup>. Note that the investment cost for the pressure vessel at high pressure now is 200 €/m<sup>3</sup> and that an investment of 250 €/kWh for the multi-stage compressor is assumed. The operational cost of the multi-stage compressor cannot be included in (2.4), because the operational cost for the multi-stage compressor are unknown:

$$c_{inv} = \frac{200 \text{ € m}^{-3}}{2208 \text{ kWh m}^{-3}} + 250 \text{ € kWh}^{-1} = 250.091 \text{ € kWh}^{-1} \quad (2.3)$$

$$c_{opr} = 0.058 \text{ € kWh}^{-1} \quad (2.4)$$

The costs for belowground reservoir storage can be calculated with the known cost parameters and the energy density of biogas:

$$c_{inv} = \frac{0.55 \text{ € m}^{-3}}{6.4 \text{ kWh m}^{-3}} = 0.086 \text{ € kWh}^{-1} \quad (2.5)$$

$$c_{opr} = \frac{0.013 \text{ € m}^{-3}}{6.4 \text{ kWh m}^{-3}} = 0.002 \text{ € kWh}^{-1} \quad (2.6)$$

The costs for torrefied food and yard waste storage can be calculated with the cost parameters for storage of biomass and the energy density of torrefied biomass. During torrefaction, the energy content of biomass can be increased up to 5.8 kWh/kg (Bergman & Kiel, 2005). The overall density of food and yard waste is about 775 kg/m<sup>3</sup> (Verhulst, 2014). However due to torrefaction the energy density of biomass decreases to 240 kg/m<sup>3</sup> (Bergman & Kiel, 2005), which means that the energy density of torrefied biomass is 1392 kWh/m<sup>3</sup>:

$$c_{inv} = \frac{18 \text{ € m}^{-3}}{1392 \text{ kWh m}^{-3}} = 0.013 \text{ € kWh}^{-1} \quad (2.7)$$

$$c_{opr} = 0.015 \text{ € kWh}^{-1} \quad (2.8)$$

The outcome of the investment cost and operational cost calculations is depicted in Table 2-1. It can be seen that the investment cost of the high-pressure biogas storage is very high. The operational cost for high-pressurized storage is also high because of the high energy need of the compressor but the exact costs are unknown. Both the investment and operational costs for the storage of torrefied food and yard waste are relatively low. Also belowground reservoir storage has low investment and operational costs compared to the other biogas storage options.

**Table 2-1: Comparing investment and operational costs between different storage options**

Storage option	Investment cost (€/kWh)	Operational cost (€/kWh)
Low-pressurized biogas storage (6 bar)	3.125	0.058
High-pressurized biogas storage (345 bar)	250.091	-
Belowground reservoir biogas storage	0.086	0.002
Storage of torrefied food and yard waste	0.013	0.015

## 2.4. Conclusions

Within this literature overview, biogas storage was compared for gas grid storage, compressed tank storage under low-pressure, compressed tank storage under high-pressure, and belowground reservoir storage. Gas grid storage was found to have too little storage capacity for large biogas production systems. Thereby smaller systems will probably not be able to gain access to the gas grid for biogas storage.

Thereafter, compressed tank storage under high-pressure brings along large investment costs due to the expensive multi-stage compressor. Also because of the fact that the multi-stage compressor is very energy intensive, the operational cost is also higher.

Belowground reservoir storage is more suitable for large systems. Belowground reservoir storage is the biogas storage option with the lowest investment and operational costs. However the storage of biogas in depleted natural gas reservoirs is not possible in smaller energy supply systems without access to these reservoirs.

It has also been found that storage of food and yard waste without pre-treatment is very inefficient due to the high moisture content of the waste. Adding a torrefaction pre-treatment of food and yard waste significantly reduces the dry matter biomass loss during storage from 0.9% per day to almost none.

Assuming that the energy supply chain of Figure 1-2 is a small supply system (e.g. a building or an office), the conclusion can be drawn that compressed tank storage is the best biogas storage option. A low-pressurized tank is herein preferred, because of the large investment cost and the high energy intensity of the high-pressurized storage. It can also be concluded that a pre-treatment of food and yard waste is necessary before storage. In the next chapters, there has been looked at the possibility of the system of Figure 1-2 with a torrefaction pre-treatment of food and yard waste and the low-pressurized storage of biogas within a compressed tank.

## Chapter 3. Biogas and biomass storage capacity

This chapter further investigates the energy storage system of Figure 1-2 with a torrefaction pre-treatment of food and yard waste and a low-pressurized storage of biogas within a compressed tank. This chapter shows how the newsvendor model is used to determine the most profitable storage capacity of biomass and biogas in this storage system.

### 3.1. Cost parameters for newsvendor model

The energy storage system contains biogas and biomass storage. The newsvendor model can be used to determine the most profitable storage capacity of these storages. To be able to use this model, it is first necessary to look at the different kind of costs that come along with storage of biomass and biogas. These costs can then be used for calculating the collective overage and underage cost for the newsvendor model.

At first, there is the operational cost  $c_{opr}$  of the system. The operational cost contains all the payments and costs for energy investments to operate the biogas and biomass production system like demand-related costs, operation-related costs like labour, maintenance, repairs, and monitoring, but also capital-related costs like design, acquisition of land for construction, and infrastructure that is needed for the system (Hahn et al., 2014).

Also substrate cost  $c_{subs}$  is encountered within the storage system. In the case of food and yard waste storage, the cost contains mainly out of the costs for collecting and transporting the waste. For biogas storage, this cost contains the cost for the biogas production processes. With this information, the overall production cost  $c$  can be calculated:

$$c = c_{opr} + c_{subs} \quad (3.1)$$

The salvage value  $v$  or the price for which an excess of biogas or biomass would be sold, is usually zero. An excess of biogas that cannot be stored will namely be burned away to prevent the excess of biogas to be released into the atmosphere. With help of (1.1) from chapter 1, it is now possible to have an equation for the overage cost within a biogas supply chain:

$$c_o = c - v = c_{opr} + c_{subs} - 0 \quad (3.2)$$

Penalties for an underproduction of biogas or biomass consist out of the energy price  $p_{energy}$  and a not complied demand penalty  $p_{ncd}$ . When there is an energy shortage, external energy has to be imported with a price that is equal to  $p_{energy}$ . However, an energy shortage will inevitably lead to damage to the system. This means that this damage should be taken into account in the calculations with a not complied demand penalty  $p_{ncd}$ . Formulation of the underage penalty then looks like this:

$$p = p_{energy} + p_{ncd} \quad (3.3)$$

Taking together (1.2) from chapter 1, (3.1) and (3.3) now gives an equation for the underage cost within a biomass or biogas storage system:

$$c_u = p - c = p_{energy} + p_{ncd} - c_{opr} - c_{subs} \quad (3.4)$$

### 3.2. Most profitable biogas storage capacity

The statistically most profitable biogas storage capacity can be determined when using the critical ratio of the newsvendor model. The critical ratio of the overage and underage cost is defined as the probability of the demand being greater than what the storage capacity can handle. The derivation of the critical ratio is shown in appendix A.

$$F_D = \frac{c_u}{c_o + c_u} \quad (3.5)$$

To calculate the amount of standard deviations  $z$  that the storage should be above the mean demand, it is assumed that the demand has a normal distribution. The  $z$  value can now be calculated with the `invNorm` function with a standard normal distribution. The `invNorm` function translates the optimal in-stock probability  $F_D$  into the number of standard deviations that the storage capacity should be removed from the mean biogas demand to reach this in-stock probability:

$$z = \text{invNorm}(F_D, 0, 1) \quad (3.6)$$

The optimal storage capacity can then be calculated with the mean and the standard deviation of the biogas demand, corrected for the efficiency of the generator that converts the biogas into electricity:

$$Q_{biogas}^* = \frac{\mu_{D,biogas} + z * \sigma_{D,biogas}}{\eta_{generator}} \quad (3.7)$$

In the case of biogas storage, the mean biogas demand is the mean total energy demand subtracted by the mean wind and solar energy supply:

$$\mu_{D,biogas} = \mu_{DT} - \mu_{WT+PV} \quad (3.8)$$

The standard deviation of the biogas demand is then given by the sum of the standard deviations of the total energy demand and the wind and solar energy supply:

$$\sigma_{D,biogas} = \sigma_{DT} + \sigma_{WT+PV} \quad (3.9)$$

### 3.3. Most profitable biomass storage capacity

The most profitable biomass storage capacity can also be determined using newsvendor model. The digester capacity determines the demand from the biomass storage. However for as far as the digester capacity allows, all food and yard waste that is supplied is not stored but goes directly to the digester. The difference with biogas storage therefore is that the biomass demand from storage is now defined as the capacity of the digester minus the waste supply. The capacity of the digester is fixed and has thus no standard deviation, while the waste supply has random fluctuations. This gives for the calculation of the most profitable biomass storage capacity:

$$Q_{biomass}^* = \mu_{D,biomass} + z * \sigma_{D,biomass} \quad (3.10)$$

With the mean biomass demand and standard deviation calculated as follows:

$$\mu_{D,biomass} = \max (DC - \mu_{FYW}, 0) \quad (3.11)$$

$$\sigma_{D,biomass} = 0 + \sigma_{FYW} \quad (3.12)$$

## Chapter 4. Biogas and biomass storage level

News vendor model assumes the storage level to be empty at the end of each period, which is not the case for the storage of biogas and biomass. In this chapter a model is developed for the energy supply system as explained in chapter 3, in which the biogas or biomass leftover from a previous period is used into a next period. Every cycle in the model is equal to one day. There are three random variables that differ in every period: the random energy demand  $R_{demand,i}$ , the random renewable energy production  $R_{renewables,i}$ , and the random food and yard waste supply  $R_{waste,i}$ . Investigation in the fluctuations of these values is done at the end of the chapter.

### 4.1. The multi-period model

When food and yard waste is supplied, a part of the waste is stored and a part of the waste goes directly to the digester. However the supplied waste is only stored when the random waste supply exceeds the capacity of the digester. The new biomass inventory level,  $M_{inv,i}$ , in the storage tank can then be described as:

$$M_{inv,i} = \min(M_{b,inv,i} + R_{waste,i} - \min(DC, R_{waste,i}), Q_{biomass}) \quad (4.1)$$

In (4.1),  $M_{b,inv,i}$  is the biomass inventory level at the beginning of cycle  $i$ ,  $DC$  is the digester capacity and  $Q_{biomass}$  is the capacity of the biomass storage.

The amount of biomass that is brought to the digester,  $S_{digester,i}$ , consists of a part of the waste supply. When the waste supply does not exceed the capacity of the digester, also a part of the biomass storage is digested. The supply of biomass to the digester cannot exceed the digester capacity:

$$S_{digester,i} = \min(R_{waste,i} + M_{inv,i}, DC) \quad (4.2)$$

For biogas, the excess of wind and solar energy,  $R_{excess,i}$ , that is converted into biogas for storage depends on the energy demand and the renewable energy production in the specific period and is described by (4.3). The max function makes sure that  $R_{excess,i}$  cannot be negative. Herein,  $\eta_{elchem}$  is the total efficiency of the electrochemical conversions of electricity into biogas:

$$R_{excess,i} = \max(R_{renewables,i} - R_{demand,i}, 0) * \eta_{elchem} \quad (4.3)$$

New biogas produced  $P_{biogas,i}$  during the cycle can be due to the conversion of an excess of renewable energy and due to the digestion of food and yard waste:

$$P_{biogas,i} = \max(R_{excess,i}, 0) + S_{digester,i} \quad (4.4)$$

The biomass that is leftover at the end of cycle  $i$  depends on the amount of stored biomass that has been used in the digester:

$$M_{e,inv,i} = M_{inv,i} - (S_{digester,i} - \min(R_{waste,i}, DC)) \quad (4.5)$$

The efficiency of the digester is not taken into account in the production of biogas, because this efficiency is for simplicity reasons already included in the random food and yard waste supply. The anaerobic digester conversion factor  $AD_{conv}$  in kWh/kg is used to convert the waste that is supplied in kg,  $R_{s,waste,i}$ , into the biogas that can be produced with this waste in kWh:

$$R_{waste,i} = R_{s,waste,i} * AD_{conv} \quad (4.6)$$

Due to limited biogas storage capacity, it is sometimes not possible to store all biogas that is produced. Therefore, the new biogas inventory level in cycle  $i$ ,  $I_{inv,i}$ , can be described by:

$$I_{inv,i} = \min(P_{biogas,i} + I_{b,inv,i}, Q_{biogas}) \quad (4.7)$$

In (4.7),  $Q_{biogas}$  is the storage capacity that can be chosen by newsvendor, and  $I_{b,inv,i}$  is the inventory level at the beginning of cycle  $i$ .

Biogas from storage is only used when the energy demand is higher than the renewable energy production, and the biogas that is used cannot be more than the biogas inventory level. However, the biogas from storage is first converted into electricity before it can be used to satisfy energy demand. The overall efficiency of the electricity generation from biogas  $\eta_{generator}$  is 20.8% (Pipatmanomai et al., 2009). This means that in the model the biogas  $U_{biogas,i}$  that is used to satisfy the demand in each cycle also needs to be corrected for the efficiency of the generator:

$$U_{biogas,i} = \max(IF(I_{inv,i} * \eta_{generator} > R_{demand,i} - R_{renewables,i}, R_{demand,i} - R_{renewables,i}, I_{inv,i} * \eta_{generator}), 0) \quad (4.8)$$

The energy shortage that is encountered in cycle  $i$ ,  $E_{shortage,i}$ , is dependent on the part of the demand that can be satisfied by the renewable energy production and the used biogas:

$$E_{shortage,i} = \max(R_{demand,i} - R_{renewables,i} - U_{biogas,i}, 0) \quad (4.9)$$

The inventory level at the end of the cycle,  $I_{e,inv,i}$ , is then described by:

$$I_{e,inv,i} = \max(I_{inv,i} - \frac{U_{biogas,i}}{\eta_{generator}}, 0) \quad (4.10)$$

Note that the inventory level at the end of cycle  $i$  does not have to be the same as the inventory level at the beginning of cycle  $i + 1$ , because the biogas or biomass storage efficiency  $\eta_s$  could be lower than 1. This means that the inventory levels of respectively biomass and biogas at the beginning of cycle  $i + 1$  will then be:

$$M_{b,inv,i+1} = M_{e,inv,i} * \eta_{s,biomass} \quad (4.11)$$

$$I_{b,inv,i+1} = I_{e,inv,i} * \eta_{s,biogas} \quad (4.12)$$

The total system cost in cycle  $i$ ,  $W_{biogas,i}$ , can then be calculated from the cost parameters of the system for which further elaboration is available in the next sub-chapter:

$$W_{biogas,i} = p_{energy} * U_{biogas,i} - c_{subs,biomass} * R_{waste,i} - c_{s,biomass} * M_{e,inv,i} - c_{subs,biogas} * P_{biogas,i} - c_{s,biogas} * I_{e,inv,i} - E_{shortage,i} * (p_{energy} + p_{ncd}) - c_{inv,i} \quad (4.13)$$

In (4.13),  $c_{inv,i}$  is the investment cost for the system made in cycle  $i$ . The total cost of the system after  $n$  number of cycles is then calculated by taking the sum of profit of every cycle:

$$W_{biogas,total} = \sum_{i=1}^n W_{biogas,i} \quad (4.14)$$

## 4.2. Cost parameters

Five main cost parameters are present in the model: the biomass substrate cost  $c_{subs,biomass}$ , the operational costs for biomass storage  $c_{opr,biomass}$ , the biogas substrate cost  $c_{subs,biogas}$ , the operational costs for biogas storage  $c_{opr,biogas}$ , and the total investment cost of the system  $c_{inv}$ .

The biomass substrate cost consists only of the cost for transporting feedstock to the place where it can be processed. This cost is estimated to be 0.40 €/kg waste (Gebrezgabher et al., 2010). Biomass first needs a torrefaction pre-treatment before it can be stored. Therefore the biomass storage cost consists of the operational cost for the torrefaction, which is estimated on 15 €/kWh (Svanberg et al., 2013). The operational cost of biogas storage for a low-pressurized biogas storage is estimated on 0.058 €/kWh (Hahn et al., 2014). The biogas substrate cost consists of the operational cost of both the electrochemical reactors and the digester.

### 4.2.1. The electrochemical reactors

The electrochemical reactor consists of two consecutive reactions: first there is electrolysis wherein the electrons together with water are converted into hydrogen gas and oxygen. The electrolysis has a conversion efficiency of 70%. The hydrogen gas is then converted into biogas via methanation, a reaction in which hydrogen and carbon dioxide are converted into methane. The conversion efficiency of methanation is 78%, which gives an overall power-to-gas efficiency of 55%. The investment cost for the electrolysis and methanation reactors is estimated on 1400 €/kW of capacity. Assuming a capacity of 1000 kW, which is equivalent to the energy supply of a large building or office, the investment for the electrochemical reactors will then be 1.4 M€. The operational cost for the overall electrochemical reaction is estimated to be 0.60 €/kWh (Götz et al., 2016).

### 4.2.2. The digester

The food and yard waste is converted into biogas via anaerobic digestion. During this process, the organic matter in food and yard waste is biologically degraded and converted into biogas. To maintain a stable digestion, it is important that the temperature changes in the digester are very small. This means that the digester needs to be held on a constant temperature (Zhang et al., 2014). Moreover Zhang et al. (2014) concluded that overall, anaerobic digestion under thermophilic conditions (50-60 °C) does not have an advantage over digestion under mesophilic conditions (30-40 °C). Therefore the temperature in the digestion is chosen to be 40 °C. The temperature of the waste entering the digester is assumed to be room temperature (20 °C). Because water (fluid) has a greater heat capacity than food and yard waste (solid), the maximal

electricity needed for the anaerobic digestion can be calculated assuming that the specific heat capacity of food and yard waste is equal to the heat capacity of water, namely  $4186 \text{ J kg}^{-1} \text{ K}^{-1}$ .

$$E_{anae\_dig} = c_{p,w} * \Delta T = 4186 \text{ J kg}^{-1} \text{ K}^{-1} * 20 \text{ K} = 83720 \text{ J kg}^{-1} = 0.023 \text{ kWh kg}^{-1} \quad (4.15)$$

The energy content of torrefied biomass is  $5.8 \text{ kWh/kg}$  (Bergman & Kiel, 2005), which means that the electricity that is needed to heat up the biomass is  $0.004 \text{ kWh/kWh}$  waste. The energy that is generated from the biogas at the end of the system can be fed back to provide the energy needed for the anaerobic digestion.

Koupaie et al. (2014) proposed two equations to estimate the investment and operating costs of anaerobic digesters. When the digester capacity  $DC$  (tonnes/year) is known, these equations can be used to calculate the costs with  $c_{inv}$  in M€ and  $c_{opr}$  in €/ton:

$$c_{inv} = 0.0342 * DC^{0.55} \quad (4.16)$$

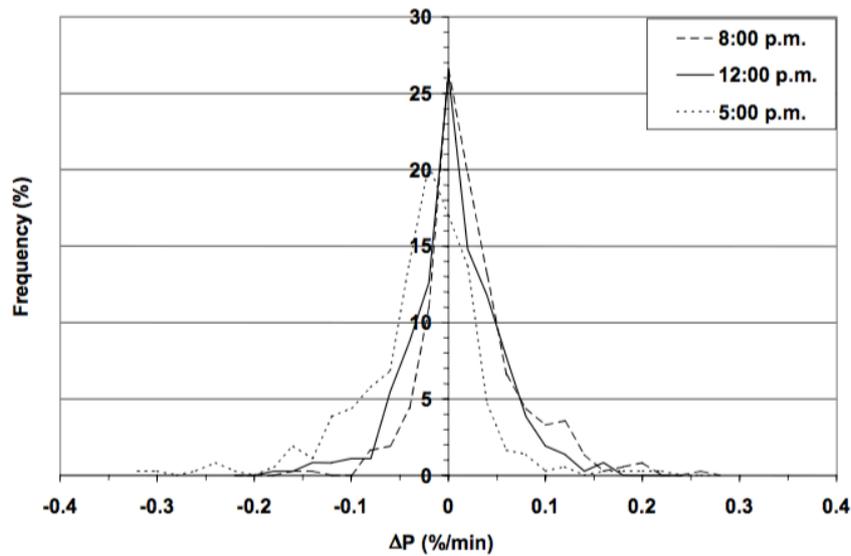
$$c_{opr} = 16722 * DC^{-0.61} \quad (4.17)$$

### 4.2.3. Investment cost

The total investment cost can be calculated by taking the sum of the investment costs of the biomass storage, the biogas storage, the digester, the electrochemical reactors, the torrefaction reactor, and the generator. The investment costs for biomass and biogas storage can be obtained from chapter 2. The investment cost of the digester can be derived from the digester capacity. The investment cost for the torrefaction reactor is  $5.51 \text{ M€}$  (Svanberg et al., 2013), while that of the generator is  $0.012 \text{ M€}$  (Pipatmanomai et al., 2009). The investment cost for the electrochemical reactors is estimated on  $1.4 \text{ M€}$ .

### 4.3. Fluctuations in renewable energy production

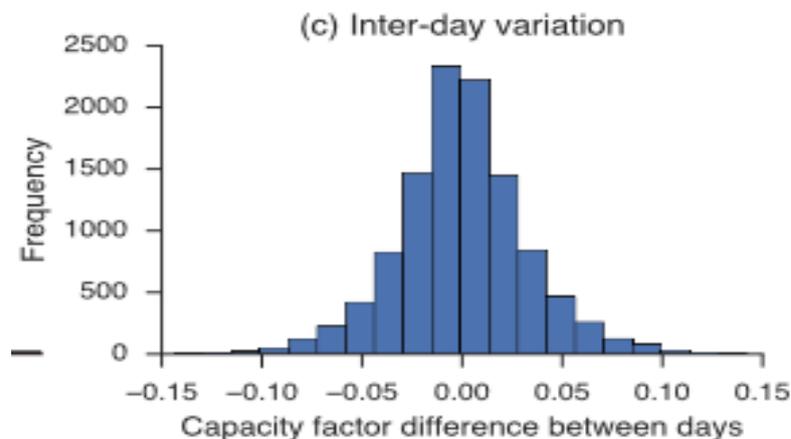
The energy that is produced by renewable energy sources is fluctuating between days. A standard deviation  $\sigma_{r,short}$  can be determined for these short-term fluctuations. In a paper published by Ernst et al. (1999), the distribution in power output of 176 wind turbines was investigated (Figure 4-1).



**Figure 4-1: Distribution of the slope of a one-hour regression for the total output of 176 wind turbines. Source: (Ernst et al., 1999)**

From Figure 4-1 it can be seen that the fluctuations in power output of wind turbines act within a normal distribution with a standard deviation of around 7,5% of the mean power output of the turbine.

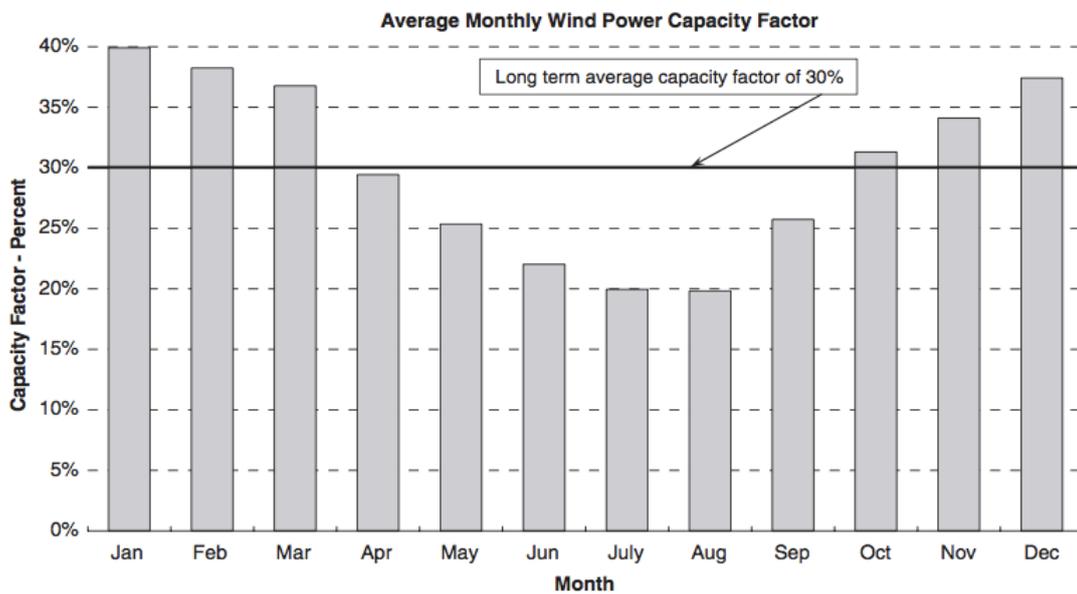
A study of Pfenninger and Staffell (2016) performed hourly simulations of photovoltaic power in the UK for the years 1985 up-to 2014 (Figure 4-2). From the resulting figure, it is clear that short-term fluctuations of solar energy also have a normal distribution but with a standard deviation of about 2.5% of the mean power output.



**Figure 4-2: Daily variability of photovoltaic power in the UK for 30 years (1980-2014). Source: (Pfenninger & Staffell, 2016)**

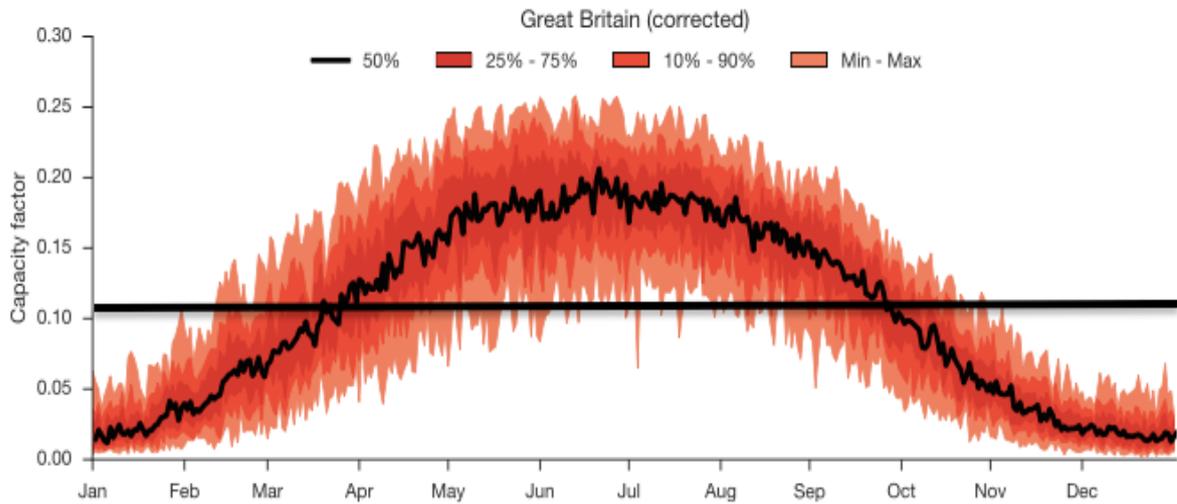
However also fluctuations over the months of the year play a huge role within a renewable energy supply. These so-called long-term fluctuations also have a standard deviation  $\sigma_{r, long}$ , but this standard deviation can only be used when considering the single-period newsvendor model. For the multi-period model, it is necessary to determine the mean daily renewable energy production for every month of the year.

A method for determining mean daily energy productions for every month is to look at historical data of the capacity factor of wind and solar energy. The capacity factor is here defined as the ratio of the energy produced and the hypothetical maximal capacity of the WT or PV unit. The availability factor or the fraction of the time that the power plant is able to produce electricity is included in the capacity factor. Sinden (2007) did an investigation in the fluctuations of wind power plants over the year in the UK for 1970-2003 (Figure 4-3).



**Figure 4-3: Monthly fluctuations of capacity factor of wind energy in the UK, averaged for 34 years of data (1970-2003). Source: (Sinden, 2007)**

Pfenninger and Staffell (2016) simulated photovoltaic power in the UK for 1985-2014, which makes a good approximation for the fluctuations of photovoltaic capacity factor over the year (Figure 4-4).



**Figure 4-4: Fluctuations in daily capacity factor of solar energy during the year in the UK from corrected hourly simulations for 1985-2014. The horizontal line is the long-term average capacity factor. Source: (Pfenninger & Staffell, 2016)**

The fluctuations in capacity factor (CF) from Figure 4-3 and Figure 4-4 for each month are shown in Table 4-1.

**Table 4-1: The fluctuations of the capacity factor for wind turbines and photovoltaic power for each month of the year.**

Month	Capacity factor of WT	Capacity factor of PV
January	0.400	0.025
February	0.385	0.055
March	0.363	0.095
April	0.295	0.145
May	0.255	0.17
June	0.220	0.18
July	0.200	0.175
August	0.200	0.15
September	0.265	0.125
October	0.315	0.075
November	0.345	0.04
December	0.375	0.025

The fluctuations in capacity factor can easily be translated into fluctuations in power from wind or photovoltaic power plants:

$$P = CF * C_p \quad (4.18)$$

Wherein  $P$  is the power output in a specific month,  $CF$  is the capacity factor in that month, and  $C_p$  is the theoretical maximal daily capacity of the power plant.

#### 4.4. Fluctuations in food and yard waste supply

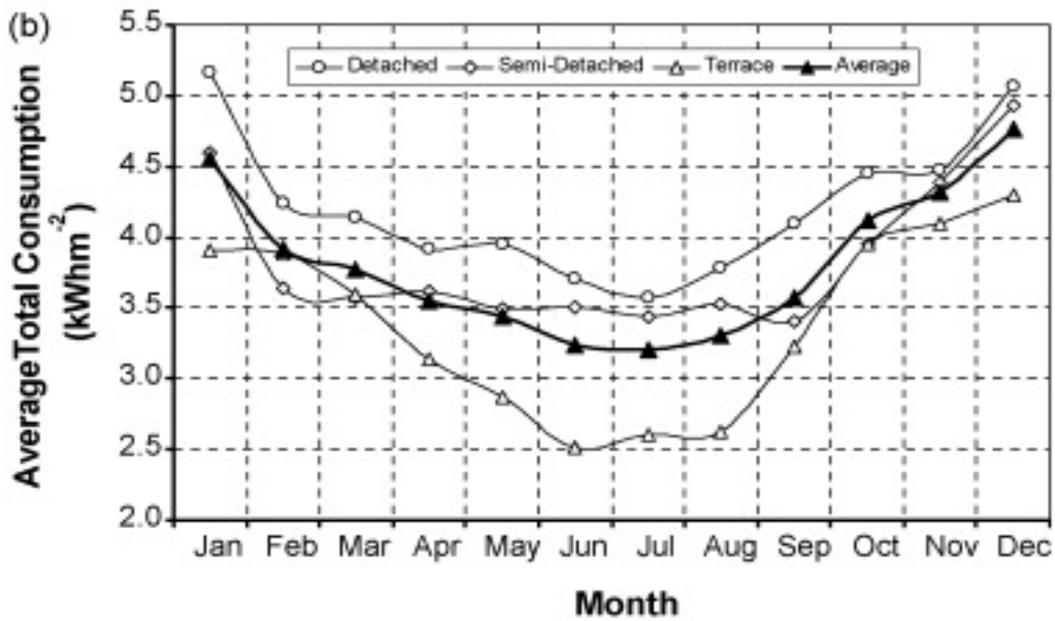
Fluctuations in production of organic food and yard waste comes from data of average waste processing in the Netherlands for the period 2002-2009 and are shown in Table 4-2 (Vereniging\_Afvalbedrijven, 2010). How these data have been obtained is shown in appendix B. The ratio of the yearly average food and yard waste production is calculated because it enables an easy translation from the average annual food and yard waste production into average monthly food and yard waste productions.

**Table 4-2. Monthly fluctuations of the organic food and yard waste production and the calculated ratio of the yearly average food and yard waste production from data of the Netherlands for 2002-2009. Source: (Vereniging\_Afvalbedrijven, 2010)**

Month	Organic food and yard waste production (tonnes/week)	Calculation for ratio of yearly average food and yard waste production	Ratio of the yearly average food and yard waste production
January	6.5	6.5/21.6	0.301
February	8.3	8.3/21.6	0.382
March	17.0	17.0/21.6	0.786
April	32.0	32.0/21.6	1.480
May	35.6	35.6/21.6	1.647
June	33.0	33.0/21.6	1.527
July	29.6	29.6/21.6	1.369
August	27.0	27.0/21.6	1.249
September	23.8	23.8/21.6	1.099
October	19.4	19.4/21.6	0.898
November	15.0	15.0/21.6	0.694
December	8.5	8.5/21.6	0.393
Yearly average	21.6	-	-

#### 4.5. Energy demand

Also the energy demand is fluctuating over the year, and these fluctuations need to be included in the multi-period model. Monthly fluctuations in energy consumption in the UK were studied by Yohanis et al. (2008). The average total consumption is here normalized for the floor area for three house types in the UK (Figure 4-5).



**Figure 4-5: The fluctuations of electricity consumption in detached, semi-detached, terrace, and average house types normalized with respect to floor area. Source: (Yohanis et al., 2008)**

The fluctuation data for average house types in the UK from Figure 4-5 are shown in Table 4-3. Also these data are translated into a ratio of the yearly average energy consumption. This enables easy translation of yearly average energy consumption into monthly average energy consumptions.

**Table 4-3. The monthly electricity consumption fluctuations and from that the calculated ratio of the yearly average energy consumption in houses in the UK.**

Month	Electricity consumption (kWh m <sup>-2</sup> )	Calculation for ratio of yearly average energy consumption	Ratio of the yearly average energy consumption
January	4.55	4.55/3.81	1.194
February	3.90	3.90/3.81	1.024
March	3.80	3.80/3.81	0.997
April	3.52	3.52/3.81	0.924
May	3.45	3.45/3.81	0.906
June	3.22	3.22/3.81	0.851
July	3.20	3.20/3.81	0.840
August	3.30	3.30/3.81	0.866
September	3.55	3.55/3.81	0.932
October	4.15	4.15/3.81	1.089
November	4.35	4.35/3.81	1.142
December	4.75	4.75/3.81	1.247
Yearly average	3.81	-	-

Because no literature about the frequency distribution of energy demand in the UK could be found, it is assumed that the variability of the energy consumption acts with a normal distribution with a standard deviation of 40% of its mean value.

## Chapter 5. Case study

In this chapter the designed models are tested in a case study: in an office building of a company in the Netherlands, the board has decided that they want to rely the building's energy supply completely on renewable energy. To be able to achieve this goal they already invested in the installation of solar panels on the roof of the building, and in small-scale wind turbines on a field next to the building of the company. They also invested in a process for the production of biogas from food and yard waste.

### 5.1. The office building

The office building of this company is assumed to have the size of an average office building of 590 m<sup>2</sup> with 100 employees and an energy demand of 11800 m<sup>3</sup> of gas and 67850 kWh of electricity per year (SwitchCo\_BV, 2016). When the energy content of gas is 6.4 kWh/m<sup>3</sup> (Chengqui et al., 1989), this means that the total energy demand in the office building is:

$$D = 11800 \text{ m}^3 * 6.4 \text{ kWh m}^{-3} + 67850 \text{ kWh} = 143370 \text{ kWh year}^{-1} = 393 \text{ kWh day}^{-1} \quad (5.1)$$

#### 5.1.1. Solar panels

The solar panels have been installed on the roof of the building, which has a surface area of 295 m<sup>2</sup>. Because the board wanted to generate as much renewable energy as possible, they decided to fill up the whole roof with solar panels. The board has chosen for solar panels with a capacity of 290 Wp (Wattpeak), which means that the panels could theoretically produce 290 W. An average solar panel has a size of 1.65 m<sup>2</sup> (Energieleveranciers, 2017). The solar panels thus have a specific capacity of 176 Wp per m<sup>2</sup>, which is equivalent to 4.22 kWh per m<sup>2</sup> per day. The office has a flat roof with an area of 350 m<sup>2</sup>. Because the whole roof has been covered with solar panels, the installed solar panels have a total maximal capacity of 1477 kWh per day.

#### 5.1.2. Wind turbines

The board was not satisfied. Therefore they also decided to invest in 8 average small-scale wind turbines with a capacity of 4.7 kW (Pitteloud & Gsänger, 2016) in an open field close to the office building. This is equivalent to a capacity of 112.8 kWh per day. These turbines thus have a total maximal capacity of 902.4 kWh per day.

#### 5.1.3. Biomass-to-biogas

Still not satisfied with the amount of energy produced by renewables, the board invested in a process to produce biogas from food and yard waste. Preferably all food and yard waste produced by the office building is used to generate biogas. The waste production in an average office building is 170 kg per employee (Milieubarometer, 2017). With the waste consisting out of 35% food and yard waste with 100 employees, the average amount of food and yard waste produced per day by the office building can be calculated:

$$\mu_{FYW,office} = 170 * 100 * 0.35 * \frac{1}{365} = 16.3 \text{ kg day}^{-1} \quad (5.2)$$

When knowing that a biogas production of 120 L/kg feedstock can be reached (Brown & Li, 2013) and that biogas has an energy content of 6.4 kWh/m<sup>3</sup> (Cheng-qui et al., 1989), the average amount of biogas production from the office waste can be calculated to be 12.5 kWh/day.

The board regarded this small amount of energy production from office waste only as not cost-efficient compared to the investments that needed to be made for the biomass-to-biogas process. Therefore they sent out a questionnaire to households in a range of 50 km from the building with the question if they were prepared to have their food and yard waste collected. 300 households responded positively on this question. Therefore the waste from 300 households is now collected for the production of biogas in the office building.

For the Netherlands in the years 2013-2015, the average amount of domestic waste was about 358 kg per inhabitant per year consisting of 35% food and yard waste (Rijksoverheid, 2016). Because the average amount of persons per household in the Netherlands is 2.2 (Rijksoverheid, 2014), the average food and yard waste production per household thus is 0.76 kg per day. For the collection of waste from 300 households, this gives a total biogas production from food and yard waste of:

$$\mu_{FYW} = \mu_{FYW,office} + \mu_{FYW,households} = 12.5 + 0.76 * 300 * 0.12 * 6.4 = 188 \text{ kWh day}^{-1} \quad (5.3)$$

Finally content with the energy produced from renewables, the board is surprised to find out that there is still an energy shortage in some periods of the year. Therefore they want to investigate in the fluctuations of renewable energy production and the effects of food and yard waste storage and biogas storage (Figure 1-2) on the costs and the energy shortages of the offices energy supply chain.

## 5.2. Fluctuations

### 5.2.1. Wind and solar energy

Although the theoretical capacity  $C_p$  of the installed wind turbines and solar panels for the power generation of the office building are respectively 902 and 1477 kWh per day, not the whole capacity is used for power production. In chapter 4, it can be seen that the yearly average capacity factor for wind turbines and solar panels is 0.30 and 0.105. Using (5.4), it can be calculated that the yearly average power production by wind and solar energy for the office building is thus 270.7 and 155.1 kWh per day.

$$P = CF * C_p \quad (5.4)$$

The fluctuations of the power production by solar energy can be calculated from the fluctuations of the capacity factor  $CF$  investigated in chapter 4 with the use of (5.4) (Table 5-1).

**Table 5-1: Outcome of the calculations for the average power output of WT and PV energy from (5.1)**

Month	Average WT power (kWh/day)	Average PV power (kWh/day)	Average WT + PV power (kWh/day)
January	361.0	36.9	397.9
February	347.4	81.2	428.7
March	327.6	140.3	467.9
April	266.2	214.2	480.4
May	230.1	251.1	481.2
June	198.5	265.9	464.4
July	180.5	258.5	439.0
August	180.5	221.6	402.0
September	239.1	184.6	423.8
October	284.3	110.8	395.0
November	311.3	59.1	370.4
December	338.4	36.9	375.3

### 5.2.2. Food and yard waste

The monthly fluctuations of the ratio of the yearly average food and yard waste production are known from chapter 4. This means that from the yearly average waste supply of 188 kWh per day, the monthly fluctuations of the supply can be calculated (Table 5-2).

**Table 5-2: Monthly fluctuations of the food and yard waste supply to the office building, derived from the fluctuations in ratio of the yearly average from chapter 4.**

Month	Average food and yard waste supply (kWh/day)
January	56.6
February	71.8
March	147.8
April	278.2
May	309.6
June	287.1
July	257.4
August	234.8
September	206.6
October	168.8
November	130.5
December	73.9

### 5.2.3. Energy consumption

The monthly fluctuations in energy demand can be calculated from the monthly fluctuations of the ratio of the yearly average energy demand (Table 5-3). These fluctuations are also given in chapter 4.

**Table 5-3: Monthly fluctuations in energy demand of the office building, calculated from the fluctuations in ratio of the yearly average from chapter 4.**

Month	Average energy demand (kWh/day)
January	469.2
February	402.4
March	391.8
April	363.1
May	356.1
June	334.4
July	330.1
August	340.3
September	366.3
October	428.0
November	448.8
December	490.1

## 5.3. Storage capacities

### 5.3.1. Biogas storage capacity

To determine the most profitable biogas storage capacity, the overage and underage costs first have to be calculated. The operational cost of biogas storage is 0.058 €/kWh (Chapter 2). The substrate cost of biogas storage consists of both the operational cost of the electrochemical reactors (0.60 €/kWh) and the operational cost of the digester. The operational cost of the digester can be calculated from (4.17) in chapter 4 when the digester capacity is equal to the yearly average food and yard waste supply of 188 kWh/day, which is equal to 893.5 tonnes/year:

$$c_{opr} = 16722 * DC^{-0.61} = 16722 * 893.5^{-0.61} = 265 \text{ € ton}^{-1} = 2.65 \text{ € kg}^{-1} \quad (5.5)$$

The anaerobic co-digestion of a mixture of 80% yard waste and 20% food waste was found to give a biogas conversion efficiency of 120 L/kg feedstock (Brown & Li, 2013), which is equivalent to a digester conversion factor  $AD_{conv}$  of 0.77 kWh/kg feedstock. The operational cost of the digester in €/kWh thus is:

$$c_{opr} = \frac{2.65 \text{ € kg}^{-1}}{AD_{conv}} = \frac{2.65 \text{ € kg}^{-1}}{0.77 \text{ kWh kg}^{-1}} = 3.45 \text{ € kWh}^{-1} \quad (5.6)$$

Now both the operational costs for the electrochemical reactors and for the digester are known. However because for a large period of the year the digester is producing much more biogas than the electrochemical reactors, it is assumed that the substrate cost for biogas production is 3.45 €/kWh.

Knowing both the parameters for operational and substrate cost, it is possible to calculate the overage cost of biogas storage with the use of (3.2):

$$c_o = c - v = c_{work} + c_{subs} - 0 = 0.058 + 3.45 - 0 = 3.51 \text{ € kWh}^{-1} \quad (5.7)$$

To calculate underage cost, it is necessary to know the energy price and the not complied demand penalty. The energy price for business use in the Netherlands was found to be 0.098 €/kWh (CBS, 2015). The financial damage from an energy shortage or not complied demand penalty is assumed to be 65 €/kWh. The underage cost according to (3.4) then is:

$$c_u = p - c = p_{energy} + p_{ncd} - c_{work} - c_{subs} = 0.098 + 65 - 0.058 + 3.45 = 61.59 \text{ € kWh}^{-1} \quad (5.8)$$

The overage and underage cost give the critical ratio:

$$F_D = \frac{c_u}{c_o + c_u} = \frac{61.59}{3.51 + 61.59} = 0.946 \quad (5.9)$$

The corresponding  $z$  value is:

$$z = invNorm(F_D, 0, 1) = invNorm(0.946, 0, 1) = 1.608 \quad (5.10)$$

The most profitable biogas storage capacity can then be calculated when knowing that the efficiency of the generator for the conversion of biogas into electricity is 20.8%. The derivation of the standard deviations is done in Appendix C:

$$Q_{biogas}^* = \frac{\mu_{D,biogas} + z * \sigma_{D,biogas}}{\eta_{generator}} = \frac{\mu_{DT} - \mu_{WT+PV} + z * (\sigma_{DT} + \sigma_{WT+PV})}{\eta_{generator}} = 2097 \text{ kWh} \quad (5.11)$$

### 5.3.2. Biomass storage capacity

For the most profitable biomass storage capacity, it is first necessary to determine the mean biomass demand:

$$\mu_{D,biomass} = \max(DC - \mu_{FYW}, 0) = \max(188 - 188, 0) = 0 \text{ kWh} \quad (5.12)$$

The digester has the same capacity as the mean food and yard waste supply. This means that on average all the supplied biomass is not stored but goes directly to the digester. The mean biomass demand therefore is 0.

The derivation of the standard deviation of the food and yard waste supply is done in Appendix C. The most profitable biomass storage capacity corresponding with the  $z$  value in (5.10) is then:

$$Q_{biomass}^* = \mu_{D,biomass} + z * \sigma_{D,biomass} = \mu_{D,biomass} + z * \sigma_{FYW} = 261 \text{ kWh} \quad (5.13)$$

## 5.4. Investment cost

The investments that need to be made are the investments for the biomass storage, the biogas storage, the digester, the electrochemical reactions, the torrefaction process, and the investments for the generator:

$$c_{inv,total} = c_{inv,biomass} + c_{inv,biogas} + c_{inv,dig} + c_{inv,elec} + c_{inv,torr} + c_{inv,gen} \quad (5.13)$$

It is known that the investment cost for the torrefaction reactor is 5.51 M€ (Svanberg et al., 2013), for the generator this is 0.012 M€ (Pipatmanomai et al., 2009), and for the electrochemical reactors 1.4 M€ (Chapter 4). The investment cost for the biomass and biogas storage are respectively 0.013 €/kWh and 3.125 €/kWh and are dependent on the storage size:

$$c_{inv,biomass} = 0.013 * Q_{biomass}^* = 0.013 * 261 = 3.4 * 10^{-6} \text{ M€} \quad (5.14)$$

$$c_{inv,biogas} = 3.125 * Q_{biogas}^* = 3.125 * 2097 = 6.6 * 10^{-3} \text{ M€} \quad (5.15)$$

The investment cost for the digester can be calculated from (4.16) in chapter 4, knowing that the digester capacity is 893.5 tonnes/year:

$$c_{inv,dig} = 0.0342 * DC^{0.55} = 0.0342 * 893.5^{0.55} = 1.44 \text{ M€} \quad (5.16)$$

The total investment cost in (5.13) is then:

$$c_{inv,total} = 3.4 * 10^{-6} + 6.6 * 10^{-3} + 1.44 + 1.4 + 5.51 + 0.012 = 8.37 \text{ M€} \quad (5.17)$$

Assuming that the investments will have to be replaced after 10 years, the yearly investment cost is then:

$$c_{inv,yearly} = \frac{8.37}{10} = 0.84 \text{ M€} \quad (5.18)$$

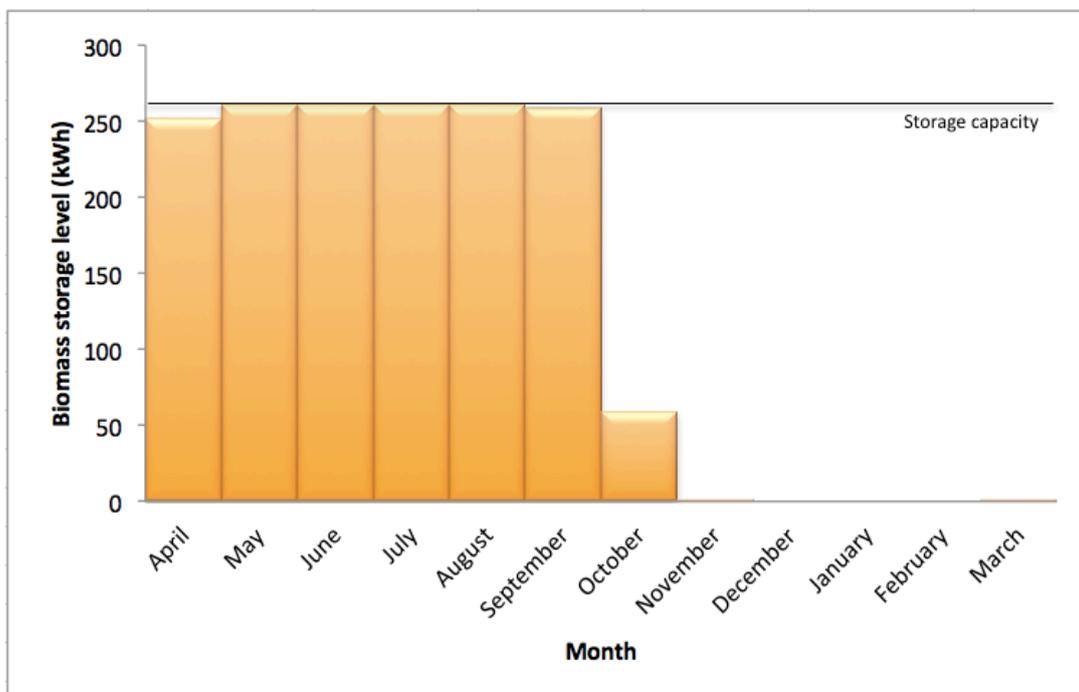
## 5.5. Results

In order to determine the changes in biomass and biogas storage level over the year, it is necessary to make sure that the cycles of the model are corresponding with the months of the year. Therefore the model counts a total of 365 cycles. Herein, the leap years have been disregarded. In Table 5-4 it is shown which cycle number corresponds with which month of the year. Every month has another mean of the random supply and demand data, calculated in this chapter. The first cycle is in the month April, because in the summer period the mean supply data exceeds the mean demand data (Table 5-1 + Table 5-3). The storages will then first have time to fill up before going into a period with low supply and high demand. It is assumed that the biomass storage is empty at the beginning of the first cycle, and that the biogas storage has a storage level of 1000 kWh at the beginning of the first cycle.

**Table 5-4: The cycle numbers that in the model have to contain the supply and demand data corresponding with a specific month of the year**

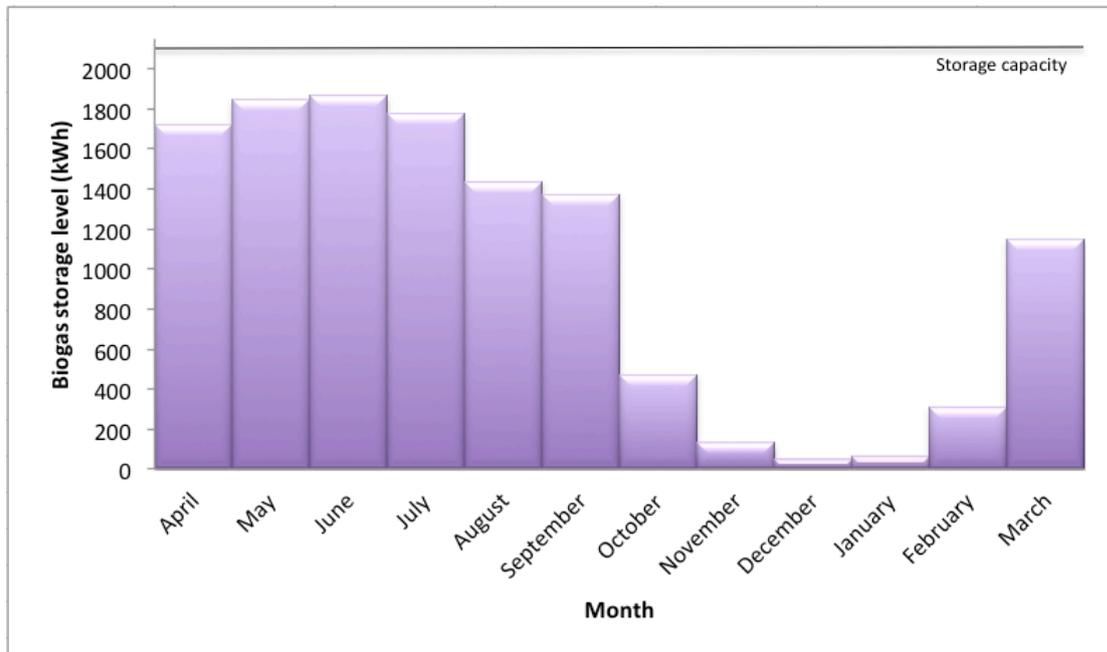
Month	Corresponding cycle numbers (n)
April	1-30
May	31-61
June	62-91
July	92-122
August	123-153
September	154-183
October	184-214
November	215-244
December	245-275
January	276-306
February	307-334
March	335-365

After running the model for 200 times, averages have been taken from the obtained data and are shown in the figures below. In Figure 5-1 it can be seen that in spring and summer months, the biomass storage is completely filled because the food and yard waste supply in this period exceeds the digester capacity. However especially in the winter, the biomass storage is depleted quickly because the food and yard waste supply is then substantially lower than the digester capacity. Thus in this period of the year, all food yard waste supplied goes directly to the digester and there is no need for storage.



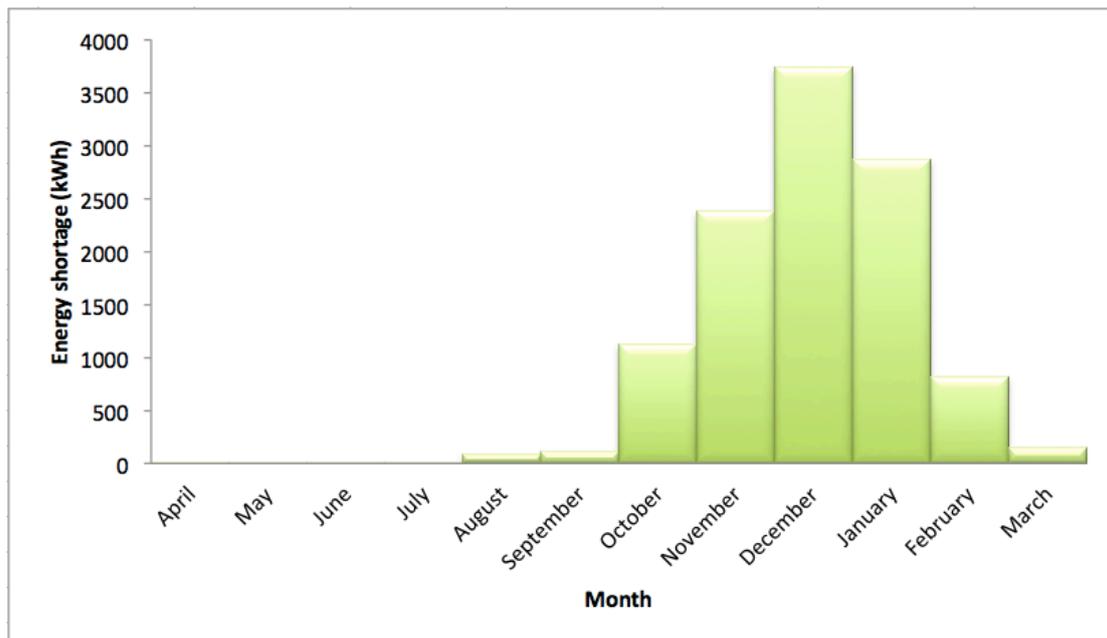
**Figure 5-1: Simulation of the monthly course of the average biomass storage level**

In Figure 5-2 for the monthly course of the biogas storage almost the same trend is seen as in Figure 5-1: in spring and summer the biogas storage is largely filled up, but in autumn the storage level decreases due to higher demands and lower supplies. In December and January, the storage level is almost entirely depleted and is no use for satisfying the demand.



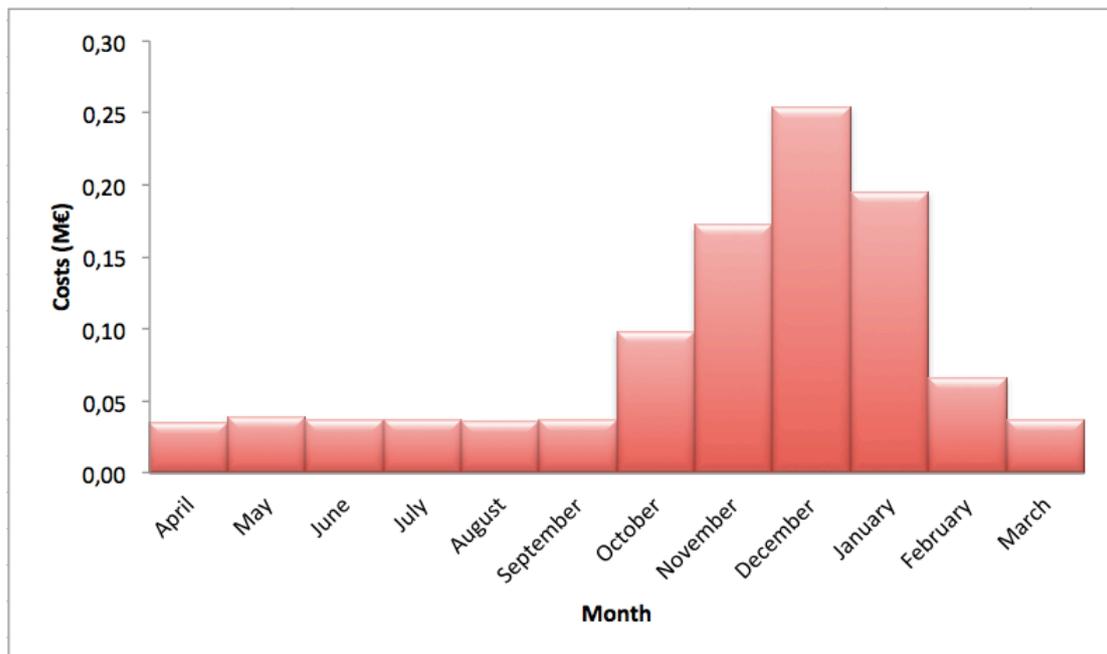
**Figure 5-2: Simulation of the monthly course of the average biogas inventory level**

As expected when looking at energy shortages in Figure 5-3, it is seen that large energy shortages occur in the autumn and winter months due to depleted biomass and biogas storages.



**Figure 5-3: Simulation of the total amount of energy shortages encountered in each month**

The same trend is seen when looking at the system costs. Because of a high penalty paid for the demand that is not satisfied in the autumn and winter, the costs of the system increase in this period (Figure 5-4).



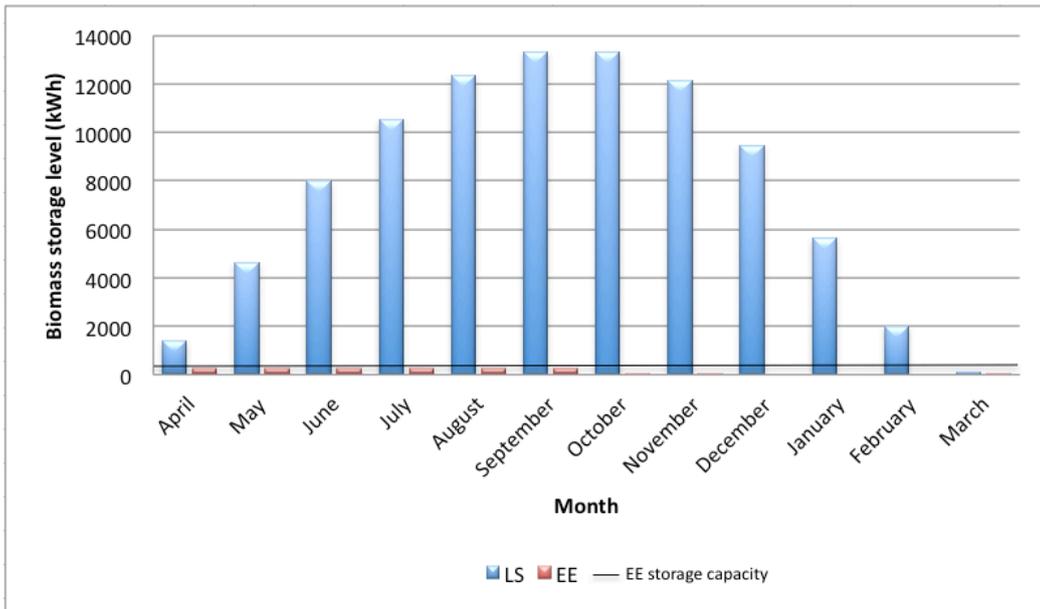
**Figure 5-4: Simulation of the monthly course of the system costs**

## 5.6. Additional results

The main problem of the system is that when the energy demand increases, the energy supply decreases in autumn and winter. These factors together create too large of an energy gap for the storage to be able to fulfill the energy demand during the whole winter. Thereafter, in spring and summer there is no room for accumulation of biomass and biogas in the storages because of only limited storage capacity.

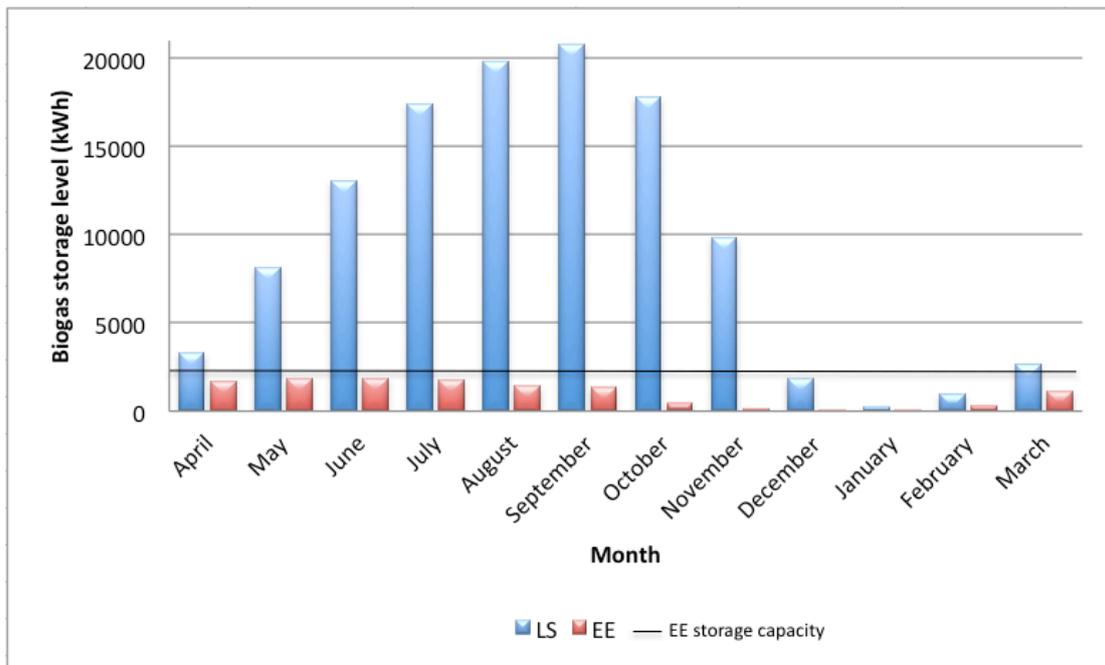
Therefore it is interesting to look at two possibilities to solve this problem: use of a very large storage of biomass and biogas in which the accumulation of biomass and biogas storage is possible in spring and summer (LS) or the same system with electricity shortages externally bought from the power grid which means that  $p_{ncd} = 0$  (EE).

Looking at the monthly biomass storage level in these two situations show the same results for the EE system as in Figure 5-1. However for the LS system it is seen that biomass storage level increases until October, and that this stored biomass can be used to keep the digester running at full capacity until February. Despite the fact that there is still a short depletion of storage in March, this would be an improvement compared to the small storage capacity (Figure 5-5).

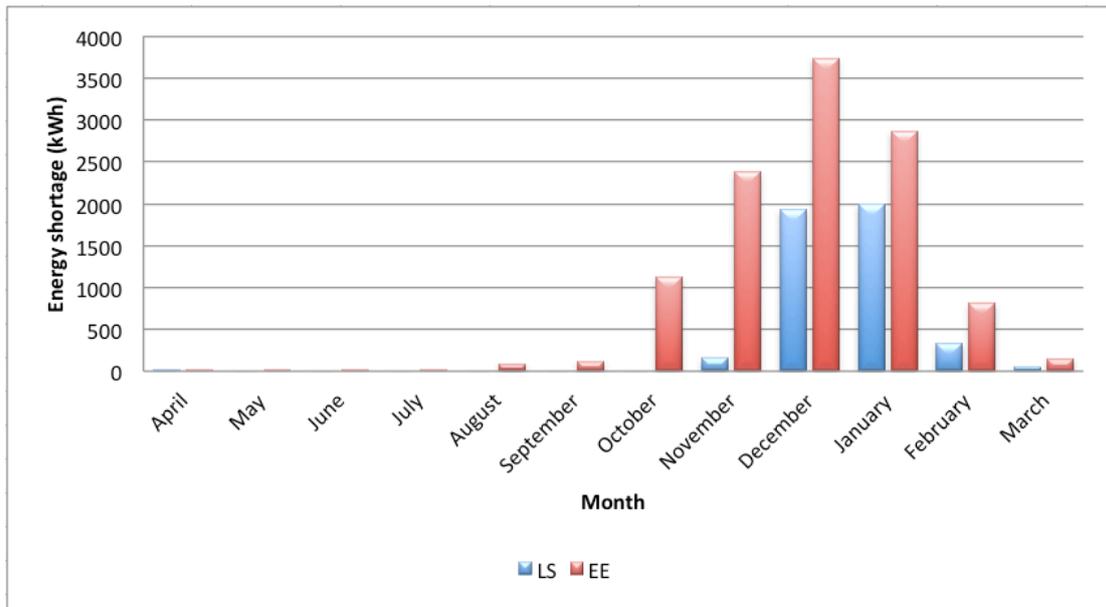


**Figure 5-5: Comparison of the monthly average biomass storage level for a large storage (LS) system and an externally bought energy (EE) system**

The monthly average biogas storage level for the LS system also shows that the biogas storage is filled up until September. However the biogas stored in the spring and summer is not enough to cover the whole winter, because in December the storage starts to get depleted (Figure 5-6). This can also be seen when looking at the comparison between the energy shortages. Although the energy shortages are smaller compared with an EE system, there still occur a lot of energy shortages in December and January (Figure 5-7).

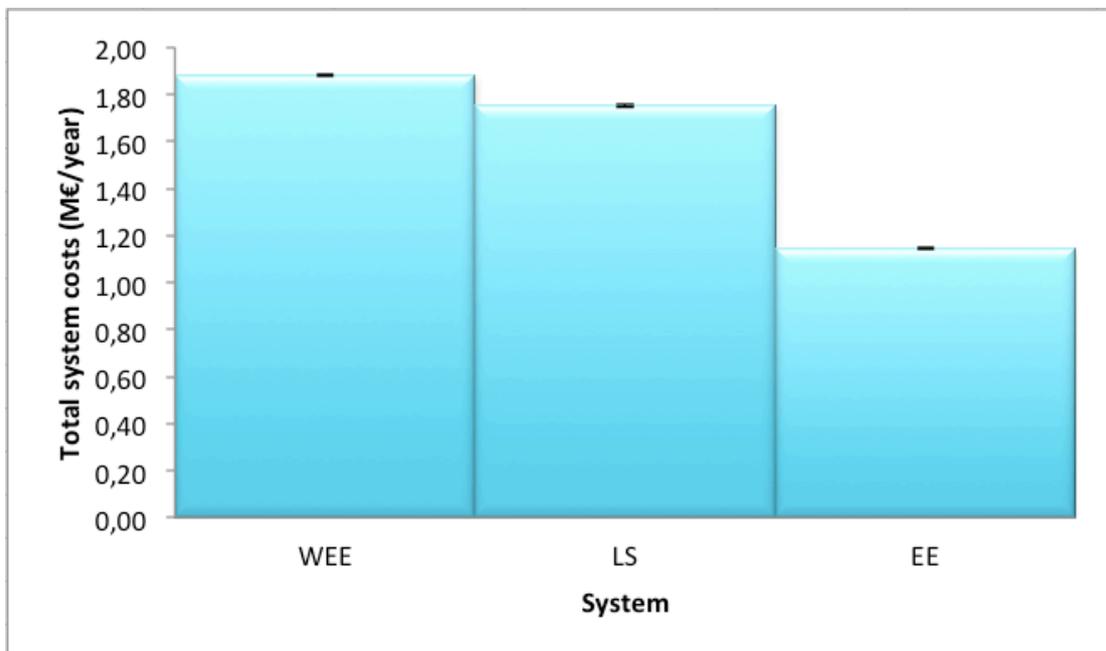


**Figure 5-6: Comparison of the monthly average biogas storage level for a large storage (LS) system and an externally bought energy (EE) system**



**Figure 5-7: Comparison of the total monthly energy shortages for a large storage (LS) system and an externally bought energy (EE) system**

The large energy shortages that occur in Figure 5-7 for the EE system are not damaging for the office building, because the shortages are externally bought from the grid. It is interesting though to compare total system cost for three systems: a normal system without externally bought electricity as investigated in 5.5 (WEE), a large storage system (LS) that allows accumulation of biomass and biogas storage, and a system in which shortages are externally bought from the grid (EE). These results are depicted in Figure 5-8 and show that externally buying a shortage of electricity from the power grid is substantially cheaper than having a large storage that allows accumulation of biomass and biogas during spring and summer.



**Figure 5-8: Comparison of the total system cost in M€ per year for a normal system without externally bought electricity from the grid (WEE), a large storage system that allows accumulation of biomass and biogas storage (LS), and a system in which shortages are externally bought from the power grid (EE)**

## Chapter 6. General discussion

In this report, an overview has been given for different biogas and biomass storage possibilities. It has also been shown that newsvendor model can be used to determine the most profitable storage capacity of biogas or biomass storages in a single-period time frame. Finally, the development of a model that considers multiple periods has been performed to enable investigating in the inventory level over a certain period. However some problems were encountered during this thesis work.

Firstly, renewable energy supply is mainly dependent on weather conditions and waste production. This supply is not depending on the size of the storage. However a supply dependent on the storage capacity had to be assumed when considering the newsvendor model. Namely when changing newsvendor model into a model for a renewable energy storage system, the order quantity has been exchanged for the storage capacity. The order quantity is equivalent to the supply in newsvendor model, which means that the model assumes that everything that is stored is also supplied. A supply yield could be added to make this situation more realistic, but the fact that the supply in newsvendor model is depending on the storage capacity cannot be changed.

Furthermore, the fluctuation data for wind and solar energy production and energy demand were obtained from the UK, while the fluctuation data for food and yard waste and the mean demand and food and yard waste data were obtained from the Netherlands. This meant that the assumption had to be made that the UK and the Netherlands have the same fluctuations in weather conditions and energy demands over the year. According to the short distances between the two countries, this might still approach reality. However having to make this assumption is not optimal.

Another problem of the model is the fact that there is not enough food and yard waste production to make the system self-sufficient. Therefore, the system will stay dependent on importing food and yard waste from other households or regions. This means that, for the system on a large scale to work, another biomass substrate or renewable energy production method will have to be found.

Also a problem is that the model assumes food and yard waste to be collected daily at the selected households. Because the food and yard waste production per household is less than one kg per day, this would mean that trucks have to drive to places for only a very small amount of food and yard waste. In reality, this would thus be a very inefficient and expensive way of collecting the waste.

The biogas is in the model assumed to be stored under low-pressure, which means that the biogas storage takes in a relatively large amount of space. For companies that do not have large biogas storages or need to transport stored energy, high-pressurized biogas storage is needed. However as explained in chapter 2, the compression of biogas is very energy intensive and brings along much larger investment cost and operational cost. Therefore for further research, a cost-analysis of the storage system with high-pressurized biogas storage should be made.

## Chapter 7. Conclusions

In this study, the ability to deal with the fluctuations that occur in renewable energy supply and energy demand over the year was investigated for a system in which renewable energy is stored in biomass and biogas. Therefore, different options for storage of biomass and biogas were compared within a literature review. It was found that the storage of food and yard waste without pre-treatment is very inefficient due to the high moisture content of the waste. Therefore, a torrefaction pre-treatment of food and yard waste before storage was proposed. It was found that the loss of dry matter during food and yard waste storage was 0.9% per day without pre-treatment, and almost none with a pre-treatment.

Furthermore, biogas storage was compared for gas grid storage, compressed tank storage under low-pressure, compressed tank storage under high-pressure, and belowground reservoir storage. Gas grid storage was found to have too little storage capacity for large biogas production systems. Thereby smaller systems would probably not be able to connect with the gas grid for biogas storage.

Compressed tank storage under high-pressure was found to have large costs due to the need for a multi-stage compressor. On the other hand, low-pressure biogas storage was found to have much lower costs. Therefore it can be concluded that when choosing the pressure in a compressed tank for biogas storage, both the large costs coming along with a high-pressurized storage and the large tank size needed for a low-pressurized storage need to be taken into consideration.

Belowground reservoir storage was found to be more suitable for large systems, because smaller systems would have difficulty getting connected with such reservoirs. However for a large system, because of the huge capacity and the low investment and operational costs of the storage, belowground reservoir storage would be a good option.

Further in this study, investigation in the specified storage system was done with torrefied food and yard waste storage and compressed biogas storage in a low-pressurized tank. The storage system was tested in a case study for an office building in the Netherlands. Newsvendor model was used for determining the storage capacity of biomass and biogas storage. The results showed that according to the newsvendor model, biogas and biomass storage capacities of respectively 2097 kWh and 261 kWh were needed for the storage system in the case study.

Thereafter, a model for following biomass and biogas storage level over one year was developed. The results of demonstrating this model in the case study of an office building in the Netherlands showed that storages were full in the spring and the summer, periods with low energy demand and high energy production. However storage capacities were not enough to prevent depletion of storage in the winter, a period with high energy demand and low energy production. Thus a storage capacity determined by newsvendor model does not allow accumulation of stored product in periods with low energy demand and high energy production. Consequently, energy shortages occur in the periods with a high energy demand and a low energy production.

Therefore, two additional systems were proposed: a system with a very large storage capacity that allows accumulation of biogas and biomass in the spring and summer for use in the winter (LS) and a system in which the energy gap in the winter is closed with external energy bought from the grid (EE). Results show that the energy shortages are indeed reduced for the LS system compared with the EE system. However, system costs are shown to reduce significantly for the EE system. It is thus cheaper to buy the lack of energy from the grid, than to use very large storage capacities.

In the end, it can thus be concluded that newsvendor model cannot be used for determining storage capacity of renewable energy systems over a long time period because of the large seasonal fluctuations of energy demands and renewable energy production. Because a huge storage capacity will be needed for allowing accumulation of stored product, the biogas storage in a compressed tank will be too expensive and also need to be reconsidered. Storage of renewable energy within the proposed system might then only be possible when using the huge storage capacity within belowground reservoirs. Because this storage technique is only available for large storage systems with access to these depleted reservoirs, it must be concluded that the proposed system is not achievable at small scale as investigated in the case study.

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## Appendix A Calculation of the critical fractile

The critical ratio can be derived when knowing that  $F_D$  is the probability that the storage capacity  $Q$  is large enough to meet demand  $D$ , or:

$$F_D = p(Q > D)$$

This means that the probability that the storage capacity  $Q$  is too small to meet demand  $D$  is defined by  $(1 - F_D)$ :

$$(1 - F_D) = p(D > Q)$$

Overage cost is present when  $Q > D$  and underage cost is present when  $D > Q$ . Knowing that the most profitable situation is a situation in which both overage and underage cost contribute equally to total cost gives:

$$F_D * c_o = (1 - F_D) * c_u$$

This can be rewritten as:

$$F_D * c_o = c_u - F_D * c_u$$

Bringing  $F_D * c_u$  to the other side gives:

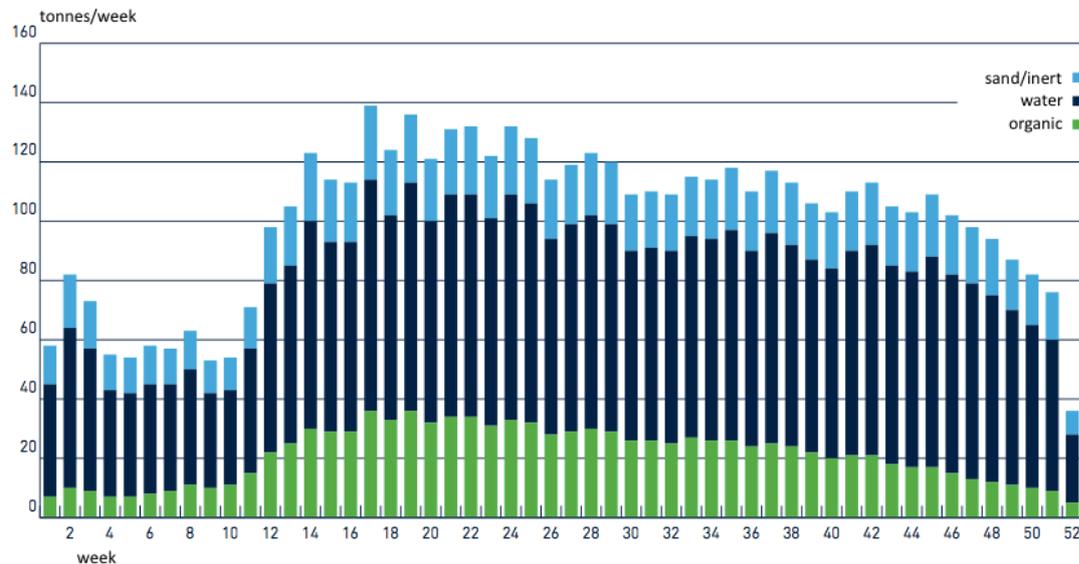
$$F_D * (c_o + c_u) = c_u$$

Dividing by  $(c_o + c_u)$  gives the critical ratio that is given in chapter 3:

$$F_D = \frac{c_u}{c_o + c_u}$$

## Appendix B Fluctuations of food and yard waste production

The food and yard waste production and composition data in the Netherlands from Vereniging Afvalbedrijven (2010) is shown in Figure B-1.



**Figure B-1. Food and yard waste production and composition data for the period 2002-2009 in the Netherlands. Source: (Vereniging Afvalbedrijven, 2010)**

Only the organic material can be used for anaerobic digestion, and thus only the data for the organic part of the waste is interesting for the fluctuations. The fluctuation data are shown per week. In Table B-1 these data have been converted into fluctuation data per month by taking the averages of the week data corresponding with certain months.

**Table B-1: Conversion of the weekly fluctuations from figure 6 into monthly fluctuations**

Month	Corresponding weeks	Average organics supply from week data (tonnes/week)
January	1-4	6.5
February	5-8	8.3
March	9-13	17.0
April	14-17	32.0
May	18-22	35.6
June	23-26	33.0
July	27-31	29.6
August	32-35	27.0
September	36-39	23.8
October	40-44	19.4
November	45-48	15.0
December	49-52	8.5

## Appendix C Calculation of the standard deviations

The standard deviation of the total biogas demand is determined with:

$$\sigma_{D,biogas} = \sigma_{DT} + \sigma_{WT+PV}$$

Herein, the standard deviation of the energy demand and the WT + PV production can be determined by the sum of the short-term standard deviation (chapter 4) and the standard deviation of the long-term fluctuations (Table 5-1 + Table 5-3). It is assumed that the short-term fluctuations of the biogas demand have a standard deviation of 40% of its mean value (Chapter 4):

$$\sigma_{DT} = \sigma_{DT,short} + \sigma_{DT,long} = \mu_{DT} * 0.4 + STDEV(Data Table 53) = 212 kWh$$

$$\sigma_{WT+PV} = \sigma_{WT+PV,short} + \sigma_{WT+PV,long} = \mu_{WT+PV} * 0.1 + STDEV(Data Table 51) = 82 kWh$$

The standard deviation of the waste supply can be calculated in the same way when for calculating the long-term standard deviation the data from Table 5-2 are used. It is assumed that the short-term fluctuations of the food and yard waste supply have a standard deviation of 10% of its mean value (Chapter 4):

$$\sigma_{FYW} = \sigma_{FYW,short} + \sigma_{FYW,long} = \mu_{FYW} * 0.1 + STDEV(Data Table 52) = 109 kWh$$

Source cover image: (Neegaard, 2011)